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ABSTRACT

We determine radial- and age-abundance gradients of the Small Magellanic Cloud (SMC) using spectra of 2062 red giant branch field stars observed by SDSS-IV / APOGEE-2S. With coverage out to ~ 9 kpc in the SMC, these data taken with the high resolution ($R \sim 22\,500$) APOGEE H -band spectrograph afford the opportunity to measure extensive radial gradients for as many as 24 abundance ratios. The SMC has an overall metallicity ($[\text{Fe}/\text{H}]$) gradient of -0.0546 ± 0.0043 dex kpc $^{-1}$. Ages are calculated for every star to explore the evolution of the different abundance gradients. As a function of age, many gradients fatten with decreasing age but begin to steepen for ages 3.7–5.6 Gyr, particularly in the α -element $[\text{X}/\text{H}]$ gradients. We previously detected similar evolutionary patterns ~ 1.7 –3.6 Gyr earlier in the Large Magellanic Cloud (LMC) which are attributed to a recent interaction between the Magellanic Clouds. It is inferred that the feature in the SMC gradients was caused by the same interaction. The age– $[\text{X}/\text{Fe}]$ trends, which track average $[\text{X}/\text{Fe}]$ over time, are fat, demonstrating a slow enhancement with respect to Fe for the SMC. When comparing the SMC gradients to the LMC and MW, normalized to disc scale length (R_d), the $[\text{X}/\text{Fe}]$ and $[\text{X}/\text{Mg}]$ gradients are similar, but there is a dichotomy between the dwarfs and the Milky Way (MW) for the $[\text{X}/\text{H}]$ gradients. The median MW $[\text{X}/\text{H}]$ gradient around -0.119 dex/ R_d whilst the Clouds have gradients of about -0.082 dex/ R_d and -0.061 dex/ R_d for the SMC and LMC, respectively.

Key words: galaxies: abundances – galaxies: dwarf – galaxies: evolution – galaxies: individual: Small Magellanic Cloud – Magellanic Clouds.

1 INTRODUCTION

The Small and Large Magellanic Clouds (MCs) are a conjoined pair of massive dwarf satellite galaxies currently approaching our Milky Way (MW). The Small Magellanic Cloud (SMC) has a stellar mass of $\sim 3\text{--}3.5 \times 10^8$ M (Skibba et al. 2012) and dark matter mass of $M_{\text{DM}}(R < 4 \text{ kpc}) = 1\text{--}1.5 \times 10^9$ M (Di Teodoro et al. 2019). The galaxy is also well within the virial radius of the MW at a distance of 62.44 kpc (Graczyk et al. 2020), and, therefore,

relatively bright, with an integrated apparent V magnitude of 2.2 ± 0.2 (McConnachie 2012). Combined, these factors make the SMC a prime candidate for resolved stellar population analyses with high-resolution spectroscopy, because it presents a large number of accessible red giant branch (RGB) stars brighter than $V \sim 18$ (e.g. Harris & Zaritsky 2006; Dobbie et al. 2014a; Nidever et al. 2020).

The SMC is a dwarf irregular galaxy (dIrr) with a complex geometry. The entire shape of the galaxy has been heavily affected by tidal interactions with the Large Magellanic Cloud (LMC), and continues to be a challenge to model. It has been shown that the SMC is very extended along the line of sight on the eastern side

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(towards the LMC), more than the extent it shows face-on and as much as 20 kpc based on observations of standard candles (Nidever et al. 2013; Scowcroft et al. 2016). Previously seen and described as a ‘distance modality’ (Nidever et al. 2013), this deepening of the eastern SMC may represent tidal material pulled out of the SMC (e.g. Almeida et al. 2024).

One of the most striking characteristics of the MCs as a whole is the trail of H I gas coming off the MCs, known as the ‘Magellanic Stream’ (MS; e.g. Mathewson, Cleary & Murray 1974; Putman et al. 2003; Brüns et al. 2005; Nidever, Majewski & Butler Burton 2008), which was discovered to extend up to 200° across the sky (Nidever et al. 2010). The Stream is thought to be made mostly of stripped SMC gas (Besla et al. 2012; Lucchini et al. 2020) in a scenario where the MCs are in their first infall to the MW (Besla et al. 2007; Kallivayalil et al. 2013).

Interacting galaxies are typically characterized by tidally or collisionally incited bursts of star formation (e.g. Privon et al. 2017). The MCs are known to have had a close interaction in the recent past based on their observed kinematics (Zivick et al. 2018; Nidever et al. 2020; Niederhofer et al. 2021; Schmidt et al. 2022). The Magellanic Bridge (MB; Hindman, Kerr & McGee 1963), a span of gas and young stars (~50 Myr old; Demers et al. 1991; Muller & Bekki 2007) between the two galaxies (stretching ~10° from the SMC to the LMC), has long been thought to be the result of their most recent interaction, only ~200 Myr ago (e.g. Gardiner, Sawa & Fujimoto 1994; Muller & Bekki 2007; Besla et al. 2012; Diaz & Bekki 2012; Schmidt et al. 2020). Additionally, the MCs are expected to have been interacting prior to that event, based on the modelling of their tidal debris (Cullinane et al. 2022) and star formation histories (Rubele et al. 2018; Mazzi et al. 2021; Massana et al. 2022). Therefore, it is logical to expect that the chemical evolution of the MCs has been significantly influenced by periodic interactions and bursts of star formation. Naturally, the chemical abundance gradients in either galaxy should be expected to respond as a consequence.

Among the attempts to explore the recent close interaction of the MCs, Nidever et al. (2020) used the *FLEXCE* code (Andrews et al. 2017) to model the chemical evolution of the LMC, and, by this means, show evidence for a spike in star formation in the LMC about 2 Gyr ago. This was accomplished by allowing the star formation efficiency (SFE) to vary as a function of time and superimposing a Gaussian peak on top of the SFE to act as the burst. Using similar modelling with *FLEXCE* and a time-evolving SFE, Hasselquist et al. (2021) was able to confirm the time frame of the star formation burst in the LMC. That work also modelled the chemical evolution of the SMC and found that the burst was weaker and happened ~3–4 Gyr earlier than in the LMC. Based on this apparent delay between the star formation bursts in the MCs due to their close interaction, it is expected that changes in the chemistry of the SMC should predate analogous changes in the LMC.

Interacting dwarf galaxy systems are important tools for understanding how the MW and other larger galaxies formed. The prevailing ‘hierarchical merging’ galaxy formation paradigm (Searle & Zinn 1978; White & Rees 1978) is that galaxies grow through a steady accumulation of merging subsystems on a growing spectrum of mass scales. Smaller, dwarf galaxies were the first type of galaxy to form, and, then these merged to form galaxies in the large range of sizes and masses that we see today. However, our knowledge of the details of these earlier processes is still incomplete. While even today the Universe is full of dwarf galaxies still engaged in the process of hierarchical merging, detailed study of this process is typically challenged by the fact that most prime examples are too faint and distant to be in the realm of resolved stellar population studies. For

this reason, the MCs present a particularly unique opportunity to dissect – with star-by-star, high resolution spectroscopic analysis – a key step in the process of galaxy assembly.

Previously, most spectroscopic studies of SMC stars could only explore its overall metallicity gradient (e.g. Dobbie et al. 2014b; Choudhury et al. 2020; De Bortoli et al. 2022; Parisi et al. 2022; Li et al. 2023) and not other abundances. This is because multi-element chemical abundance studies require high *S/N*, high-resolution spectra to derive precise elemental abundances, whereas the mean metallicity of stars is more readily measured with lower resolution ($R \sim 1000$), lower *S/N* data. However, the Apache Point Observatory Galactic Evolution Experiment (APOGEE; Majewski et al. 2017), a part of the Sloan Digital Sky Survey III (SDSS-III) (Eisenstein et al. 2011) and APOGEE-2, a part of SDSS-IV (Blanton et al. 2017), has yielded a rich data base $R \sim 22\,500$ of and $S/N > 100$ spectra and derived data products (stellar parameters and multi-element chemical abundances) for nearly 3/4 million stars across the MW and its satellite system. APOGEE-2 had as a specific science driver the exploration of the MCs, which motivated placement of a second, APOGEE-S spectrograph (Wilson et al. 2019) in the Southern Hemisphere. This work is part of a series of three papers on the Magellanic Clouds and their chemistry, as revealed by APOGEE data. Povick et al. (2024) (hereafter *Paper I*), presents a method to calculate ages of individual RGB stars using high-resolution spectroscopy, multiband photometry, and isochrones and applies it to the APOGEE-2S sample of the LMC. In Povick et al. in preparation (hereafter *Paper II*), the abundance gradients of the LMC and their temporal evolution are determined. The focus of this third paper in the series is the abundance gradients of the SMC

In this paper, after discussion of the APOGEE and *Gaia* data (Section 2), Section 3 outlines how we estimate distances and ages for the SMC stars. Section 4 outlines abundance trend calculations, while their results are presented in Section 5. From there, we discuss the implications of these results in Section 6. Finally, concluding remarks are given in Section 7.

2 DATA

For our study of the SMC, we not only use the high-resolution, high-*S/N* spectroscopic data from APOGEE, but also multiband photometry and astrometry from *Gaia*.

2.1 APOGEE data

Originally, the APOGEE survey was a single *H*-band spectrograph (Wilson et al. 2019) linked to the 2.5-m Sloan Telescope at Apache Point Observatory (APO; Gunn et al. 2006) in New Mexico. With the most recent iteration of APOGEE (APOGEE-2), a second APOGEE spectrograph was installed at the Las Campanas Observatory (LCO; Bowen & Vaughan 1973) in Chile, making it possible for APOGEE to obtain data in the Southern Hemisphere. The APOGEE data on the MCs were taken entirely as part of the second phase, APOGEE-2 programme in SDSS-IV (Blanton et al. 2017). All of the APOGEE-2 data are available in SDSS-IV data release 17 (DR17; Abdurro’uf et al. 2022). Specific information about the targeting for APOGEE and APOGEE-2 can be found in Zasowski et al. (2013, 2017), while targeting information for the APOGEE-2 MC survey is in Nidever et al. (2020), which outlines specific selection criteria (i.e. photometric cuts) that minimize MW contamination in the high fidelity MC sample.

Stellar atmospheric parameters and chemical abundances are derived from the observed spectra in a two-step process. First,

the observed spectra are fed into the APOGEE pipeline (Nidever et al. 2015) for basic reduction (1D spectral extractions from the 2D images, wavelength calibration, flat-fielding, sky subtraction, etc.). Accurate stellar parameters are then calculated from the reduced spectra using the APOGEE Stellar Parameter and Chemical Abundance Pipeline (ASPCAP; Holtzman et al. 2015; Pérez et al. 2016). This second pipeline utilizes the FERRE (Allende Prieto et al. 2006) package to match the T_{eff} , $\log(g)$, v_{micro} , $[M/H]$, $[C/M]$, $[N/M]$, $[\alpha/M]$, and v_{macro} to a library of synthetic spectra created with *synspec* (Hubeny et al. 2021). The list of lines used to derive abundances for different elements by ASPCAP can be found in Smith et al. (2021) and Shetrone et al. (2015). Elemental abundances that are measured by ASPCAP include C, Cl, N, O, Na, Mg, Al, Si, S, K, Ca, Ti, Ti II, V, Cr, Mn, Fe, Co, Ni, and Ce. For DR17, the process of deriving these abundances is nearly identical to that in previous data releases except for some details outlined in Holtzman et al. (in preparation). More information on the APOGEE derivation of abundances for the s-process element Ce can be found in Cunha et al. (2017).

As with any measurements, the APOGEE results have both statistical uncertainties as well as some systematic errors. To attempt to remove the latter, potential systematic biases in the raw APOGEE measurements are determined by inspecting stars in the solar neighbourhood with solar metallicities. Element specific abundance zero point offsets are then derived for these solar metallicity stars and applied to the entire APOGEE data base. The statistical uncertainties were calculated from the scatter seen in multiple visits to the same stars processed independently as functions of T_{eff} , $[M/H]$, and SNR.¹ For more on the specifics of the offsets and uncertainties, please refer to Jönsson et al. (2020) and Nidever et al. (2020) and the discussion therein. For calculations used here, these calibrated abundances from ASPCAP values are used unless otherwise specified. Comparing to other studies the APOGEE abundances tend to be fairly accurate and precise (Jönsson et al. 2018, 2020; Nidever et al. 2020). The typical errors in the abundances for individual stars in the SMC from APOGEE are ~ 0.052 dex for the $[X/Fe]$, ~ 0.043 dex for the $[X/H]$, and ~ 0.046 dex for the $[X/Mg]$.

APOGEE was able to observe 2062 SMC RGB stars out to ~ 9 kpc in 14 different fields (see Fig. 1), and a Kiel diagram of this sample can be found in Fig. 2. This relatively large radial coverage makes the APOGEE SMC survey well-suited for determining the abundance gradients in the galaxy. Finally the measured abundances and corresponding uncertainties are available through SDSS DR17 website. See the data availability statement at the end of the paper for more information.

2.2 *Gaia* data release 3

The *Gaia* mission (Gaia Collaboration 2016, 2022) is a massive all-sky photometric, astrometric, and spectroscopic survey at optical wavelengths. The three *Gaia* photometric bands are BP (blue), *G* (green), and RP (red). The *Gaia* Archive stores all the publicly available data and can be accessed through the *Gaia* website.²

For this work, we use the *Gaia* red clump stars (RCs) in the APOGEE fields to derive ‘proper motion distances’ (see Section 3.1). The first step was to query the *Gaia* Archive for the SMC stars using a slightly modified version of the selection used by Gaia Collaboration (2021, hereafter ‘L21’). The largest deviation from the L21 criteria

¹The objective of APOGEE is to produce spectra with SNRs of 100 per half-resolution unit (e.g. Jönsson et al. 2020).

²<https://gea.esac.esa.int/archive/>

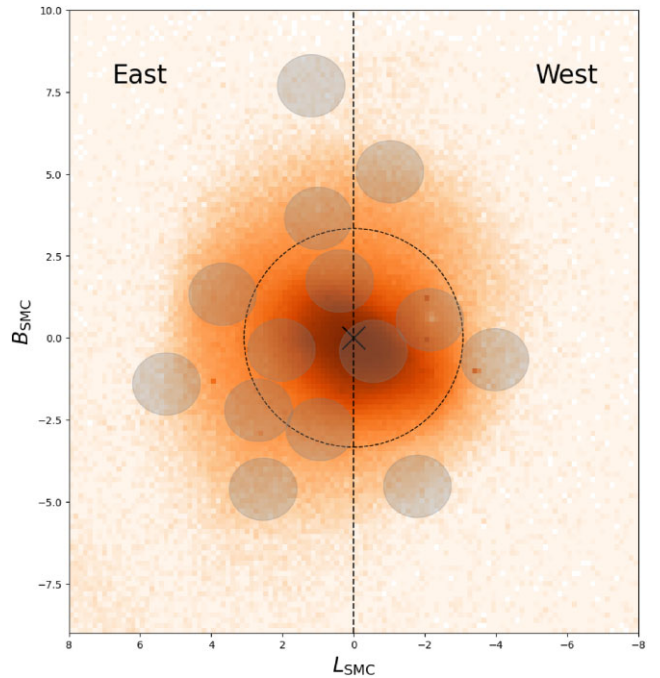


Figure 1. Stellar density map of the *Gaia* DR3 RGB with an SMC-like proper motions in an SMC-centric coordinate system in degrees. The fourteen APOGEE-2S SMC fields are highlighted in grey. The centre of the galaxy is marked with an ‘X’ at $(L_{\text{SMC}}, B_{\text{SMC}}) = (0^\circ, 0^\circ)$, which in equatorial coordinates is $(\alpha_0, \delta_0) = (13.18^\circ, -72.83^\circ)$. The vertical dashed line marks the delineation between East and West in the galaxy, and the large circle represents the boundary between the inner and outer SMC at a radius of 3.3 kpc. Note that the *Gaia* RGB density in this plot is only here for demonstration purposes, with darker regions showing a higher density of stars.

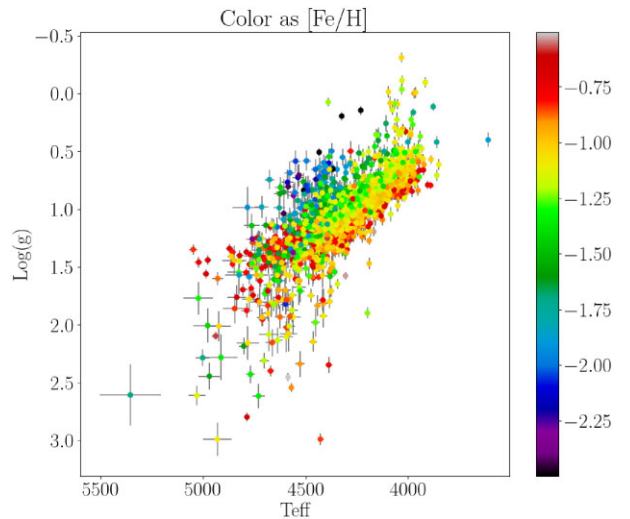


Figure 2. A Kiel diagram for APOGEE SMC RGB stars. The stars are colour-coded by their metallicity and error bars are shown in grey.

is using the centre of the SMC from Nidever et al. (2017) and some slightly more restrictive quality cuts. While it is unknown how many of these stars may be MW foreground contamination, it should be comparable to the contamination in the sample from L21. For the full ADQL query, see Appendix A.

Next, the RC stars are selected from the resulting *Gaia* table by using colour–magnitude diagram criteria determined by eye:

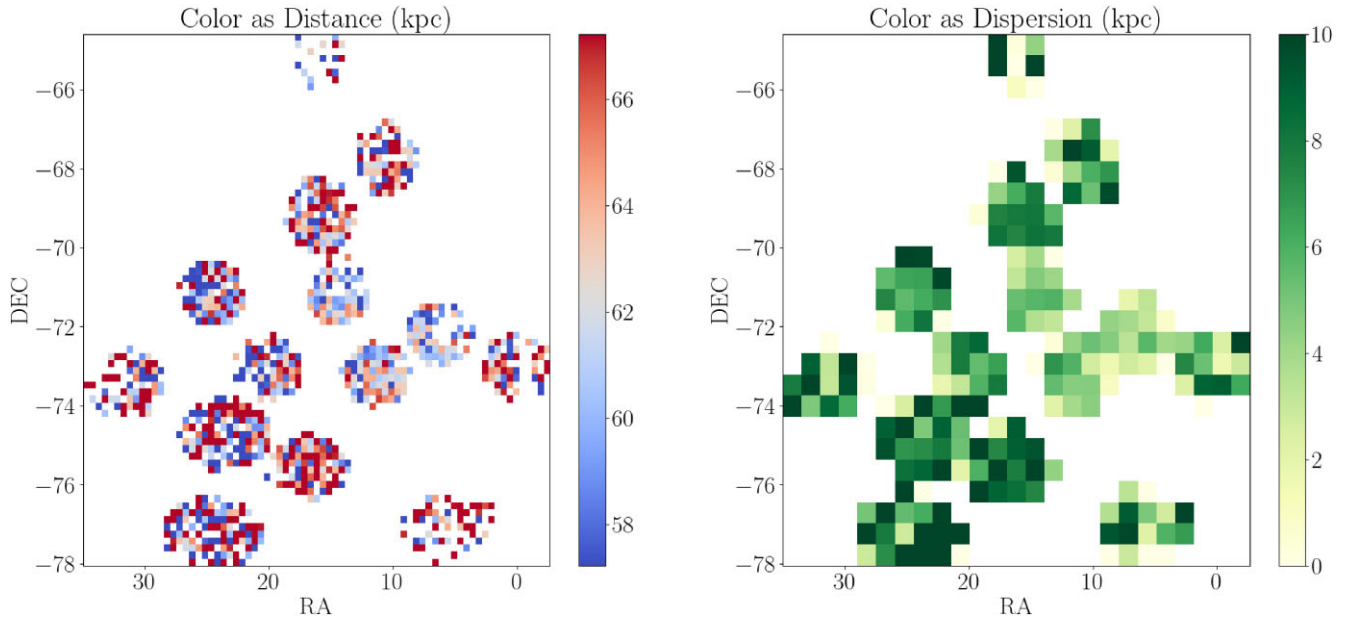


Figure 3. (Left) A map of the APOGEE SMC fields showing the mean distance in each spatial bin determined using our ‘proper motion distance’ method. In the East there is a bimodality in the distances leading to a larger range of distances. For more information about the bimodality see Almeida et al. (2024), which further explores this with the APOGEE data. (Right) A dispersion map for the calculated distances. The larger line-of-sight depth is clearly visible on the eastern side of the galaxy corresponding to where the distance bimodality can be found.

- (i) $0.875 < BP - RP < 1.2$
- (ii) $18.6 < G < 19.6$

Finally, for each APOGEE SMC field, all candidate RC stars within 0.95° of the field centre are selected, where 0.95° is the angular radius of the APOGEE plates.

3 CALCULATING DISTANCES AND AGES

In Paper I, we determined ages for individual LMC RGB stars using spectroscopically determined stellar parameters, multiband photometry, and isochrones. In Paper II, we used these ages to determine the temporal evolution of LMC elemental abundances and its radial abundance gradients. An important ingredient of our age-determination method is that we know the distances of the LMC RGB stars quite accurately because they lie predominantly within an inclined disc plane with observationally well-determined parameters. This allowed us to calculate absolute magnitudes that can be compared to isochrone photometry to constrain the star’s age. However, the SMC stars do not lie in an inclined disc plane, but, instead, have a complex, somewhat spheroidal geometry (e.g. Zaritsky et al. 2000) with a large line-of-sight depth on the eastern side. Thus, another technique to obtain the distances to SMC stars is needed to implement our age-determination method.

3.1 SMC distances

The kinematics of a star can be used to estimate its distance by way of its proper motion, which has a linear dependence on distance. The magnitude of the tangential velocity an object has is given by

$$v_t^2 = (4.74\mu d)^2, \quad (1)$$

where v_t is the tangential velocity, μ is the magnitude of the proper motion in units of mas yr^{-1} , and d is the distance to the object in units of kpc (with all quantities in a heliocentric reference frame).

For our APOGEE SMC RGB sample, the radial velocities are known from the APOGEE spectroscopy and the proper motions from *Gaia* astrometry. Although the tangential velocity (v_t) of any RGB star is unknown, it can be estimated by using the *Gaia* RC stars. These stars are standard candles, and therefore their distances can be accurately established simply from their photometry. While the RC absolute magnitude is fairly constant in near-infrared (NIR) magnitudes (Bovy et al. 2014), it has a metallicity dependence in the optical bands (Girardi 2016). Using PARSEC isochrones (Girardi et al. 2002; Bressan et al. 2012; Marigo et al. 2017), we determine that the G -band absolute magnitude of the RC for the mean metallicity of the SMC ($[\text{Fe}/\text{H}] = -1.1$) is $G_{\text{RC,SMC}} = -0.21$. After determining the distance of each individual RC star, its tangential velocity can be calculated by using its distance and proper motion via $v_t = 4.74\mu d$. Next, we calculate the mean tangential velocity of all the *Gaia* RC stars in each APOGEE field separately. Finally, the distance of an individual RGB star can be calculated from its μ under the assumption that its tangential velocity is the same as the mean RC tangential velocity in its field, using

$$d_{\text{RGB}} = v_{t,\text{RC}} / (4.74\mu). \quad (2)$$

We find that the mean distance for the SMC RGB stars using this method is 66.21 kpc. An offset of 3.77 kpc is then applied so that the mean distance of the RGB stars matches the 62.44 kpc found by Graczyk et al. (2020). It is important to mention that the 62.44 kpc value was derived using eclipsing binaries in that work. Because of this, there is an implicit assumption that the giants more or less follow the distribution of the eclipsing binaries as well as the RC stars in the galaxy.

Naturally, the actual tangential velocity of any given RGB star will deviate from the field-averaged mean. This will result in an error in our distance calculation. We can estimate this bias by using the measured radial velocity dispersion and assuming that the tangential velocity dispersion is similar. The average v_t dispersion of the 14 SMC fields is 22.7 km s^{-1} . Using propagation of errors, this v_t

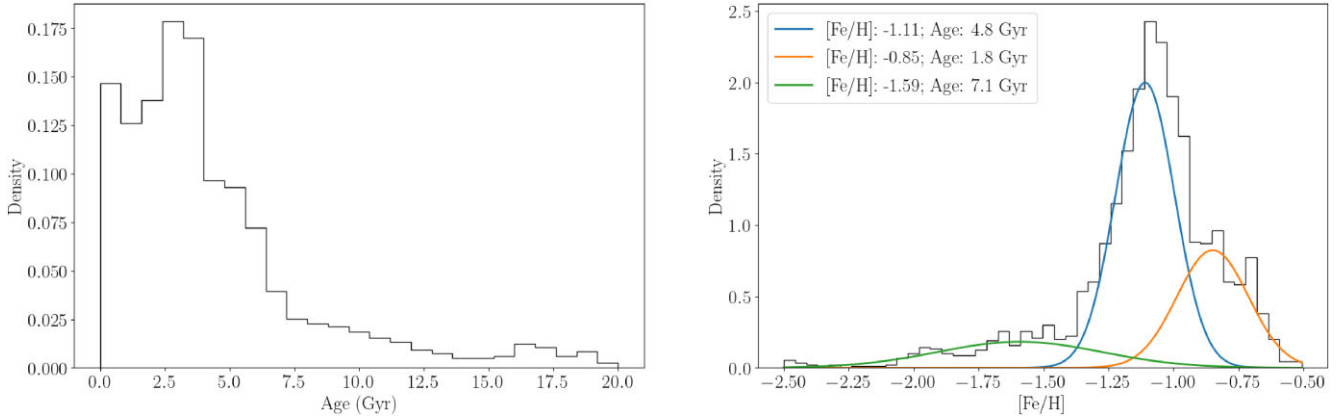


Figure 4. (*Left*) The distribution of calculated ages for the SMC stars. A large portion of the stars formed within the last ~ 7.5 Gyr in the SMC with a peak ~ 3 –4 Gyr ago. This RGB age distribution is very reminiscent to that seen for the LMC (see fig. 19 of Paper I). In addition, the feature at ~ 5 Gyr corresponds to one of the peaks in the SFH from Rubele et al. (2018). (*Right*) The distribution of $[\text{Fe}/\text{H}]$ for the APOGEE RGB stars in this study. Fitting a GMM, three populations were identified. The strongest peak in blue corresponds to a population with an average $[\text{Fe}/\text{H}]$ of -1.11 ± 0.11 and age of 4.8 ± 2.2 Gyr. The orange distribution with an average $[\text{Fe}/\text{H}]$ of -0.85 ± 0.11 and age of 1.8 ± 1.7 Gyr shows very recent star formation. An underlying population of old stars is shown green with an average $[\text{Fe}/\text{H}]$ of -1.59 ± 0.23 and age of 7.1 ± 5.3 Gyr. The two largest peaks have metallicities consistent with the two most prominent peaks found in Mucciarelli (2014).

dispersion translates to 3.25 kpc in distance. At an average SMC distance of 62.44 kpc, this amounts to a 5.2 per cent uncertainty, which is quite good. The *Gaia* proper motions of the relatively bright individual SMC RGB stars have a fractional uncertainty of 4.2 per cent which also translates to a fractional uncertainty in distance of 4.2 per cent or 2.6 kpc. Combining these two sources of uncertainty in quadrature gives us an overall distance uncertainty of 4.16 kpc or 6.7 per cent on a star-by-star basis. There are also systematic errors, as evidenced by the 3.77 kpc offset applied. Fig. 3 shows a map of the APOGEE SMC distances determined using this method showing a higher distance dispersion on the eastern side, as previously reported.

3.2 SMC ages

Using the age method outlined in Paper I and the distances from the previous section, ages can be derived for the individual SMC stars. To determine the age of a star, model photometry (*Gaia* and 2MASS) and $\log g$ are calculated by interpolating PARSEC as functions of T_{eff} , $[\text{Fe}/\text{H}]$, $[\alpha/\text{Fe}]$, and a trial age. The best-fitting age is found by varying the trial age until the model photometry matches the observed photometry. Since stars can be α -enhanced and PARSEC isochrones are based on scaled solar models, the $[\text{Fe}/\text{H}]$ are adjusted using the correction from Salaris, Chieff & Straniero (1993) (see Paper I for updated values of the coefficients used for the correction). Ages between 0.5 and 10 Gyr were found to be the most reliable when validating with the APOKASC-3 data set (Pinsonneault et al. in preparation), which combines spectroscopic data from APOGEE and asteroseismic data from Kepler (Pinsonneault et al. 2014, 2018). Additionally, the ages were validated by deriving masses for each star using the Stefan–Boltzmann equation and then calculating the ages based on the age–mass anticorrelation for giants. The average deviation from these ages was found to be approximately 0.45, demonstrating good agreement.

We find that the distribution of our derived SMC ages shown in Fig. 4 and looks quite similar to the LMC age distribution shown in fig. 19 of Paper I. The age distribution of the RGB stars in the SMC shows that the number of RGB stars increases starting about 7.5 Gyr ago with a prominent feature about 5 Gyr ago and a peak ~ 3 –4 Gyr

ago. The feature at 5 Gyr correlates with the peaks SFR between 4.0 and 6.3 Gyr ago found by Rubele et al. (2018), suggesting a potential common origin.

As a consistency check of the SMC ages, we can explore the structure in the $[\text{Fe}/\text{H}]$ distribution and compare the average ages of those structures to previous results. Fitting a Gaussian mixture model (GMM) to the observed $[\text{Fe}/\text{H}]$ values reveals three populations of stars (see Fig. 4). There is a very young population of stars with an average age of 1.8 ± 1.7 Gyr at $[\text{Fe}/\text{H}] = -0.85 \pm 0.11$, suggesting very recent star formation. The large peak corresponds to a population with an average age of 4.8 ± 2.2 Gyr and $[\text{Fe}/\text{H}] = -1.11 \pm 0.11$. This population aligns with the feature in the RGB age distribution at approximately 5 Gyr seen in the *Left* panel. Lastly, there is an underlying population of old stars with an average age of 7.1 ± 5.3 Gyr and a peak at $[\text{Fe}/\text{H}]$ of -1.59 ± 0.23 .

These results are mostly consistent with Mucciarelli (2014), which looked at the $[\text{Fe}/\text{H}]$ distribution of about 200 giant stars in the SMC and also identified three similar populations. While Mucciarelli (2014) identified the mean peak with typical old stars formed up to 8 Gyr ago and the formation of old clusters, our results suggest it aligns with the abrupt change in many abundance gradients between 3.7 and 5.6 Gyr ago (see Sections 5.2 and 6.2), the slight discrepancy may be due to combination of these factors. Lastly, the young metal-rich populations in both studies are consistent, with Mucciarelli (2014) proposing this feature as a result of both the recent starburst and the formation of intermediate-age clusters.

The 6.7 per cent or 4.16 kpc distance uncertainty that we calculated in Section 3.1 does have an impact on the ages. Propagating the uncertainty forward shows that the distance uncertainty produces an average age uncertainty up to 24 per cent of the calculated age.

4 ABUNDANCE GRADIENT CALCULATION

Here we discuss the details of how the SMC radial abundance gradients are determined for each of the abundance ratios measured by the APOGEE observations. However, how we define radial distances for SMC stars must be handled differently than how we did so for LMC stars in Paper II.

4.1 SMC radius

Because the SMC does not have a well-shaped stellar disc, but rather a more spheroidal shape, the best way to project the stellar sky positions to a specific galactic position is not obvious. Therefore we have elected to derive our abundance gradients simply in terms of each star's distance from the centre of the SMC as projected on the plane of the sky. Thus, we determine the SMC radius of each star by converting the celestial coordinates (α , δ) into angular coordinates (ρ , ϕ), where ρ is the angular radius from the centre of the SMC and ϕ is the position angle. The angular coordinates in terms of α and δ are

$$\begin{aligned}\cos \rho &= \cos \delta_0 \cos \delta \cos(\alpha - \alpha_0) + \sin \delta_0 \sin \delta, \\ \sin \rho \cos \phi &= -\cos \delta \sin(\alpha - \alpha_0), \\ \sin \rho \sin \phi &= \cos \delta_0 \sin \delta - \sin \delta_0 \cos \delta \cos(\alpha - \alpha_0),\end{aligned}\quad (3)$$

where (α_0, δ_0) is the centre of the SMC at $(13.18^\circ, -72.83^\circ)$ from Nidever et al. (2017). Converting the angular radius, ρ , to a linear radius is done by

$$R = D \tan \rho, \quad (4)$$

where D is the distance to the centre of the SMC, adopted as 62.44 ± 0.44 kpc from Graczyk et al. (2020).

4.2 Determining abundance gradients with MCMC

Radial abundance gradients are determined by fitting abundance trends with radius in a galaxy. The convention is to use a simple linear model to accomplish this, and therefore the functional form of the model adopted here is

$$[\text{X}/\text{Fe}] = \nabla_R R + [\text{X}/\text{Fe}]_0, \quad (5)$$

where $[\text{X}/\text{Fe}]$ is the abundance ratio normalized to iron, ∇_R is the gradient of the line, R is the radius (distance from the centre of the SMC), and $[\text{X}/\text{Fe}]_0$ is the central abundance ratio.

Measuring chemical abundances with respect to hydrogen as the fiducial element is taken as the ‘absolute’ abundance for other elements. However, to monitor temporal variations in the contributions of chemical yields from different nucleosynthetic processes in the overall chemical evolution of a galaxy it is useful to normalize out the overall increase in metallicity with time. To do so, it is common to look at variations in abundance ratios from solar-scaled values by normalizing against $[\text{Fe}/\text{H}]$ – that is, $[\text{X}/\text{Fe}] = [\text{X}/\text{H}] - [\text{Fe}/\text{H}]$. However, Weinberg et al. (2019) have argued that magnesium is a better fiducial element for abundance ratios because it is released into the interstellar medium almost exclusively through Type II SNe (Andrews et al. 2017), whereas iron has contributions from both SNe II and SNe Ia, where the latter are subject to delays related to the time required for the creation of white dwarf binaries. Thus, we determine gradients for $[\text{X}/\text{Fe}]$, $[\text{X}/\text{H}]$, and $[\text{X}/\text{Mg}]$, as well as for the key diagnostic ratios $[\text{C}/\text{N}]$ and $[\alpha_{\text{h}}/\alpha_{\text{ex}}]$. The $[\text{C}/\text{N}]$ of a star has been shown to be a good indicator of age for metal rich giant stars (Ness et al. 2016). This has been exclusive to the MW thus far, but in the future it might be possible to extend this to other galaxies and/or metal poor giants. On the other hand, $[\alpha_{\text{h}}/\alpha_{\text{ex}}]$ is the ratio of the typically lighter hydrostatic α -elements to the heavier explosive α -elements (see Section 5.1.2).

The gradients and central abundances in equation (5) are found using maximum-likelihood estimation with the likelihood function:

$$\ln \mathcal{L} = \frac{1}{2} \left[\sum_i \frac{([\text{X}/\text{Fe}]_i - \nabla_R R_i - [\text{X}/\text{Fe}]_0)^2}{\sigma_i^2} - \ln 2\pi \sigma_i^2 \right], \quad (6)$$

Table 1. The age bins used throughout this work, which are the same as used for our analysis of the LMC in Povick et al. (2023b). N is the total number of stars in each bin and $N_{\text{SNR}>100}$ is the number of stars in each bin that have an SNR over 100. For a few stars ages could not be derived; this leads to a discrepancy between the sum of the N column values and the previously stated sample size in Section 2.1.

Bin	Age range (Gyr)	N	$N_{\text{SNR}>100}$
1	$t \leq 2.2$	613	213
2	$2.2 < t \leq 3.7$	503	172
3	$3.7 < t \leq 5.6$	422	164
4	$5.6 < t \leq 8.4$	247	83
5	$8.4 < t$	263	76

where the distance of each individual star from the centre of the SMC is R_i , the abundance of the star is $[\text{X}/\text{Fe}]_i$, and the error in the abundance is σ_i .

For added robustness when fitting the abundance gradients, all stars with $\text{S/N} < 100$ are removed, the stars are binned in radius (widths of 1 kpc), and a model is fit to the median of the binned values with weighting using the median absolute deviation (MAD) from the median. After this fit, any outlier stars further than $3 \times \sigma$ are rejected and the model is refit. This is done because there is a large abundance scatter at each radius especially in the outer galaxy. Uncertainties in the gradients and central abundances are found by implementing a Markov chain Monte Carlo (MCMC) analysis using the EMCEE (Foreman-Mackey et al. 2013) PYTHON package. This package is built upon the algorithms presented in Goodman & Weare (2010).

4.3 Stellar age binning

As mentioned above, we use the calibrated spectroscopic parameters (T_{eff} , $\log g$, and $[\text{Fe}/\text{H}]$) and photometry as well as the distances calculated from Section 3.1 to determine ages using the method from Paper I. To simplify comparison of the evolution of abundance gradients between the LMC and SMC, the same age bins from Paper I are used here. Originally, these age bins were chosen to ensure each contained an equal number of stars, while also providing sufficient age resolution to see underlying structure in the LMC gradients. The same binning scheme is used here to facilitate direct comparisons between the two papers. The particular age ranges for each bin can be found in Table 1.

4.4 Age- $[\text{X}/\text{Fe}]$ trends

In addition to radial abundance trends, we also explore the age-abundance ratio trends for the $[\text{X}/\text{Fe}]$ abundance ratio, as well as for $[\text{C}/\text{N}]$, $[\alpha_{\text{h}}/\text{Fe}]$, $[\alpha_{\text{ex}}/\text{Fe}]$, and $[\alpha_{\text{h}}/\alpha_{\text{ex}}]$. Stars were divided by their SMC position angle into east and west regions. The eastern part of the SMC is known to have a larger line-of-sight depth compared to that in the western part of the galaxy (Nidever et al. 2013). On the other hand, the western part of the SMC contains the counterbridge (Diaz & Bekki 2012) and the west halo (Dias et al. 2016). By dividing the sample along an east–west line, these structures are better isolated and probed. In addition, each of the angular bins was further divided into two radial annular bins. Stars were classified as either inner ($R < 3.3$ kpc) or outer ($3.3 \leq R$ kpc) SMC. This radial cutoff was chosen because the inner SMC is morphologically more elliptical for $R < 3^\circ$ compared to the outer portion of the galaxy (Nidever et al. 2011), which corresponds to 3.3 kpc.

The age-abundance ratio trends are found by splitting the stars into different age bins and finding the abundance median and MAD

Table 2. Radial gradients for the abundant elements carbon and nitrogen.

Element	∇_R [X/Fe] (dex kpc ⁻¹)	∇_R [X/H] (dex kpc ⁻¹)	∇_R [X/Mg] (dex kpc ⁻¹)
C	-0.0267 ± 0.0029	-0.0929 ± 0.0077	-0.0196 ± 0.0033
N	-0.0048 ± 0.0018	-0.0427 ± 0.0046	-0.0008 ± 0.0031
C + N	-0.0117 ± 0.0017	-0.0676 ± 0.0059	-0.0059 ± 0.0022
[C/N]	-0.0203 ± 0.0040	...	...

scatter of each bin. Note that the age bins here are not the same as the ones used for exploring the evolution of the radial abundance gradients. The optimal number of bins (linear in age) was found to be 15 after trying different schemes. This number minimized the amount of bins with low numbers while also not washing out the general trend.

5 RESULTS

Below, we present the main results of the radial gradients calculated for 24 abundance ratios (see Sections 5.1 and 5.2) and age–abundance ratio trends (see Section 5.3).

5.1 The SMC radial abundance ratio gradients

The SMC radial abundance gradients are discussed separately in element groups. Generally, abundance ratio gradients for lighter species are presented before heavier ones.

5.1.1 Carbon and nitrogen

This work looks at the individual gradients for carbon and nitrogen, the composite C + N gradients, and the [C/N] abundance ratio. The largest contributor to measured carbon and nitrogen elements is intermediate mass stars that undergo Type II SNe explosions (Kobayashi et al. 2006; Ventura et al. 2013). Dredge-up (which is not corrected for here) does affect the observed C and N values of a star, but the observed C + N abundances do not change much (Gratton et al. 2000).

The carbon gradients of [C/Fe], [C/H], and [C/Mg] all are steep, especially the [C/H] gradient, with a value -0.0929 ± 0.0077 dex kpc⁻¹ (see Table 2). On the other hand, in comparison, the nitrogen gradients are very shallow. The largest nitrogen gradient is -0.0427 ± 0.0046 dex kpc⁻¹ for [N/H]. The C + N gradients fall in between the carbon and nitrogen gradients, which is expected because the C + N abundances are calculated using a weighted average of the individual carbon and nitrogen abundances. Lastly, the [C/N] gradient is low, relatively speaking, with a value of -0.0203 ± 0.0040 dex kpc⁻¹.

5.1.2 α -Elements

There are a number of α elements measured by APOGEE including O, Mg, Si, S, Ca, Ti, and overall α . Enrichment of α -elements in the interstellar medium (ISM) primarily occurs through Type II SNe (Nomoto, Kobayashi & Tominaga 2013; Weinberg et al. 2019). From individual α -elements, it is possible to calculate the average hydrostatic α -abundance ($[\alpha_h/\text{Fe}] = ([\text{O}/\text{Fe}] + [\text{Mg}/\text{Fe}])/2$), the average explosive α -element abundance ($[\alpha_{\text{ex}}/\text{Fe}] = ([\text{Si}/\text{Fe}] + [\text{Ca}/\text{Fe}] + [\text{Ti}/\text{Fe}])/3$), and the ratio of the average hydrostatic α -abundance to the average explosive α -abundance ($[\alpha_h/\alpha_{\text{ex}}] = [\alpha_h/\text{Fe}] - [\alpha_{\text{ex}}/\text{Fe}]$). Hydrostatic α -elements are so named because they are created from hydrostatic burning

Table 3. Table of radial abundance gradients for the α -elements.

Element	∇_R [X/Fe] (dex kpc ⁻¹)	∇_R [X/H] (dex kpc ⁻¹)	∇_R [X/Mg] (dex kpc ⁻¹)
O	$+0.0024 \pm 0.0013$	-0.0635 ± 0.0054	$+0.0029 \pm 0.0010$
Mg	$+0.0074 \pm 0.0019$	-0.0643 ± 0.0053	...
Si	$+0.0067 \pm 0.0016$	-0.0512 ± 0.0048	-0.0029 ± 0.0015
S	$+0.0172 \pm 0.0090$	-0.0502 ± 0.0094	$+0.0139 \pm 0.0084$
Ca	$+0.0001 \pm 0.0013$	-0.0668 ± 0.0050	-0.0072 ± 0.0019
Ti	-0.0115 ± 0.0018	-0.0677 ± 0.0057	-0.0075 ± 0.0022
α	$+0.0004 \pm 0.0009$	-0.0681 ± 0.0051	-0.0023 ± 0.0011
α_h	$+0.0051 \pm 0.0017$	-0.0648 ± 0.0053	$+0.0014 \pm 0.0005$
α_{ex}	-0.0001 ± 0.0011	-0.0647 ± 0.0055	-0.0044 ± 0.0017
$[\alpha_h/\alpha_{\text{ex}}]$	$+0.0040 \pm 0.0011$	...	...

Table 4. Table of radial abundance gradients for the odd-Z elements.

Element	∇_R [X/Fe] (dex kpc ⁻¹)	∇_R [X/H] (dex kpc ⁻¹)	∇_R [X/Mg] (dex kpc ⁻¹)
Na	$+0.0214 \pm 0.0084$	-0.0337 ± 0.0086	$+0.0140 \pm 0.0087$
Al	-0.0123 ± 0.0028	-0.0713 ± 0.0066	-0.0159 ± 0.0018
K	$+0.0061 \pm 0.0029$	-0.0541 ± 0.0049	$+0.0044 \pm 0.0026$

inside of a star while the explosive α -elements are created during Type II SNe itself (Carlin et al. 2018).

Regardless of the fiducial element, all of the α -abundances have a wide range of values, as seen in Table 3. It is immediately clear that the [X/Fe] gradients are almost all positive, which is the opposite of what is seen in the [X/H] and [X/Mg] gradients. The only negative [X/Fe] gradients are for [Ti/Fe], with a value of -0.0115 ± 0.0018 dex kpc⁻¹, and $[\alpha_{\text{ex}}/\text{Fe}]$, with a value of -0.0001 ± 0.0011 dex kpc⁻¹. The $[\alpha_{\text{ex}}/\text{Fe}]$ is probably negative because of the [Ti/Fe] values. The average of the [Si/Fe], [Ca/Fe], and [Ti/Fe] gradients is negative due to the steep negative gradient of [Ti/Fe], so it would be expected that the $[\alpha_{\text{ex}}/\text{Fe}]$ would also be negative.

5.1.3 Odd-Z elements

The odd-Z elements are produced mostly in Type II SNe with a slight metallicity dependence (Nomoto et al. 2013; Weinberg et al. 2019). Regardless of the fiducial element, the K gradients fall between the Na and Al gradients (see Table 4).

5.1.4 Iron peak elements

An important group of elements are those in the iron peak, which includes V, Cr, Mn, Fe, Co, and Ni. These elements are produced through Type Ia SNe, although there is a significant contribution from Type II SNe as well (Kobayashi et al. 2006).

The iron abundance, or metallicity, is a very important property of a star as it is essentially a measure of its overall heavy element content. The [Fe/H] does not stand out among the [X/H] gradients, even with its value of -0.0546 ± 0.0043 dex kpc⁻¹, but the [Fe/Mg] gradient is the steepest of those of the iron peak [X/Mg] elements at -0.1230 ± 0.0097 dex kpc⁻¹ (see Table 5). As for the other gradients, there does not seem to be any discernible pattern with atomic number. The steepest [X/Fe] gradient belongs to [V/Fe], with a value of -0.0237 ± 0.0107 dex kpc⁻¹. At -0.0339 ± 0.0107 dex kpc⁻¹, vanadium also has the steepest non-iron [X/Mg] gradient. The shallowest iron peak gradient is different for each fiducial element.

Table 5. Table of radial abundance gradients for the iron peak elements.

Element	$\nabla_R [X/Fe]$ (dex kpc ⁻¹)	$\nabla_R [X/H]$ (dex kpc ⁻¹)	$\nabla_R [X/Mg]$ (dex kpc ⁻¹)
V	-0.0237 ± 0.0107	-0.0633 ± 0.0101	-0.0339 ± 0.0107
Cr	-0.0059 ± 0.0037	-0.0551 ± 0.0064	-0.0090 ± 0.0045
Mn	-0.0130 ± 0.0014	-0.0784 ± 0.0049	-0.0146 ± 0.0033
Fe	...	-0.0546 ± 0.0043	-0.1230 ± 0.0097
Co	-0.0081 ± 0.0033	-0.0653 ± 0.0061	-0.0100 ± 0.0034
Ni	-0.0028 ± 0.0006	-0.0574 ± 0.0048	-0.0005 ± 0.0021

5.1.5 The neutron capture element cerium

One of the more massive elements with a measured abundance from APOGEE is cerium. It is an element created through both the *r*- and *s*-neutron-capture processes (Prantzos et al. 2020). This is a difficult abundance for APOGEE to measure, so while gradients have been calculated for [Ce/Fe], [Ce/H], and [Ce/Mg], it is best not to make any strong conclusions due to the larger uncertainties. The [Ce/Fe] and [Ce/Mg] gradients have values of -0.0596 ± 0.0021 and -0.0599 ± 0.0039 , respectively. The [Ce/H] abundance is very large at -0.1115 ± 0.0094 dex kpc⁻¹ (see Table 6).

5.2 The evolution of the SMC abundance ratio gradients

As previously mentioned (Section 4.3), we have calculated ages for the individual RGB stars in the SMC subset of the APOGEE catalogue. Using age bins from Table 1, the evolution of all the abundance gradients is determined. A table with all the numeric values of the [X/Fe] gradients as functions of age using these age bins can be found in Table 7. Due to their size the tables containing the [X/H] and [X/Mg] gradients as functions of age can be found in Appendix B, in Tables B1 and B2, respectively.

The evolutionary trends for all of the gradients with each fiducial can be seen in Figs 5, 6, and 7. For each abundance ratio the

red points represent the gradient of the oldest stars while purple points show the gradient for the youngest stars, such that age/time runs left to right for each element ratio in the plots. Each of the nucleosynthetic groups of elements are grouped together, and for each group atomic number generally increases going to the right. A line in black has been added to connect the gradients to make the trends more obvious. The radial trends from which all of the gradients are derived are shown in Figs 8, C1, C2, C3, C4, and C5. Note that many of these figures have been placed in Appendix C as they can be quite large. When fitting the radial trends, the number of stars falls off towards the outer galaxy leading to larger dispersions and sporadic behaviour when tracking the median abundance ratio value. Coupled with the different number of stars in each age bin and with the number of stars with good abundance values this can sometimes lead to a mismatch between the fit radial trends and data especially for the oldest stars. This is precisely why outlier removal was used in Section 4.2.

5.2.1 Carbon and nitrogen

The carbon and nitrogen abundance gradients show different evolutionary trends depending on the particular fiducial element chosen. Starting first with Fe there is definite variation within the C and N gradients (see Fig. 5). In the figure, the [C/Fe] gradient has a U-shaped trend with a critical point for the stars in the 5.6–8.4 Gyr bin. Here U-shaped means that a gradient has experienced a fattening in the past, but then for more recent times has steepened. The individual trends may open up or down. For these stars there is an increase in the central [C/Fe] abundance, after which it remains constant around -0.4 dex (see Fig. 8). The [N/Fe] gradient hovers around 0.0 dex kpc⁻¹, but for the stars with the youngest ages the gradient becomes quite negative, relatively speaking, with a value of -0.0409 ± 0.0040 dex kpc⁻¹. The means that recently the [N/Fe] has increased rapidly in the last few Gyr in the SMC centre. The

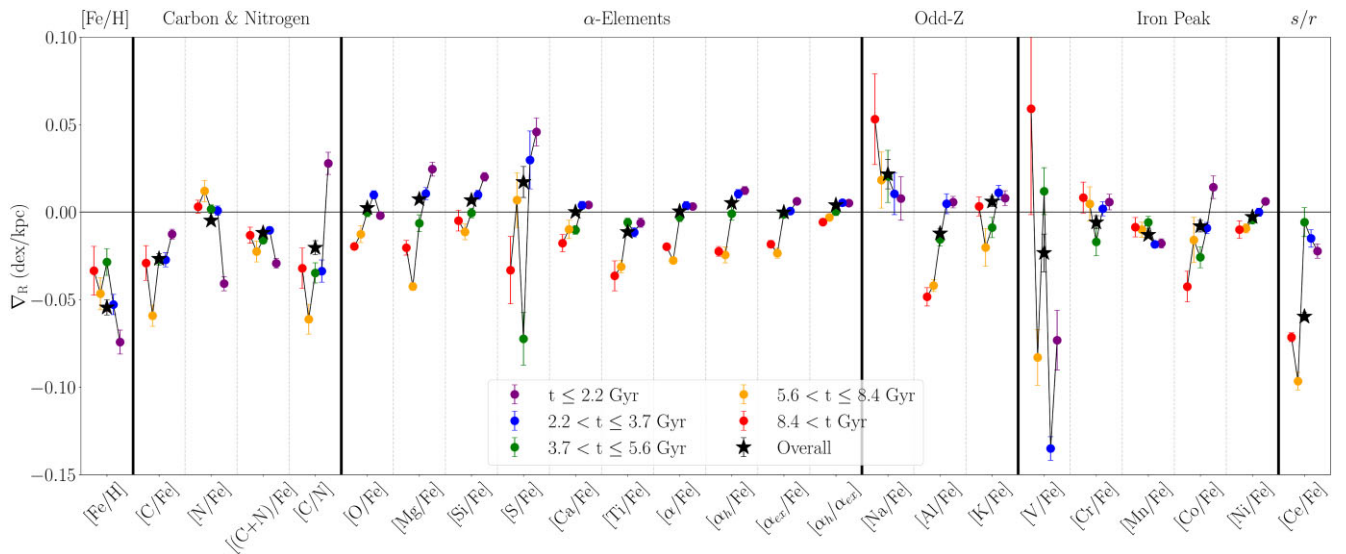


Figure 5. A figure showing all of the calculated [X/Fe] gradients for C, N, C + N, O, Mg, Si, S, Ca, Ti, α , α_h , α_{ex} , Na, Al, K, V, Cr, Mn, Co, Ni, and Ce (see Table 7 for the values of the coloured dots). [Fe/H], [C/N], and $[\alpha_h/\alpha_{ex}]$ are also included here. [Fe/H] is on the left to provide context for the rest of the gradients. As in the text, the elements have been broken up into groups based on their shared formation/enrichment mechanisms (i.e. carbon and nitrogen, α -elements, odd-Z, iron peak elements, and s/r-process elements). The different colours represent the different age bins used throughout the paper that are in Table 1. The oldest age bin (ages older than 8.4 Gyr) is represented by a red dot on the left side of each column while the youngest age bin (anything younger than or equal to 2.2 Gyr) is a purple dot on the right side of each column. The overall gradients have been included as black stars (see Tables 2–6 for the values of these gradients). To make the gradient-age trends stand out, a black line has been included connecting the points.

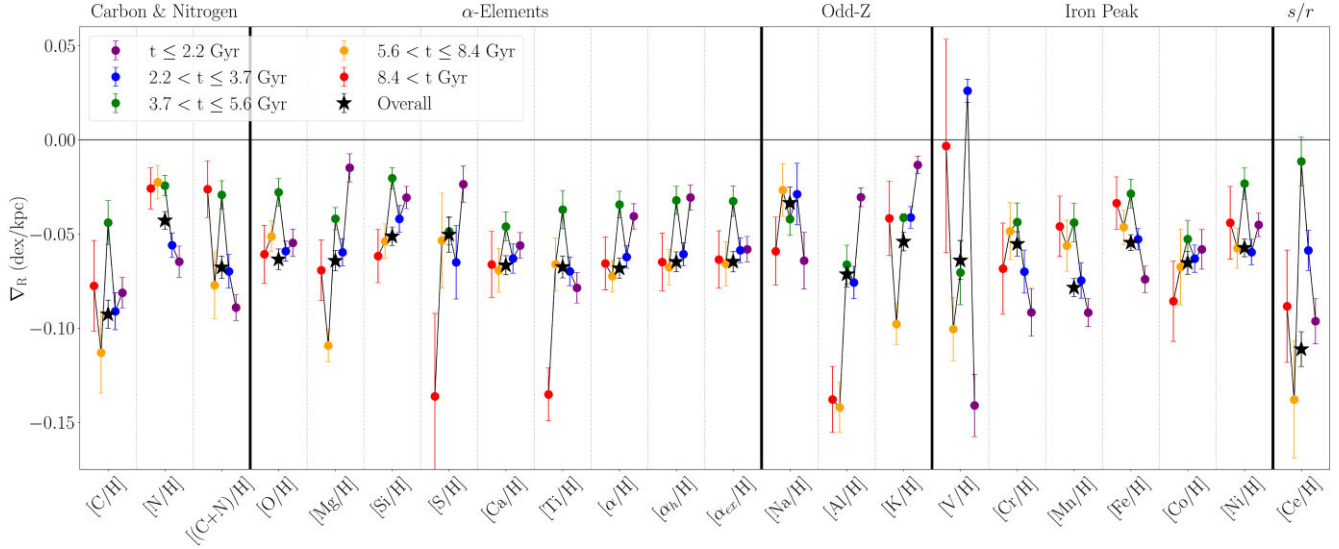


Figure 6. The same as Fig. 5, but for the $[X/H]$ gradients. The value of each gradient in singular can be found in Table B1. For many elements the gradients of older stars are typically steeper, but for the stars younger than ~ 3.7 – 5.6 Gyr the gradients tend to be steeper again.

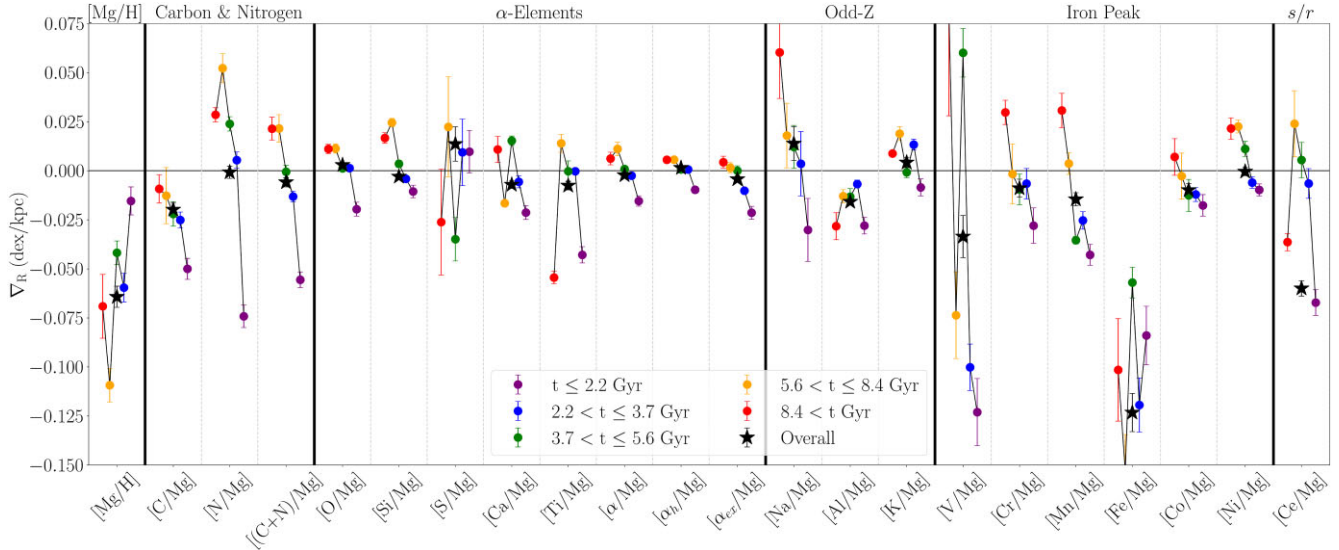


Figure 7. The same as Fig. 5, but for the $[X/Mg]$ gradients. The value of each gradient in singular can be found in Table B2. Note that $[Mg/H]$ has been included on the left side to help provide context for the rest of the gradients.

$[(C+N)/Fe]$ gradient hovers around $-0.0020 \text{ dex kpc}^{-1}$. The $[C/N]$ gradient has a similar behaviour to $[C/Fe]$, though it does become positive for stars in the youngest age bin.

The $[X/H]$ gradients for carbon and nitrogen all become more steeply negative for all but the oldest two age bins (see Fig. 6). The $[N/Fe]$ gradient has a U-shaped trend with an extremum point in the $5.6 < t \leq 8.4$ Gyr age bin. As for the $[C/H]$ and $[(C+N)/H]$, if the oldest age bin is not considered, these also show a U-shaped trend, but the maximum point happens later than for $[N/H]$, at around 3.7 – 5.6 Gyr ago.

Lastly, for the carbon and nitrogen ratios with respect to magnesium, $[C/Mg]$ shows a steepening trend with time while the $[N/Mg]$ and $[(C+N)/Mg]$ gradients start out positive for the oldest stars and then invert, becoming negative (see Fig. 7). The $[N/Mg]$ gradient inversion lags the $[(C+N)/Mg]$ gradient inversion, which happens in the 3.7 – 5.6 Gyr age bin.

5.2.2 α -elements

The α -element gradients have various evolutionary trends as seen in Fig. 5. The $[Mg/Fe]$ and $[Si/Fe]$ gradients have parallel evolutionary patterns as evidenced by the same general shape of their gradient trends. The radial trends from Fig. C1 also show evolution in parallel for $[Mg/Fe]$ and $[Si/Fe]$, though the 5.6 – 8.4 gradient is much steeper for $[Mg/Fe]$. The relative evolution of $[Ca/Fe]$ and $[Ti/Fe]$ are similar in that they both tend to fatten out, but the gradients for stars younger than 3.7 Gyr tend to be slightly positive and the corresponding $[Ti/Fe]$ gradients are negative (see Fig. 5). Both $[O/Fe]$ and $[S/Fe]$ evolve differently from the rest of the individual α -element gradients, but $[O/Fe]$ is similar to $[Ca/Fe]$. The composite α -element gradients of $[\alpha/Fe]$, $[\alpha_h/Fe]$, and $[\alpha_{ex}/Fe]$ evolve much like $[Ca/Fe]$ or $[Ti/Fe]$ (see Fig. 5). The radial trends of these also evolve similarly (see Fig. C2). The $[\alpha_h/\alpha_{ex}]$ gradient does not show much evolution and remains fairly flat for the whole history of the SMC.

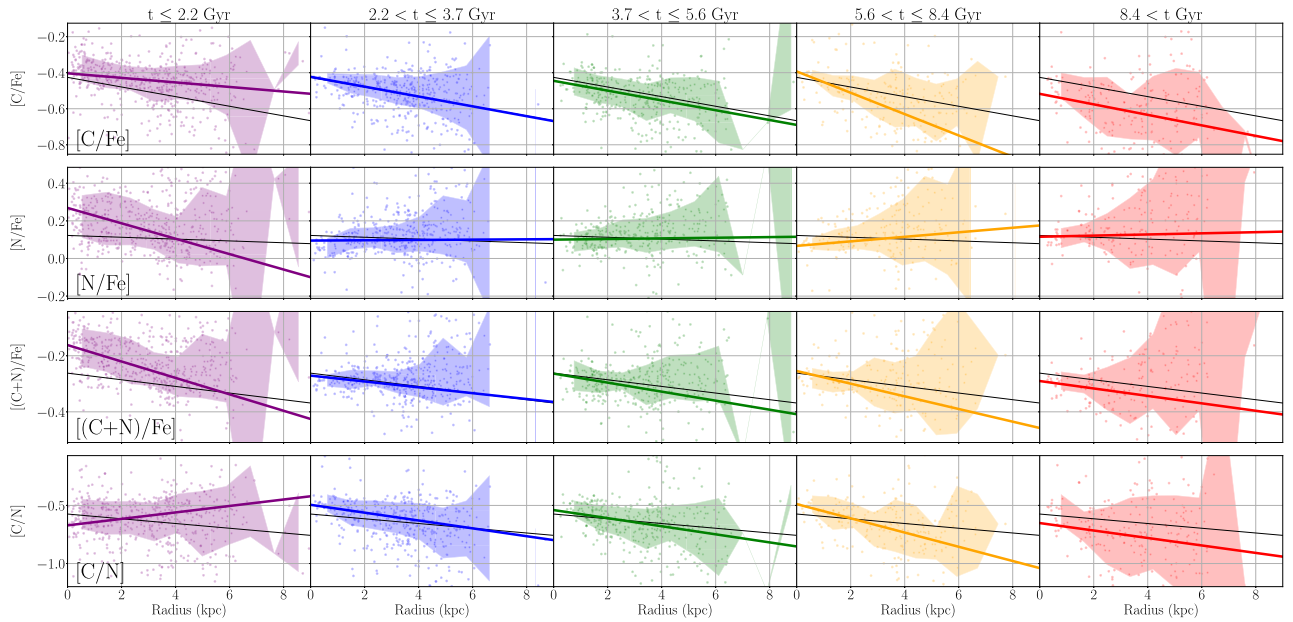


Figure 8. The radial abundance trends for the carbon and nitrogen abundances. For each row, age increases from left to right. The solid coloured line is the fitted linear model, the coloured dots show the observed stars in each age bin, and the colour band shows the 1σ dispersion around the median of the observed data. Typically the number of stars falls off at further radii and this does produce some clearly spurious effects such as a very large dispersion or missing dispersion around the fit trends or data points. All of these effects can be attributed to low number statistics. The black line is the fit to all of the data without any age binning and serves as a reference fiducial. These plots show that each of the various abundance ratios increase over time, with the fitted trend lying below the reference fiducial for older age bins and above for younger age bins. The youngest $[N/Fe]$ and $[C/N]$ trends stand out by showing much larger gradients than the other age bins. Also the $[C/N]$ gradient clearly inverts for the youngest age bin probably due to the rapid increase in $[N/Fe]$ recently.

Many of the evolutionary trends for the $[X/H]$ gradients of the α -elements have a notable maximum for stars with ages between 3.7 and 5.6 Gyr (see Fig. 6). While not necessarily a global extremum, these trends for the gradients show a significant change in the evolution trajectory. The $[Mg/H]$, $[Si/H]$, $[\alpha/H]$, and $[\alpha_h/H]$ gradients have this maximum, but then turn downturn with the 2.2–3.7 Gyr age bin gradients becoming steeper. These gradients then fatten to around the 3.7–5.6 Gyr value or even more for the gradients of the youngest star. The $[O/H]$, $[Ca/H]$, $[Ti/H]$, and $[\alpha_{ex}/H]$ abundance ratios have global extrema for the 3.7–5.6 Gyr age bin stars. The $[Ca/H]$ evolutionary trend is also the only trend that shows a positive concave feature. The $[S/H]$ gradient does not have a clear evolutionary trend and is fairly constant with time.

The individual α -elements show quite a bit of variation in their evolution while the composite abundances are similar (see Fig. 7). The evolution seen in $[O/Mg]$ is comparable to the composite abundances. $[S/Mg]$ does not have a clear evolutionary trend. The $[Ti/Mg]$ gradients evolution has a U-shape with a critical point between 5.6 and 8.4 Gyr ago.

5.2.3 Odd-Z elements

Fig. 5 shows that all of the odd-Z elements have different evolutionary trends. The $[Na/Fe]$ gradient starts as significantly positive with a value of $+0.0531 \pm 0.0259 \text{ dex kpc}^{-1}$ and then fattens out to $+0.0077 \pm 0.0124 \text{ dex kpc}^{-1}$ for the youngest ages. The $[Al/Fe]$ gradient starts around $\approx -0.0500 \text{ dex kpc}^{-1}$ before fattening for more recent ages with very slightly positive gradients for stars younger than 3.7 Gyr. The $[K/Fe]$ gradient has a U-shaped trend in its evolution, but its extremum point is between 5.6 and 8.4 Gyr ago, with these stars having a gradient of $-0.0202 \pm 0.0108 \text{ dex kpc}^{-1}$. The central abundance values of the $[X/Fe]$ abundance ratios show

that the central value remains mostly constant regardless of the radial slope (see Fig. C3).

For the odd-Z $[X/H]$ gradients, both $[Na/H]$ and $[K/H]$ exhibit a U-shaped trend, while the $[Al/H]$ fattens over time (see Fig. 6). The $[Na/H]$ has a potential extremum point at the same time as most other elements while the $[K/Fe]$ extremum point happens for stars aged 5.6–8.4 Gyr.

The $[X/Mg]$ gradients for the odd-Z elements evolve differently (see Fig. 7). Much like the $[Na/Fe]$ and $[Na/H]$, the $[Na/Mg]$ gradient starts steep and positive and becomes shallower over time. Sometime between 2.2 and 3.7 Gyr ago the $[Na/Mg]$ gradient inverts. The $[Al/Mg]$ gradient shows a U-shaped trend in its evolution with a potential extremum point for the stars in the 3.7–5.6 Gyr age bin. Its trend is reminiscent of the shape seen for $[Na/H]$. The $[K/Mg]$ gradient evolutionary trend shows an overall downward tendency, but oscillates as it fattens.

5.2.4 Iron peak elements

Multiple $[X/Fe]$ gradients show a potential U-shaped trend except for $[V/Fe]$ (see Fig. 5). While the trend is not as prominent, it is visible for $[Cr/Fe]$, $[Mn/Fe]$, and $[Ni/Fe]$. Both $[Cr/Fe]$ and $[Mn/Fe]$ have an extremum point around the 3.7–5.6 Gyr age bin, while the heavier iron peak elements ($[Co/Fe]$ and $[Ni/Fe]$) have an extremum point earlier around the 5.6–8.4 Gyr age bin. The radial trends show that the central abundances for the lighter iron peak elements are fairly constant over time (see Fig. C4). This is less true for the heavier iron peak elements and $[Fe/H]$.

Many of the iron peak elements do exhibit a U-shaped trend with an extremum point at the same time as most of the other elements that also have a U-shaped trend (see Fig. 6). This is true for $[Cr/H]$, $[Mn/H]$, $[Fe/H]$, and $[Ni/H]$ as well as potentially $[Co/H]$. The $[V/H]$ gradient's evolution shows a lot of large, sporadic excursions, and

therefore it is challenging to say what the gradient truly is doing over time.

The $[X/Mg]$ gradients for Cr, Mn, Co, and Ni have similar evolutionary trends, but V and Fe are outliers (see Fig. 7). The $[Cr/Mg]$, $[Mn/Mg]$, $[Co/Mg]$, and $[Ni/Mg]$ all show a downward trend. All of these start positive for the oldest stars, but eventually they invert and become negative. The $[V/Mg]$ gradient shows an evolution similar to the $[V/H]$ gradient evolution. The $[Fe/Mg]$ does have a critical point in its evolution for stars aged 3.7–5.6 Gyr.

5.2.5 The neutron capture element cerium

For the $[Ce/Fe]$ gradient, the oldest two age bins have very negative values compared to the other age bins (see Fig. 5). The radial trends show the dispersion in the $[Ce/Fe]$ tends to be on the larger side (see Fig. C5). The fattening and then subsequent steepening in the gradient evolution can also be seen in the radial trends quite clearly. This contrasts with what is seen in Fig. 6, where the gradient potentially shows the U-shaped trend with an extremum point in the 3.7–5.6 Gyr age bin. The $[Ce/Mg]$ gradient does show temporal evolution, though it is fairly complex.

5.3 Age- $[X/Fe]$ trends

Overall, the age- $[X/Fe]$ trends for the SMC are mostly fat, though some show an increase in abundance for younger ages. For each of the plots pertinent to this section (Figs 9, D1, D2, D3, D4, and D5), if an age- $[X/Fe]$ is above the black line then that region is overabundant and if the trend is below then the opposite is true. The black line is the fiducial age- $[X/Fe]$ trend and was found the exact same way as the others without any spatial binning unlike the colored lines.

5.3.1 Carbon and nitrogen

The age- $[X/Fe]$ trends for the carbon and nitrogen abundances are mostly fat (see Fig. 9). The $[C/Fe]$ abundance in the SMC very gradually increases over time throughout the galaxy. The western side of the galaxy for radii <3.3 kpc is overabundant with the trend falling above the fiducial line. The outer galaxy is underabundant in both the east and west.

The age- $[N/Fe]$ trend reveals that throughout the SMC there was an increase in $[N/Fe]$ within the last Gyr or so. Also, the outer galaxy is nitrogen-rich in both the eastern and western side for old stars, though the west is more nitrogen-rich. The inner west tends to be close to the fiducial or slightly underabundant. The $[(C+N)/Fe]$ age- $[X/Fe]$ trend looks analogous to the $[N/Fe]$ trend because it matches the fiducial throughout the galaxy and the outer west region is the most different.

An interesting feature with the age- $[C/N]$ trend is the underabundance for all ages in the west for radii >3.3 kpc, but the overabundance for the inner radii of the west. There may also be a very slight hump between 0.0 and 5.0 Gyr.

5.3.2 α -elements

Overall, the individual α -elements have very fat age- $[X/Fe]$ trends with somewhat larger deviations from this behaviour at recent times (see Fig. D1). The lightest individual α -element is $[O/Fe]$ and the age- $[O/Fe]$ trends in the east of the SMC follow the global fiducial, for the most part. There is actually a slight hump in the fiducial trendline and this is seen in the inner eastern region as well. The west is more complex with the younger stars in the inner region being oxygen-poor. The outer western region shows that the oldest stars

are much more overabundant in $[O/Fe]$ and the youngest stars are also slightly overabundant, but the ages between ~ 5.5 Gyr and $\gtrsim 7.5$ Gyr are underabundant in oxygen.

The age- $[Mg/Fe]$ trend shows that the stars with radii <3.3 kpc have a downturn trend in magnesium. The outer SMC in the east has a fat age- $[Mg/Fe]$ trend. The outer west region has an age- $[Mg/Fe]$ trend that is similar to the age- $[O/Fe]$ trend in the same age bin, but the magnitude of the difference in the trends are smaller than what is seen in $[O/Fe]$.

The next lightest individual α -element is silicon. Both the inner and outer regions have fat age- $[X/Fe]$ trends in the east region. The inner western SMC appears to be deficient in silicon for ages younger than 5 Gyr. The $[Si/Fe]$ in the outer west regions looks very similar to the age- $[Mg/Fe]$ trend in the same area.

Looking at the $[S/Fe]$ and $[Ca/Fe]$ age-abundance trends, both are very fat and do not show much deviation from the fiducial trendline or bin-to-bin. The $[Ti/Fe]$ abundance is also quite fat like these abundances, except that there is a slight tendency to increase over time.

The composite α -abundance age- $[X/Fe]$ trends look similar to the individual abundance ones (see Fig. D2). The age- $[\alpha/Fe]$ trend shows that the eastern SMC follows the fiducial trendline better than in the west. There is also a bump present in the abundance for ages less than 5 Gyr. For younger stars, with ages that are $\lesssim 2.5$ Gyr in the inner western SMC, there is a deficiency in α -abundance. Stars with similar ages in the outer west region show an overabundance of $[\alpha/Fe]$, while between ~ 5 and ~ 12.0 Gyr the stars are $[\alpha/Fe]$ -poor. However, the oldest stars are $[\alpha/Fe]$ -rich.

The age- $[\alpha_h/Fe]$ trend in the east, at all radii, looks a lot like the age- $[\alpha/Fe]$ trend. This is also the case for stars at radii <3.3 kpc in the west as the age- $[\alpha_h/Fe]$ trend looks like the analogous trend in $[\alpha/Fe]$. The outer west of the SMC has similar trends for $[\alpha_h/Fe]$ and $[\alpha/Fe]$, but the dip in $[\alpha_h/Fe]$ for intermediate ages only happens ~ 4 Gyr to just past 7.5 Gyr. The explosive α -element abundance, $[\alpha_{ex}/Fe]$, has similar behaviour to $[\alpha_h/Fe]$, but the age- $[X/Fe]$ trend is fatter.

The age- $[\alpha_h/\alpha_{ex}]$ trend shows a slight downturn in the inner galaxy for radii <3.3 kpc with a deficiency for younger stars in the west. The outer east regions has a slight overabundance compared to the fiducial trendline. Finally, the outer west SMC $[\alpha_h/\alpha_{ex}]$ looks like $[\alpha_h/Fe]$, but with more exaggerated deviations from the fiducial trendline.

5.3.3 Odd-Z elements

For the odd-Z elements, the eastern SMC has essentially fat age- $[X/Fe]$ trends for $[Na/Fe]$, $[Al/Fe]$, and $[K/Fe]$ (see Fig. D3). This is also true for stars with radii <3.3 kpc for $[Al/Fe]$ and $[K/Fe]$. This is not the case the inner SMC which is $[Na/Fe]$ -poor especially for ages over 5 Gyr. The outer galaxy age- $[Na/Fe]$ trend shows that it is rich in $[Na/Fe]$ for most of the lifetime of the SMC. The western region for radii larger than 3.3 kpc shows that the galaxy is poor in $[Al/Fe]$ for ages between ~ 4 and ~ 8 Gyr. The outer western part of the SMC has a more complicated age- $[K/Fe]$ trend, but the average trend appears to somewhat follow the fiducial trendline.

5.3.4 Iron peak elements

Much like other groups of elements, the iron peak age- $[X/Fe]$ trends are also mostly fat, though some deviate from this pattern (see Fig. D4). The $[V/Fe]$ abundance for the youngest stars in the inner galaxy show an increasing abundance with age, while this is less so for the outer galaxy. The eastern outer galaxy does show this increase more

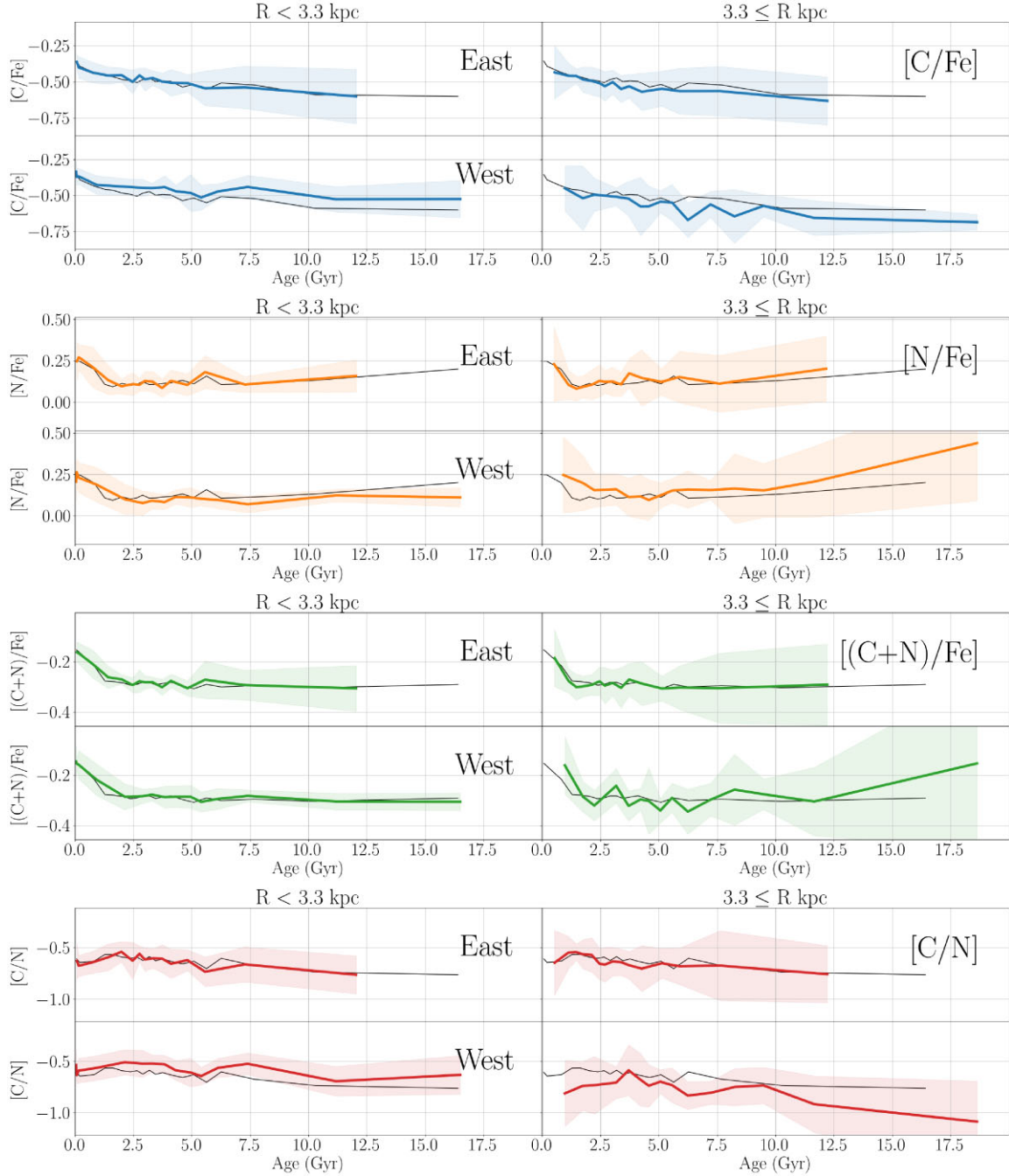


Figure 9. The age-[X/Fe] trends for the SMC for carbon and nitrogen. The top row in each panel shows the age-[X/Fe] trends for the eastern part of the SMC and the bottom row shows the trends in the west. The SMC is split into two radial bins that contain an equal number of stars corresponding to the inner ($R < 3.3$ kpc) and outer ($3.3 \leq R$ kpc) galaxy. For each sub-panel the age-[X/Fe] trend is included with a band of 1σ in addition the black fiducial line (found with the same method for the other trends) shows the age-[X/Fe] trend without any positional binning, meaning that the whole sample of stars was used. Clearly the [N/Fe] and [(C+N)/Fe] have a sharp increase at recent times.

than in the west, but nowhere near the inner galaxy. In the inner west regions, the oldest stars are typically deficient in [V/Fe] relative to the fiducial line, regardless for most ages the stars follow the fiducial line. In the out west regions there is an overabundance of [V/Fe].

The age-[Cr/Fe] trend stays close to solar for all times and radii < 3.3 kpc. This is also the case for the stars at larger radii on the eastern side. The outer SMC in the west shows a different behaviour with a [Cr/Fe] deficiency for ages ~ 10 Gyr. The age-[Mn/Fe] trend looks similar to the [Cr/Fe] one. The average value is less than solar

and is around -0.2 dex. The outer west is [Cr/Fe] poor for ages $\lesssim 8$ Gyr.

There is a steady increase from ≈ -1.5 dex up to ≈ -0.6 at the current day for the inner galaxy. The outer eastern region also shows this trend although it only reaches up to ≈ -1.0 dex at the present time. The outer west region is the most divergent from the rest of the galaxy as evidenced by the deviation from the fiducial trendline. While the outer west region does show an increase in [Fe/H], around 2.5 Gyr the trend turns down showing a decrease in [Fe/H] for that

part of the galaxy. Also, the outer west of the galaxy is metal-poor compared to the fiducial trendline for the older stars.

The age-[Co/Fe] trend is very flat staying slightly under the solar value. This is also case for [Ni/Fe], which is just under solar as well and follows the fiducial. The greatest deviations from the fiducial trendline happen in the outer west of the SMC. The average of the trends still follow the fiducial for both [Co/Fe] and [Ni/Fe].

5.3.5 The neutron capture element cerium

Looking at the age-[Ce/Fe] trend in Fig. D5, it is clear that the SMC [Ce/Fe] abundance increases over time with a more substantial increase for ages less than 5 Gyr. The eastern part of the SMC is neither deficient nor overabundant in cerium as there is almost no difference between the global fiducial trend and those for each radial bin. On the other hand, the west shows an overabundance in cerium for the inner SMC for ages $\gtrsim 5$ Gyr, but the outer galaxy is underabundant.

6 DISCUSSION

Below, we discuss the implications of our APOGEE abundance gradient results for the SMC. First is the overall metallicity gradient of the SMC and how it compares to literature values, second what the evolution of the calculated gradients and age-abundance trends are, and finally how the SMC compares to the LMC and MW.

6.1 SMC metallicity gradient

Here the metallicity ([Fe/H]) gradient calculated with APOGEE is compared to many other literature sources. Most of the literature sources gradients in units of dex deg^{-1} and to compare to this work, these have been converted to units of dex kpc^{-1} .³ Also, the literature sources discussed here are not exhaustive but demonstrate the range of measured values in the SMC radial metallicity gradient.

The overall metallicity gradient of the SMC in this work was found to be $-0.0546 \pm 0.0043 \text{ dex kpc}^{-1}$, which overlaps with gradients found by Idiart et al. (2007), Dobbie et al. (2014b), Parisi et al. (2022), and De Bortoli et al. (2022). For convenience Table 8 contains every single [Fe/H] calculated for the different age bins. See Fig. 10, Table 9 for a quantitative comparison to these and other literature sources.

Idiart et al. (2007) did a study of the chemical evolution of the SMC using planetary nebulae (PNe). In particular, they were interested in the evolution of oxygen in the galaxy as well as its age-metallicity relation. Using their data, the metallicity gradient of the SMC is $-0.0300 \pm 0.0500 \text{ dex kpc}^{-1}$, which does overlap with all of the gradients herein when accounting for the uncertainty. The actual value is close to that found for the 3.7–5.6 Gyr age bin and the gradient for the oldest stars.

Although Dobbie et al. (2014b) used field stars and CaT metallicities, they found a gradient of $-0.0688 \pm 0.0101 \text{ dex kpc}^{-1}$. This is consistent with the gradient of the youngest stars in the APOGEE sample, but not the others.

Choudhury et al. (2020) use a different metallicity-estimation technique to explore the metallicity distribution of the SMC. Metallicities were derived by relating the slope of the RGB branch in the Y versus $Y - K_s$ colour-magnitude diagram (CMD). The slopes were calculated for 1180 subregions of the SMC. The calculated gradient using the RGB slope metallicities is $-0.0028 \pm 0.0046 \text{ dex kpc}^{-1}$.

³We multiply by $\frac{180}{62.44\pi} \text{ deg/kpc}$ and make use of the small angle approximation.

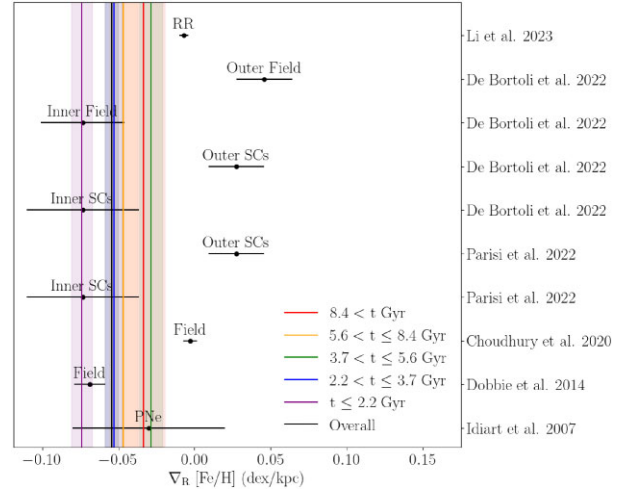


Figure 10. A comparison of the [Fe/H] gradients found in this work to multiple literature values. The vertical lines and bands correspond to the gradients for each of the age bins with the associated errors (see Table 8) and are plotted to provide context. The literature values are shown as points. The gradients calculated by De Bortoli et al. (2022) out to 3.4° overlap with the overall gradient as well as values found by Idiart, Maciel & Costa (2007) and Dobbie et al. (2014b). Around half of the literature gradients overlap with any of the gradients calculated in this work.

Table 6. Table of radial abundance gradients for cerium.

Element	$\nabla_R [X/\text{Fe}]$ (dex kpc $^{-1}$)	$\nabla_R [X/\text{H}]$ (dex kpc $^{-1}$)	$\nabla_R [X/\text{Mg}]$ (dex kpc $^{-1}$)
Ce	-0.0596 ± 0.0021	-0.1115 ± 0.0094	-0.0599 ± 0.0039

Recently Parisi et al. (2022) again revisited the metallicity gradient of the SMC using the CaT technique. The inner ($R < 3.4^\circ$) metallicity gradient was found to be $-0.0734 \pm 0.0367 \text{ dex kpc}^{-1}$, while the outer ($R > 3.4^\circ$) clusters have a gradient of $+0.0275 \pm 0.0184 \text{ dex kpc}^{-1}$. Clearly the inner cluster gradient overlaps with metallicity gradient found in this work.

The CaT technique is used to derive metallicities in De Bortoli et al. (2022). In that work, they explore the gradient of the inner ($R < 3.4^\circ$) and outer ($R > 3.4^\circ$) SMC using both field stars and star clusters. Both of the outer gradients fall far outside the range of any of the gradients calculated in this work. With the outer field stars having a gradient of $+0.0459 \pm 0.0184 \text{ dex kpc}^{-1}$ and the outer clusters having a slightly shallower gradient of $+0.0275 \pm 0.0184 \text{ dex kpc}^{-1}$. Both of the inner gradients overlap with the overall metallicity gradient and many other ones calculated here.

The final literature source discussed here is Li et al. (2023). In that work, metallicities are found for RR Lyrae stars in *Gaia* by using G -metallicity relations and near-IR period-absolute magnitude-metallicity relations. The gradient found was $-0.0070 \pm 0.0030 \text{ dex kpc}^{-1}$, which is consistent with Choudhury et al. (2020), but none of the gradients found in this work.

This variation in the literature values for the SMC gradient is reminiscent of what is seen for the LMC gradient (Paper II). Interestingly, if there is agreement with the literature values it tends to be with the youngest gradients with potential overlap with the overall gradient, especially when considering the inner SMC gradients in the literature (see Fig. 10). This may be due to a selection bias as there are more stars towards to centre of the SMC and the fact that the centre tends to be slightly younger on average. It could also be attributed

Table 7. A table of the different [X/Fe] gradients for each of the age bins for C, N, C + N, O, Mg, Si, S, Ca, Ti, α , α_h , α_{ex} , Na, Al, K, V, Cr, Mn, Co, Ni, and Ce. Spaces have been added marking the division of the previously defined groups of elements (see Section 5.2). In general descending down the table corresponds to an increase in atomic number. Each age bin has its own separate column. [Fe/H], [C/N], and $[\alpha_h/\alpha_{ex}]$ have also been included here. The inclusion of the [Fe/H] is to provide context for the many different [X/Fe] gradients.

Element	$t \leq 2.2$ ∇_R (dex kpc $^{-1}$)	$2.2 < t \leq 3.7$ ∇_R (dex kpc $^{-1}$)	$3.7 < t \leq 5.6$ ∇_R (dex kpc $^{-1}$)	$5.6 < t \leq 8.4$ ∇_R (dex kpc $^{-1}$)	$8.4 < t$ ∇_R (dex kpc $^{-1}$)
[C/Fe]	-0.0126 ± 0.0028	-0.0273 ± 0.0040	-0.0272 ± 0.0034	-0.0592 ± 0.0060	-0.0291 ± 0.0099
[N/Fe]	-0.0409 ± 0.0040	$+0.0008 \pm 0.0026$	$+0.0017 \pm 0.0025$	$+0.0120 \pm 0.0061$	$+0.0030 \pm 0.0037$
[(C + N)/Fe]	-0.0293 ± 0.0028	-0.0104 ± 0.0020	-0.0161 ± 0.0008	-0.0226 ± 0.0059	-0.0133 ± 0.0046
[C/N]	$+0.0278 \pm 0.0063$	-0.0338 ± 0.0064	-0.0348 ± 0.0058	-0.0612 ± 0.0085	-0.0321 ± 0.0115
[O/Fe]	-0.0020 ± 0.0016	$+0.0098 \pm 0.0024$	-0.0002 ± 0.0024	-0.0126 ± 0.0048	-0.0197 ± 0.0019
[Mg/Fe]	$+0.0245 \pm 0.0040$	$+0.0106 \pm 0.0034$	-0.0064 ± 0.0048	-0.0426 ± 0.0022	-0.0204 ± 0.0042
[Si/Fe]	$+0.0201 \pm 0.0025$	$+0.0099 \pm 0.0025$	-0.0005 ± 0.0027	-0.0114 ± 0.0045	-0.0049 ± 0.0060
[S/Fe]	$+0.0458 \pm 0.0080$	$+0.0298 \pm 0.0166$	-0.0724 ± 0.0150	$+0.0069 \pm 0.0156$	-0.0332 ± 0.0192
[Ca/Fe]	$+0.0041 \pm 0.0017$	$+0.0039 \pm 0.0022$	-0.0102 ± 0.0025	-0.0099 ± 0.0052	-0.0178 ± 0.0049
[Ti/Fe]	-0.0061 ± 0.0026	-0.0116 ± 0.0026	-0.0059 ± 0.0024	-0.0312 ± 0.0036	-0.0364 ± 0.0086
[α /Fe]	$+0.0032 \pm 0.0013$	$+0.0036 \pm 0.0024$	-0.0030 ± 0.0025	-0.0277 ± 0.0012	-0.0198 ± 0.0013
[α_h /Fe]	$+0.0122 \pm 0.0023$	$+0.0104 \pm 0.0025$	-0.0010 ± 0.0037	-0.0245 ± 0.0045	-0.0225 ± 0.0027
[α_{ex} /Fe]	$+0.0062 \pm 0.0013$	$+0.0006 \pm 0.0019$	-0.0012 ± 0.0019	-0.0235 ± 0.0028	-0.0184 ± 0.0021
[α_h/α_{ex}]	$+0.0051 \pm 0.0015$	$+0.0053 \pm 0.0016$	$+0.0004 \pm 0.0024$	-0.0031 ± 0.0019	-0.0057 ± 0.0016
[Na/Fe]	$+0.0077 \pm 0.0124$	$+0.0104 \pm 0.0119$	$+0.0204 \pm 0.0149$	$+0.0183 \pm 0.0160$	$+0.0531 \pm 0.0259$
[Al/Fe]	$+0.0057 \pm 0.0033$	$+0.0048 \pm 0.0057$	-0.0156 ± 0.0039	-0.0420 ± 0.0034	-0.0484 ± 0.0052
[K/Fe]	$+0.0079 \pm 0.0043$	$+0.0111 \pm 0.0042$	-0.0089 ± 0.0058	-0.0202 ± 0.0108	$+0.0032 \pm 0.0055$
[V/Fe]	-0.0732 ± 0.0170	-0.1351 ± 0.0067	$+0.0119 \pm 0.0134$	-0.0830 ± 0.0159	$+0.0591 \pm 0.0606$
[Cr/Fe]	$+0.0057 \pm 0.0045$	$+0.0019 \pm 0.0040$	-0.0170 ± 0.0080	$+0.0047 \pm 0.0098$	$+0.0082 \pm 0.0089$
[Mn/Fe]	-0.0179 ± 0.0026	-0.0185 ± 0.0020	-0.0059 ± 0.0034	-0.0101 ± 0.0043	-0.0087 ± 0.0055
[Fe/H]	-0.0742 ± 0.0068	-0.0529 ± 0.0057	-0.0286 ± 0.0076	-0.0466 ± 0.0092	-0.0335 ± 0.0139
[Co/Fe]	$+0.0142 \pm 0.0065$	-0.0091 ± 0.0032	-0.0258 ± 0.0060	-0.0160 ± 0.0129	-0.0426 ± 0.0088
[Ni/Fe]	$+0.0061 \pm 0.0008$	-0.0001 ± 0.0023	-0.0045 ± 0.0010	-0.0093 ± 0.0026	-0.0101 ± 0.0050
[Ce/Fe]	-0.0223 ± 0.0041	-0.0151 ± 0.0051	-0.0058 ± 0.0083	-0.0966 ± 0.0050	-0.0714 ± 0.0026

Table 8. A table of only the [Fe/H] gradients calculated for the SMC in this work to make it easier to refer back to the previously calculated values.

Age bin (Gyr)	∇_R (dex kpc $^{-1}$)	Error (dex kpc $^{-1}$)
overall	-0.0546	0.0043
$t \leq 2.2$	-0.0742	0.0068
$2.2 < t \leq 3.7$	-0.0529	0.0057
$3.7 < t \leq 5.6$	-0.0286	0.0076
$5.6 < t \leq 8.4$	-0.0466	0.0092
$8.4 < t$	-0.0335	0.0139

Table 9. Table of literature values for the [Fe/H]-gradient of the SMC. All but Li et al. (2023) and Choudhury et al. (2020) use CaT equivalent widths to the [Fe/H].

Source	∇_R (dex kpc $^{-1}$)	Method
Idiart et al. (2007)	-0.0300 ± 0.0500	PNe
Dobbie et al. (2014b)	-0.0688 ± 0.0101	CaT Field
Choudhury et al. (2020)	-0.0028 ± 0.0046	RGB Slope
Parisi et al. (2022)	-0.0734 ± 0.0367	CaT Inner SCs
—	$+0.0275 \pm 0.0184$	CaT Outer SCs
De Bortoli et al. (2022)	-0.0734 ± 0.0367	CaT Inner SCs
—	$+0.0275 \pm 0.0184$	CaT Outer SCs
—	-0.0734 ± 0.0275	CaT Inner Field
—	$+0.0459 \pm 0.0184$	CaT Outer Field
Li et al. (2023)	-0.0070 ± 0.0030	Gaia G Band RR

to the over representation of younger stars in samples of RGB stars. More data will be needed to make sure that these results are robust and to fill in the gaps between the APOGEE fields. Even with this, the metallicity gradient found in this work is the largest gradient study that uses high resolution spectra of individual stars.

6.2 Evolution of abundance gradients of the SMC

Abundance gradients for 24 abundance ratios were calculated using 2062 field RGB stars in the SMC. Combining these gradients with ages calculated using the method in Paper II makes it possible to study the evolution of each of the gradients.

While there are extremum points in the trends of the gradients for most elements, many have one for stars aged 3.7–5.6 Gyr. Abundances with this critical point appearing in their evolution includes [Cr/Fe], most of the [X/H] gradients, [Ca/Mg], [Na/Mg], [Al/Mg], and [Fe/Mg] as seen in Figs 5, 6, and 7. The fact that this feature is so ubiquitous in many elements from different element groups, suggests a major galaxy-wide event caused it.

In Paper II, it was found that extremum points in the evolution of LMC abundance gradients are possibly connected to starbursts from intergalactic interactions. It is known that an LMC–SMC interaction produced a starburst in each galaxy (Cignoni et al. 2012, 2013; Dobbie et al. 2014b; Nidever et al. 2020; Hasselquist et al. 2021). The starburst in the LMC was found to happen about 2 Gyr ago in Nidever et al. (2020) and is consistent with the change in the abundance trends in Paper II. The turnover in the gradient evolution for the SMC was found to happen earlier around 3.7–5.6 Gyr ago.

Cignoni et al. (2012, 2013) derive SFHs using *HST* data, revealing clear evidence of a starburst in the SMC’s bar 4–6 Gyr ago and across the entire SMC 5–7 Gyr ago. This is consistent with Dobbie et al. (2014b), which found an increase in the star formation 5–6 Gyr ago in the SMC due to an interaction between the LMC and Hasselquist et al. (2021) found that the SMC did experience a burst of star formation 3–4 Gyr before the LMC. Qualitatively the results of that paper agree with this work, but the time of the burst is somewhat different even with using the same data. In that work the time of the starburst was determined by fitting chemical evolution models to the data. Also, Massana et al. (2022) found bursts of star formation at ~ 3 and ~ 2 Gyr in the SMC, while the LMC star formation ramps up at ~ 3 Gyr ago but does not peak until ~ 2 Gyr ago. As previously mentioned, Rubele et al. (2018) finds a peak in the SFR of the SMC between 4.0 and 6.3 Gyr ago. This peak lines up with the turnover in the U-shaped trends of the abundance gradients suggesting a correlation.

There are some inconsistencies in the age ranges for the starburst/burst of star formation between photometric and spectroscopic results. These discrepancies arise due to various factors, such as errors in the derived ages, photometric crowding in the fields, or small sample sizes. Nevertheless, there are clear similarities that support the conclusion that the SMC experienced a burst of star formation prior to the one in the LMC.

Additionally, examining the $[\text{Fe}/\text{H}]$ distribution for the SMC stars in Fig. 4, the largest peak has an average $[\text{Fe}/\text{H}]$ of -1.11 ± 0.11 and an age of 4.8 ± 2.2 Gyr, suggesting that a significant portion of these stars formed around that time. This timing aligns with the starburst that is likely responsible for the U-shaped gradient-age trends.

Radial migration is a process whereby stars move to a different radius because additional angular momentum is imparted on them (e.g. Sellwood & Binney 2002). Naturally this will change the observed gradients especially for older stars so the present day gradients may not be representative of the gradients when the stars formed. Lu et al. (2024) and Ratcliffe et al. (2023) find that while radial migration has affected the gradients in the MW, past interactions produce a signature steepening of gradients when it would be expected to see a fattening. But Schroyen et al. (2013) showed that dwarf galaxy metallicity gradients are less affected by radial migration than larger galaxies. This could be used to argue that the SMC gradients have changed less due to radial migration. Regardless, it is best to keep in mind radial migration when ruminating about the results in this work and to think of the evolutionary trends as more age-dependent trends.

Additionally, in Paper II it was found that many of the age- $[\text{X}/\text{Fe}]$ trends have a turnover with an extremum point due to an LMC starburst which further helps pinpoint the time frame of the burst. This is not what is seen in the SMC. The trends for the SMC are essentially flat with a few showing some slight increase or decrease for extremely young ages. There is no feature in the trends at the time of the burst. Most trends stay close to the fiducial trendline regardless of the spatial bin. This suggests that the SMC has experienced a slower enrichment history throughout the galaxy. Any disparities with the global fiducial trend are mostly in the outer western region of the galaxy.

6.3 Comparing the SMC to the LMC and MW

In addition to comparing the calculated $[\text{Fe}/\text{H}]$ gradient to other literature values, we also compare the SMC abundance gradients to those of the LMC and MW using the same method outlined in Section 4 and the same APOGEE data. This allows us to conduct an homogeneous comparison of abundance gradients across a factor of ~ 500 in total galaxy mass (SMC: $2 \times 10^9 M_\odot$, Stanimirović,

Staveley-Smith & Jones 2004; LMC: $1.38 \times 10^{11} M_\odot$, Erkal et al. 2019; MW: $1.28 \times 10^{12} M_\odot$, Watkins et al. 2019) in a uniform manner. Gradients for the LMC were previously calculated using the APOGEE data in Paper II. We determine our own MW radial abundance gradients here.

MW RGB stars were selected from the APOGEE `allStar` file⁴ using a slightly modified version of the selection from Jönsson et al. (2020):

- (i) $1.5 < \log g < 3.5$
- (ii) $[\text{C}/\text{N}] > 0.04 - 0.46[\text{M}/\text{H}] - 0.0028 \cdot dT$

where

$$dT = T_{\text{eff,spec}} - (4400 + 552.6 \cdot (\log g_{\text{spec}} - 2.5) - 324.6 \cdot [\text{M}/\text{H}])$$

and where $T_{\text{eff,spec}}$, and $\log g_{\text{spec}}$ are the `TEFF_SPEC` and `LOGG_SPEC` columns in the `allStar` summary file, respectively. After this initial selection, a second selection was used to pick out stars close to the MW midplane using:

- (i) $4.0 \leq R \leq 15.0$ kpc
- (ii) $|Z| \leq 1.0$ kpc,

where R is the galactic radius of a star, and Z is the vertical distance from the midplane. The selection criterion on R was chosen so that there is large radial coverage, but that structures of the inner MW (i.e. bar and bulge) did not ‘contaminate’ the disc sample. Once the selection is done, the method in Section 4 is used to calculate the radial abundance gradients. Each of the galaxy gradients are scaled by the exponential disc radial scale length of each galaxy to remove the bias of different galaxy sizes. The radial scale of the disc for the SMC is 1.25 kpc (Gonidakis et al. 2009), for the LMC is 1.667 kpc (Choi et al. 2018), and for the MW is 2.15 kpc (Bovy & Rix 2013).

It is important to mention that the APOGEE LMC and SMC samples should be relatively free from MW contamination in that the number of MW stars is negligible. The contamination was minimized using selection cuts in ASPCAP stellar parameters, radial velocities, and proper motions from *Gaia* DR2 (Gaia Collaboration 2018) as outlined in Nidever et al. (2020). In that paper, it is stated that if a star in the MC sample is actually from the MC, then most likely it will be a halo star. Since the MW halo is made up of older metal-poor stars this would skew the metallicity in the MCs to be more metal poor depending on how substantial the fraction of MW stars is.

In the top panel of Fig. 11, the SMC, LMC, and MW really stand out from each other in their $[\text{X}/\text{H}]$ gradients. The LMC gradients appear the shallowest followed by the SMC and then the MW. While not exactly the same, both of the Clouds have more similar gradients between themselves, $-0.082 \text{ dex}/R_d$ in the SMC and $-0.061 \text{ dex}/R_d$ in the LMC versus the $-0.119 \text{ dex}/R_d$ in the MW. The clear separation between the Clouds and the MW for the $[\text{X}/\text{H}]$ suggest that there may exist a mass dependence in these gradients. The median $[\text{X}/\text{Mg}]$ gradients for the Clouds are $\sim -0.075 \text{ dex}/R_d$ and the MW median gradient is roughly 50 per cent steeper with a value of $-0.120 \text{ dex}/R_d$.

In contrast, the patterns in the $[\text{X}/\text{Fe}]$ gradients of the three galaxies look very similar (bottom panel of Fig. 11). There are only a few elements for which a substantial difference occurs such as the case with $[\text{Ce}/\text{Fe}]$. For some elements, the gradients for the Clouds look alike (e.g. $[\text{N}/\text{Fe}]$, $[\text{C}/\text{N}]$, $[\text{O}/\text{Fe}]$, $[\alpha/\text{Fe}]$, etc.) while there are elements for which the LMC and MW look alike or the SMC and the MW do. Since the clouds and the MW have had a very

⁴https://www.sdss.org/dr17/irspec/spectro_data/

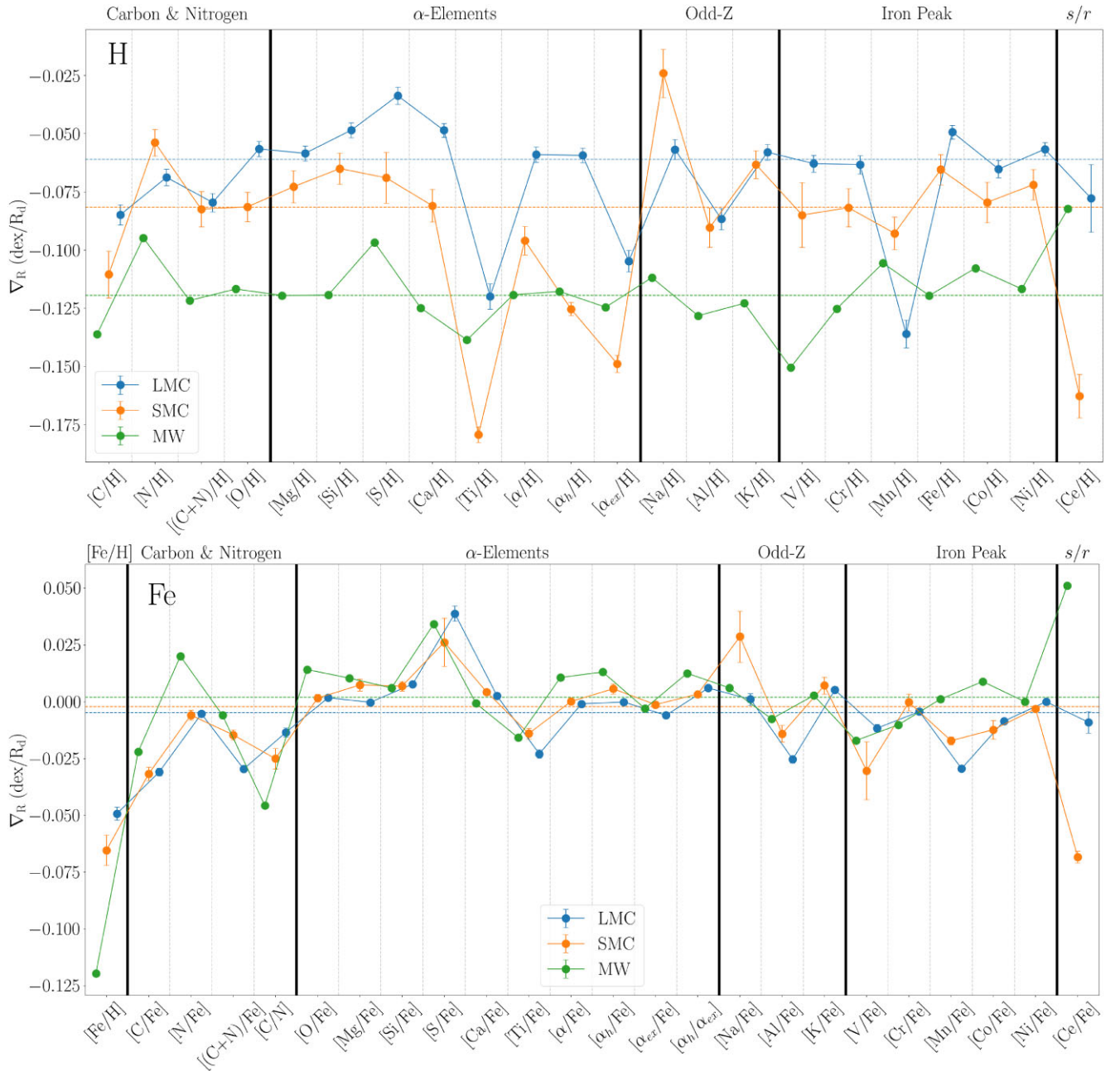


Figure 11. A comparison of the overall gradients for the SMC, LMC, and MW for the $[X/H]$ and $[X/Fe]$. The dashed lines show the median $[X/H]$ or $[X/Fe]$ gradients in their respective panels. (Top) The gradients for $[X/H]$ in the dwarfs are fatter compared to the MW gradients hinting at a potential mass dependence. The upper blue curve shows the LMC gradients, the middle orange curve shows the SMC gradients, and the lower green curve shows the MW gradients. The median MW $[X/H]$ gradient is -1.19 dex/ R_d while the SMC and LMC have median gradients of -0.082 dex/ R_d and -0.061 dex/ R_d , respectively. (Bottom) The same as the top panel but for the $[X/Fe]$ gradients. Other than a few instances, the gradients of the galaxies are typically very similar in value as the median gradients are all around 0.0 dex/ R_d .

different accretion and formation history, the overall consistency of the patterns in the radial $[X/Fe]$ gradients (in dex/ R_d) may suggest that these are a fairly universal aspect of galaxies.

As for the $[X/Mg]$ gradients (Fig. E1), the three galaxies have comparable gradients except in a few elements. The largest separation between the galaxies occurs with $[Fe/Mg]$ and $[Ce/Mg]$ and is similar in many ways to what is seen for the $[X/H]$ gradients. Possibly these gradients are galaxy mass sensitive. The median $[X/Mg]$ gradients for all three galaxies is fat.

7 SUMMARY

We calculated radial abundance gradients for 24 abundance ratios and their temporal evolution with an MCMC technique using 2062 APOGEE DR17 RGB stars in the SMC. In addition, age-abundance trends for $[C/N]$ and $[\alpha_h/\alpha_{ex}]$ were measured.

The SMC has an overall RGB metallicity gradient of -0.0546 ± 0.0043 dex kpc $^{-1}$, which is steeper than the LMC, but nowhere near as steep as the MW field star gradient. Accounting for disc scale length, the metallicity gradient of the SMC is $-0.0654 \pm$

0.0067 dex/ R_d , the LMC is -0.0525 ± 0.0035 dex/ R_d , and the MW is -0.1196 ± 0.0009 dex/ R_d . The calculated SMC gradient agrees with gradients from Dobbie et al. (2014b), Parisi et al. (2022), and De Bortoli et al. (2022). There is better agreement on the inner SMC metallicity gradient calculated in the literature, regardless of the source using GCs or field stars.

Further comparing the overall SMC gradients to the LMC and MW show that in many cases the gradients are too similar to distinguish between the three galaxies. This is true for the [X/Fe] and [X/Mg] gradients, but not with the [X/H] gradients. The radial iron gradients, regardless of the fiducial element, deviate from each other for all three galaxies, though the MCs have closer gradients. The median gradient for the [X/Fe] and [X/Mg] are very similar for all three galaxies, but this is not the case for [X/H]. For the [X/H] abundances, the median MW gradient is around -0.125 dex/ R_d , while the Clouds have median gradients around -0.075 dex/ R_d .

There are a substantial number of gradients with extremum points in their evolution for stars aged 3.7–5.6 Gyr old including [Cr/Fe], [C/H], [(C + N)/H], [Mg/H], [Ca/H], [Ti/H], [α /H], [α_h /H], [α_{ex} /H], [Cr/H], [Mn/H], [Fe/H], [Co/H], [Ni/H], [Ce/H], [Ca/Mg], [Na/Mg], [Al/Mg], and [Fe/Mg]. Each of these gradients have a U-shape as a function of age. Similar to what the LMC gradients in Paper II show, the extremum point in their evolution corresponds to the starburst triggered by a close interaction between the LMC and SMC, though the starburst in the SMC happens before the LMC.

For the most part, the age–[X/Fe] trends are flat for the SMC, even more so than what was found in Paper II with the LMC. In most cases with any discernible differences, the outer SMC in the west seems to be more chemically different compared to the rest of the galaxy. Unfortunately, there is no feature in the trends which can help pinpoint the starburst due to the LMC–SMC interaction as was found in Paper II.

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Software: ASTROPY (Astropy Collaboration 2013, 2018), MATPLOTLIB (Hunter 2007), NUMPY (Harris et al. 2020), SCIPY (Virtanen et al. 2020)

DATA AVAILABILITY

All APOGEE DR17 data used in this study is publicly available and can be found at: https://www.sdss4.org/dr17/data_access/.

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APPENDIX A: GAIA ADQL QUERY

Here is the *Gaia* ADQL query used to get a sample of SMC stars from which the RC is selected for determining the APOGEE field RC proper motions.

```
SELECT * FROM gaiadr3.gaia_source_lite as g
WHERE 1 = CONTAINS(POINT(g.ra,g.dec),
CIRCLE(13.18333333,-72.82833333,11))
AND g.phot_g_mean_mag<20.5
AND g.parallax IS NOT NULL
AND g.phot_bp_mean_mag IS NOT NULL
AND g.phot_rp_mean_mag IS NOT NULL
AND g.phot_g_mean_mag IS NOT NULL
AND g.parallax<0.2
AND g.parallax>-0.2
```

```

AND g.pmra>=-3.0
AND pmra<=3.0
AND g.pmdec>=-3.0
AND pmdec<=3.0
AND g.phot_g.mean.flux.over.error>3.0
AND g.phot_bp.mean.flux.over.error>3.0
AND g.phot_rp.mean.flux.over.error>3.0

```

APPENDIX B: ∇_R [X/H] AND ∇_R [X/Mg] TABLES

The tables for the [X/H] and [X/Mg] gradients, which do not appear in the main body of the paper.

Table B1. The same as Table 7, but for the [X/H] gradients.

Element	$t \leq 2.2$ ∇_R (dex kpc $^{-1}$)	$2.2 < t \leq 3.7$ ∇_R (dex kpc $^{-1}$)	$3.7 < t \leq 5.6$ ∇_R (dex kpc $^{-1}$)	$5.6 < t \leq 8.4$ ∇_R (dex kpc $^{-1}$)	$8.4 < t$ ∇_R (dex kpc $^{-1}$)
[C/H]	-0.0812 ± 0.0081	-0.0910 ± 0.0098	-0.0440 ± 0.0117	-0.1131 ± 0.0215	-0.0776 ± 0.0241
[N/H]	-0.0647 ± 0.0082	-0.0560 ± 0.0064	-0.0244 ± 0.0055	-0.0225 ± 0.0088	-0.0258 ± 0.0110
[(C + N)/H]	-0.0891 ± 0.0068	-0.0698 ± 0.0089	-0.0292 ± 0.0075	-0.0772 ± 0.0177	-0.0262 ± 0.0150
[O/H]	-0.0547 ± 0.0072	-0.0591 ± 0.0054	-0.0279 ± 0.0073	-0.0513 ± 0.0082	-0.0608 ± 0.0154
[Mg/H]	-0.0149 ± 0.0074	-0.0597 ± 0.0072	-0.0419 ± 0.0059	-0.1092 ± 0.0086	-0.0693 ± 0.0161
[Si/H]	-0.0307 ± 0.0059	-0.0420 ± 0.0071	-0.0204 ± 0.0056	-0.0539 ± 0.0092	-0.0618 ± 0.0142
[S/H]	-0.0236 ± 0.0096	-0.0651 ± 0.0195	-0.0486 ± 0.0072	-0.0535 ± 0.0251	-0.1362 ± 0.0441
[Ca/H]	-0.0561 ± 0.0068	-0.0631 ± 0.0078	-0.0461 ± 0.0077	-0.0693 ± 0.0117	-0.0662 ± 0.0175
[Ti/H]	-0.0786 ± 0.0081	-0.0699 ± 0.0076	-0.0371 ± 0.0102	-0.0661 ± 0.0140	-0.1352 ± 0.0141
[α /H]	-0.0407 ± 0.0067	-0.0622 ± 0.0060	-0.0344 ± 0.0071	-0.0724 ± 0.0084	-0.0657 ± 0.0141
[α_h /H]	-0.0306 ± 0.0067	-0.0607 ± 0.0061	-0.0321 ± 0.0074	-0.0677 ± 0.0094	-0.0649 ± 0.0153
[α_{ex} /H]	-0.0582 ± 0.0068	-0.0586 ± 0.0066	-0.0326 ± 0.0081	-0.0658 ± 0.0118	-0.0636 ± 0.0153
[Na/H]	-0.0642 ± 0.0151	-0.0288 ± 0.0164	-0.0421 ± 0.0086	-0.0267 ± 0.0140	-0.0592 ± 0.0181
[Al/H]	-0.0305 ± 0.0050	-0.0758 ± 0.0086	-0.0663 ± 0.0103	-0.1421 ± 0.0133	-0.1379 ± 0.0175
[K/H]	-0.0134 ± 0.0047	-0.0412 ± 0.0057	-0.0413 ± 0.0020	-0.0978 ± 0.0108	-0.0417 ± 0.0198
[V/H]	-0.1411 ± 0.0166	$+0.0260 \pm 0.0061$	-0.0705 ± 0.0171	-0.1005 ± 0.0168	-0.0033 ± 0.0566
[Cr/H]	-0.0916 ± 0.0126	-0.0700 ± 0.0114	-0.0437 ± 0.0101	-0.0486 ± 0.0151	-0.0684 ± 0.0242
[Mn/H]	-0.0918 ± 0.0074	-0.0747 ± 0.0095	-0.0440 ± 0.0102	-0.0562 ± 0.0136	-0.0460 ± 0.0161
[Fe/H]	-0.0741 ± 0.0070	-0.0528 ± 0.0057	-0.0286 ± 0.0076	-0.0464 ± 0.0091	-0.0336 ± 0.0139
[Co/H]	-0.0582 ± 0.0105	-0.0631 ± 0.0072	-0.0528 ± 0.0100	-0.0675 ± 0.0201	-0.0857 ± 0.0213
[Ni/H]	-0.0452 ± 0.0063	-0.0597 ± 0.0068	-0.0233 ± 0.0083	-0.0575 ± 0.0107	-0.0441 ± 0.0193
[Ce/H]	-0.0963 ± 0.012	-0.0587 ± 0.0107	-0.0115 ± 0.0129	-0.1380 ± 0.0310	-0.0884 ± 0.0298

Table B2. The same as Table 7, but for the [X/H] gradients. The [Mg/H] have been provided here to give context for all of the gradients using the Mg fiducial.

Element	$t \leq 2.2$ ∇_R (dex kpc $^{-1}$)	$2.2 < t \leq 3.7$ ∇_R (dex kpc $^{-1}$)	$3.7 < t \leq 5.6$ ∇_R (dex kpc $^{-1}$)	$5.6 < t \leq 8.4$ ∇_R (dex kpc $^{-1}$)	$8.4 < t$ ∇_R (dex kpc $^{-1}$)
[C/Mg]	-0.0500 ± 0.0054	-0.0252 ± 0.0041	-0.0221 ± 0.0062	-0.0127 ± 0.0143	-0.0093 ± 0.0072
[N/Mg]	-0.0742 ± 0.0058	$+0.0054 \pm 0.0041$	$+0.0239 \pm 0.0037$	$+0.0522 \pm 0.0074$	$+0.0285 \pm 0.0036$
[(C + N)/Mg]	-0.0556 ± 0.0040	-0.0132 ± 0.0027	-0.0006 ± 0.0033	$+0.0215 \pm 0.0070$	$+0.0214 \pm 0.0058$
[O/Mg]	-0.0196 ± 0.0035	$+0.0013 \pm 0.0014$	$+0.0012 \pm 0.0008$	$+0.0113 \pm 0.0024$	$+0.0111 \pm 0.0024$
[Mg/H]	-0.0154 ± 0.0072	-0.0596 ± 0.0073	-0.0418 ± 0.0060	-0.1094 ± 0.0086	-0.0691 ± 0.0162
[Si/Mg]	-0.0106 ± 0.0032	-0.0041 ± 0.0011	$+0.0035 \pm 0.0018$	$+0.0245 \pm 0.0021$	$+0.0167 \pm 0.0027$
[S/Mg]	$+0.0097 \pm 0.0109$	$+0.0094 \pm 0.0170$	-0.0349 ± 0.0111	$+0.0223 \pm 0.0255$	-0.0262 ± 0.0270
[Ca/Mg]	-0.0213 ± 0.0036	-0.0057 ± 0.0030	$+0.0153 \pm 0.0024$	-0.0166 ± 0.0016	$+0.0108 \pm 0.0066$
[Ti/Mg]	-0.0429 ± 0.0042	-0.0003 ± 0.0011	-0.0003 ± 0.0053	$+0.0140 \pm 0.0046$	-0.0545 ± 0.0031
[α /Mg]	-0.0154 ± 0.0027	-0.0025 ± 0.0012	$+0.0008 \pm 0.0017$	$+0.0111 \pm 0.0034$	$+0.0062 \pm 0.0032$
[α_h /Mg]	-0.0097 ± 0.0018	$+0.0006 \pm 0.0007$	$+0.0006 \pm 0.0004$	$+0.0057 \pm 0.0012$	$+0.0055 \pm 0.0011$
[α_{ex} /Mg]	-0.0214 ± 0.0033	-0.0102 ± 0.0008	$+0.0000 \pm 0.0025$	$+0.0015 \pm 0.0025$	$+0.0043 \pm 0.0030$
[Na/Mg]	-0.0302 ± 0.0160	$+0.0035 \pm 0.0164$	$+0.0121 \pm 0.0109$	$+0.0179 \pm 0.0164$	$+0.0603 \pm 0.0234$
[Al/Mg]	-0.0280 ± 0.0042	-0.0068 ± 0.0020	-0.0133 ± 0.0041	-0.0130 ± 0.0033	-0.0283 ± 0.0069
[K/Mg]	-0.0085 ± 0.0043	$+0.0133 \pm 0.0028$	-0.0008 ± 0.0028	$+0.0188 \pm 0.0036$	$+0.0088 \pm 0.0011$

Table B2 – continued

Element	$t \leq 2.2$ ∇_R (dex kpc $^{-1}$)	$2.2 < t \leq 3.7$ ∇_R (dex kpc $^{-1}$)	$3.7 < t \leq 5.6$ ∇_R (dex kpc $^{-1}$)	$5.6 < t \leq 8.4$ ∇_R (dex kpc $^{-1}$)	$8.4 < t$ ∇_R (dex kpc $^{-1}$)
[V/Mg]	-0.1231 ± 0.0171	-0.1002 ± 0.0119	$+0.0601 \pm 0.0124$	-0.0737 ± 0.0221	$+0.0799 \pm 0.0519$
[Cr/Mg]	-0.0280 ± 0.0090	-0.0066 ± 0.0078	-0.0095 ± 0.0079	-0.0017 ± 0.0153	$+0.0297 \pm 0.0062$
[Mn/Mg]	-0.0429 ± 0.0053	-0.0254 ± 0.0044	-0.0354 ± 0.0019	$+0.0036 \pm 0.0055$	$+0.0307 \pm 0.0087$
[Fe/Mg]	-0.0840 ± 0.0149	-0.1194 ± 0.0138	-0.0570 ± 0.0078	-0.1530 ± 0.0185	-0.1016 ± 0.0261
[Co/Mg]	-0.0177 ± 0.0055	-0.0121 ± 0.0036	-0.0126 ± 0.0082	-0.0028 ± 0.0117	$+0.0070 \pm 0.0093$
[Ni/Mg]	-0.0098 ± 0.0030	-0.0060 ± 0.0030	$+0.0111 \pm 0.0039$	$+0.0225 \pm 0.0033$	$+0.0215 \pm 0.0055$
[Ce/Mg]	-0.0672 ± 0.0066	-0.0065 ± 0.0076	$+0.0054 \pm 0.0090$	$+0.0239 \pm 0.0168$	-0.0364 ± 0.0044

APPENDIX C: RADIUS-ABUNDANCE-AGE TRENDS

The radius-[x/Fe]-age trends for the α -elements, odd-Z elements, iron peak elements, and neutron capture elements that do not appear in the main body of the paper.

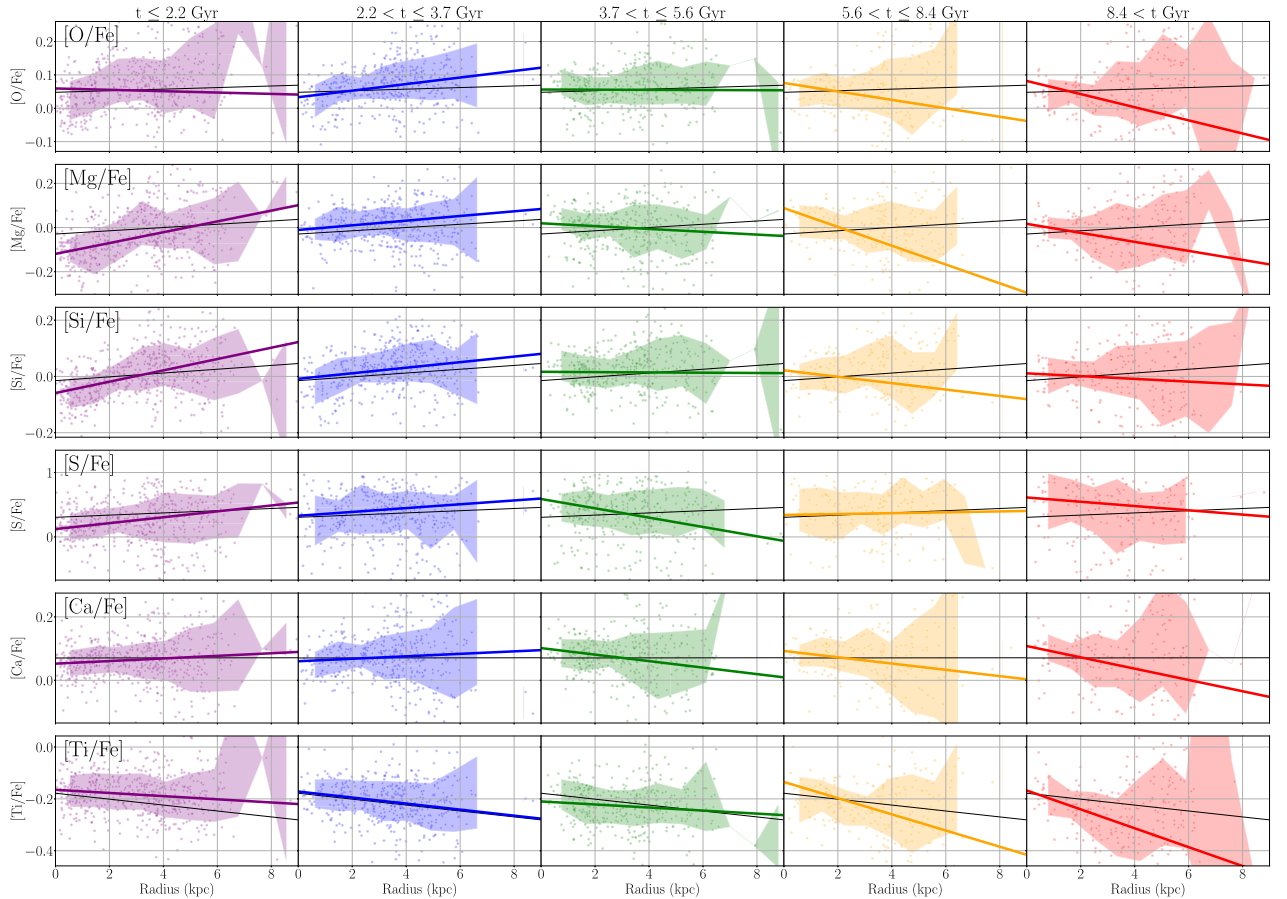


Figure C1. The same as Fig. 8, but with the individual α -element abundances. These trends show that the oldest two age bins generally have negative gradients while the younger ones have positive gradients.

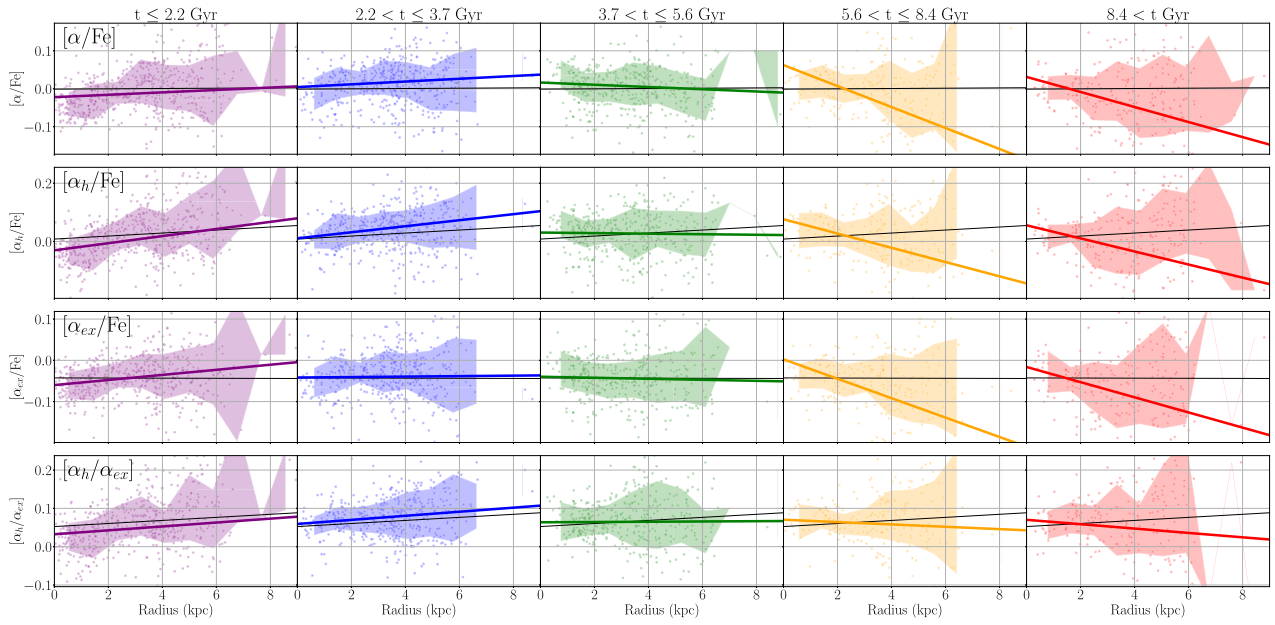


Figure C2. The radial abundance trends for the composite α -element abundances. The gradients for these ratios look very similar to the individual α -element gradients as would be expected.

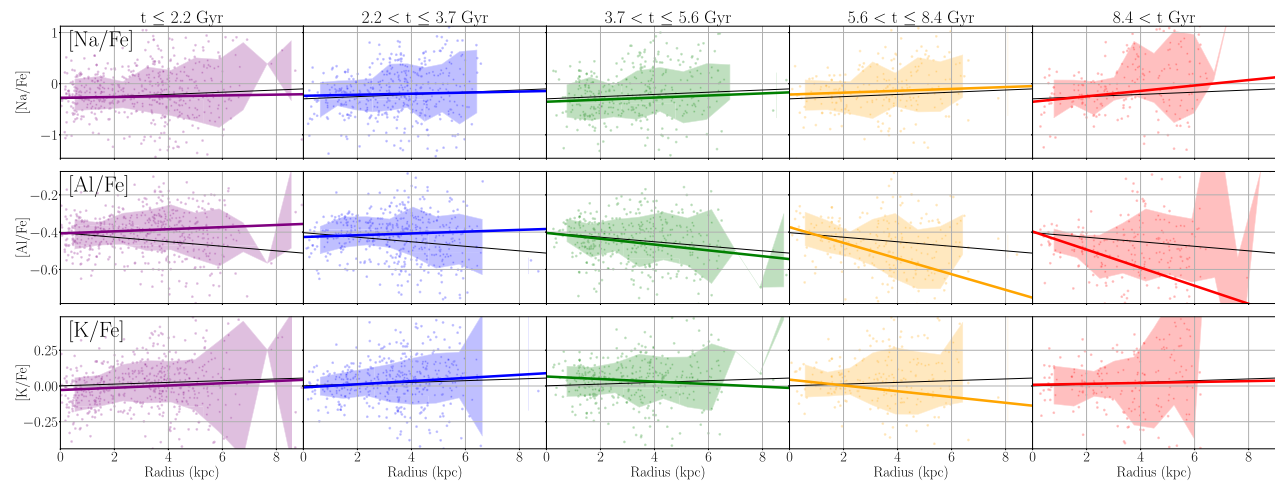


Figure C3. The radial abundance trends for the odd-Z abundances. The central abundances of the odd-Z elements do not change much with age. Both the gradients for $[\text{Na}/\text{Fe}]$ and $[\text{Al}/\text{Fe}]$ become fatter, but $[\text{K}/\text{Fe}]$ stays more or less the same.

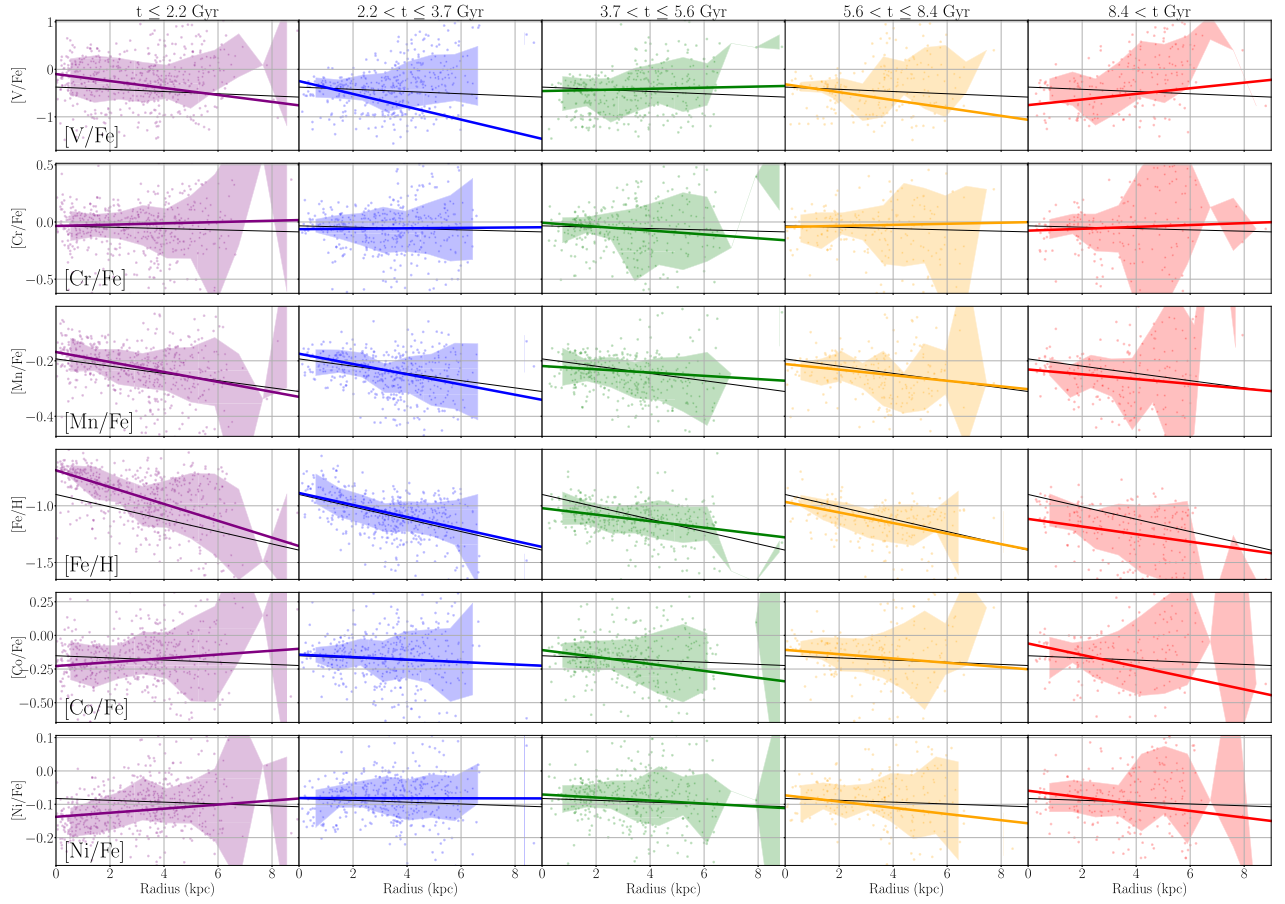


Figure C4. The radial abundance trends for the iron peak abundances. Many of the trends show that many of the gradients do not change much with age. $[V/Fe]$ shows the most change with age among the iron peak elements.

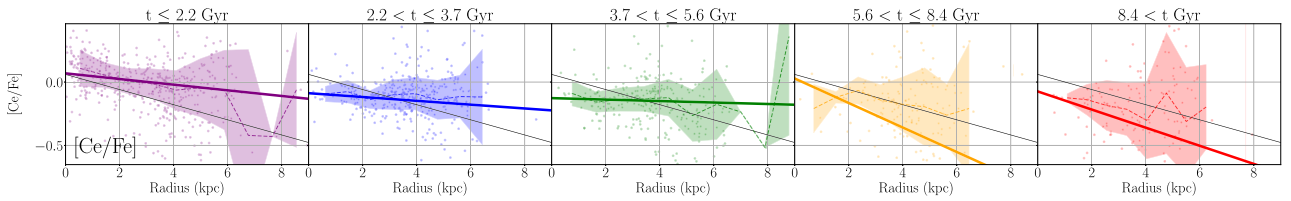


Figure C5. The radial abundance trends for the neutron capture abundances. The trends show that the two oldest age bins have steeper gradients compared to the three youngest bins.

APPENDIX D: AGE- $[X/Fe]$ TRENDS

The age- $[X/Fe]$ trends for the α -elements, odd-Z elements, iron peak elements, and neutron capture elements that do not appear in the main body of the paper.

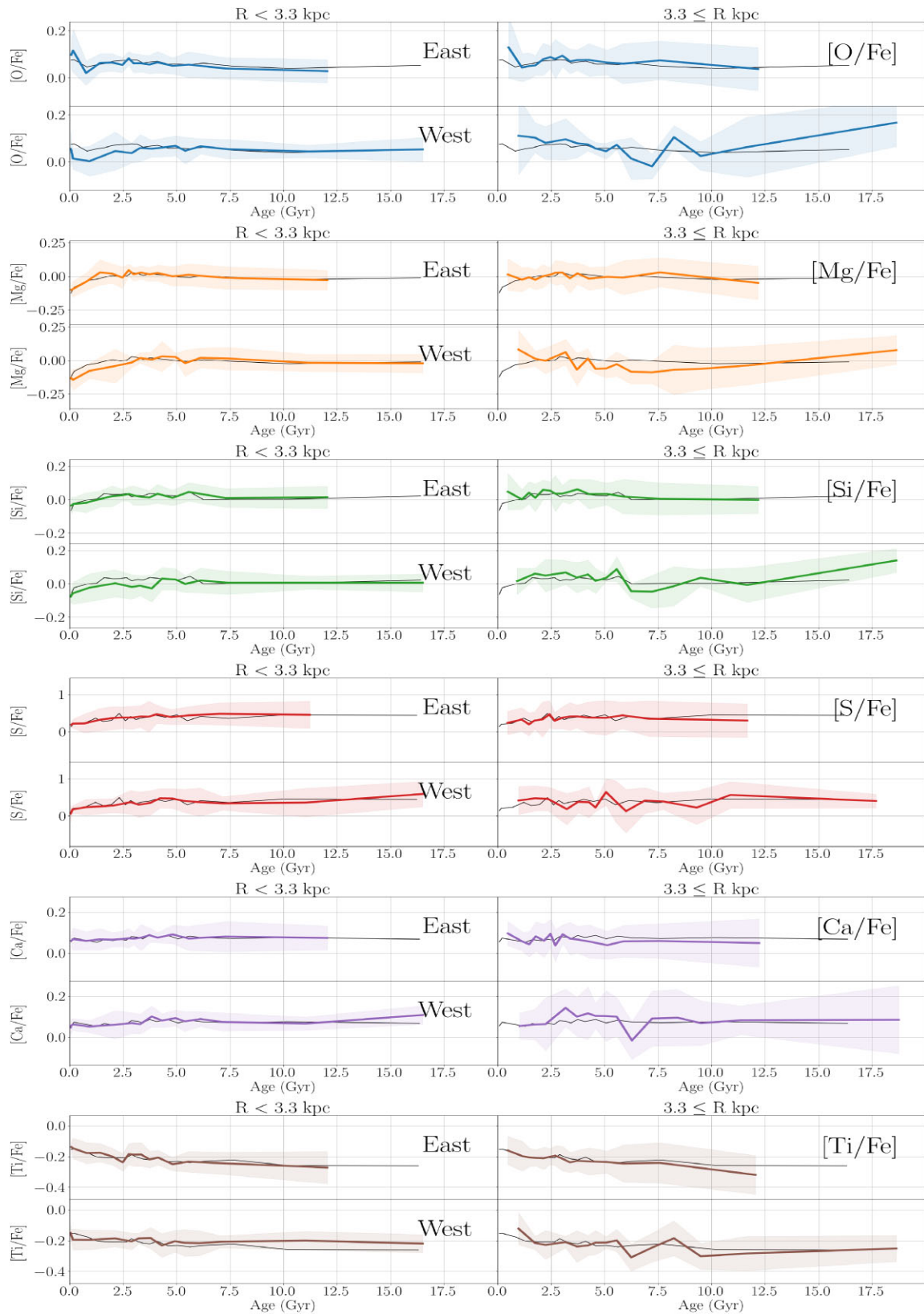


Figure D1. The age-[X/Fe] trends for the SMC for the individual α -element abundances. The trends for these elements are mostly flat, even more so than the ones found in Fig. 9. Nevertheless there appears to be a slight increase in [O/Fe] and [Ti/Fe] very recently while [Mg/Fe] shows a decrease at the same time.

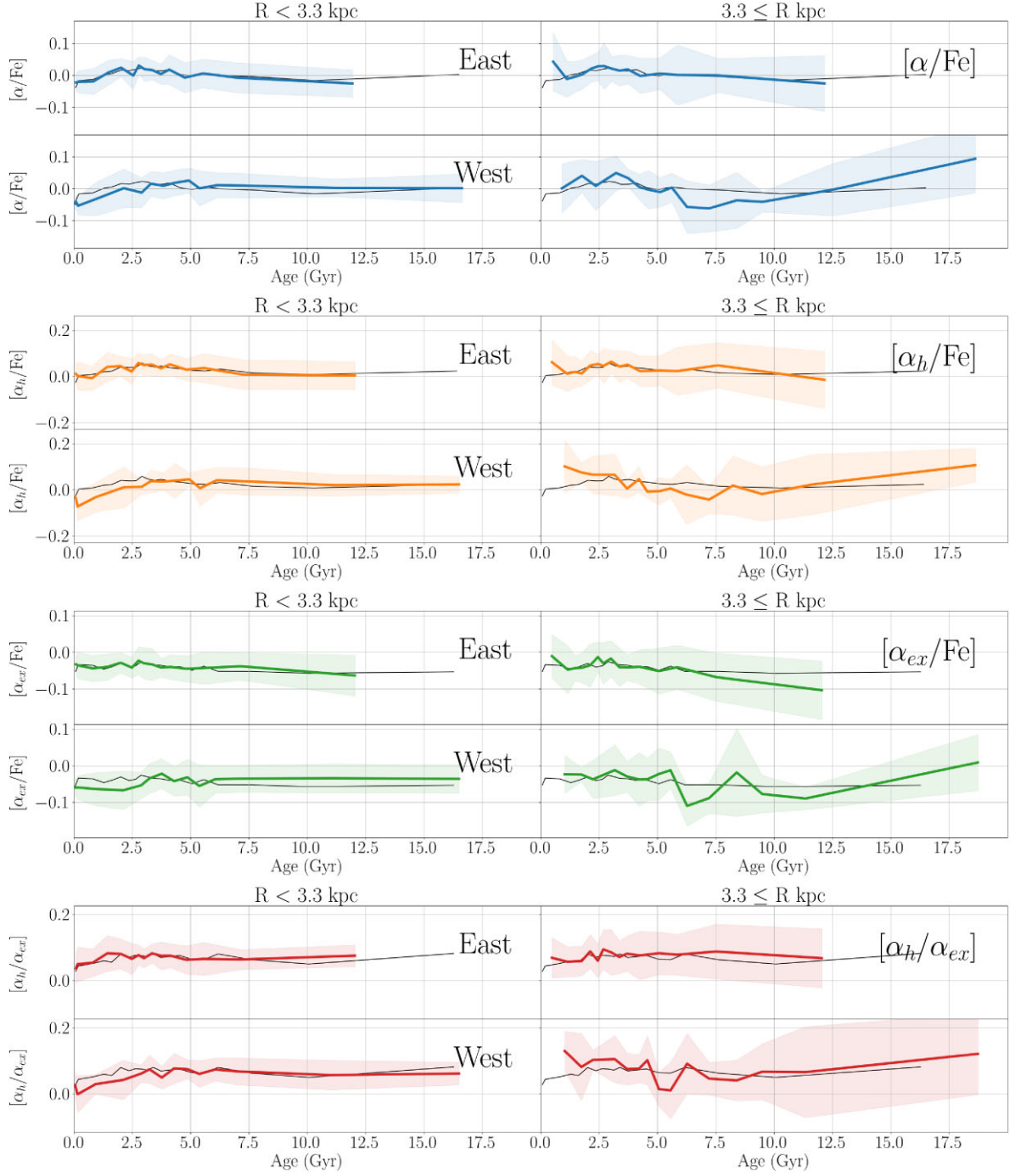


Figure D2. The age-[X/Fe] trends for the SMC for the composite α -element abundances. Some of the composite α abundance ratios shows a slight decrease for stars formed in the last 2.5 Gyr.

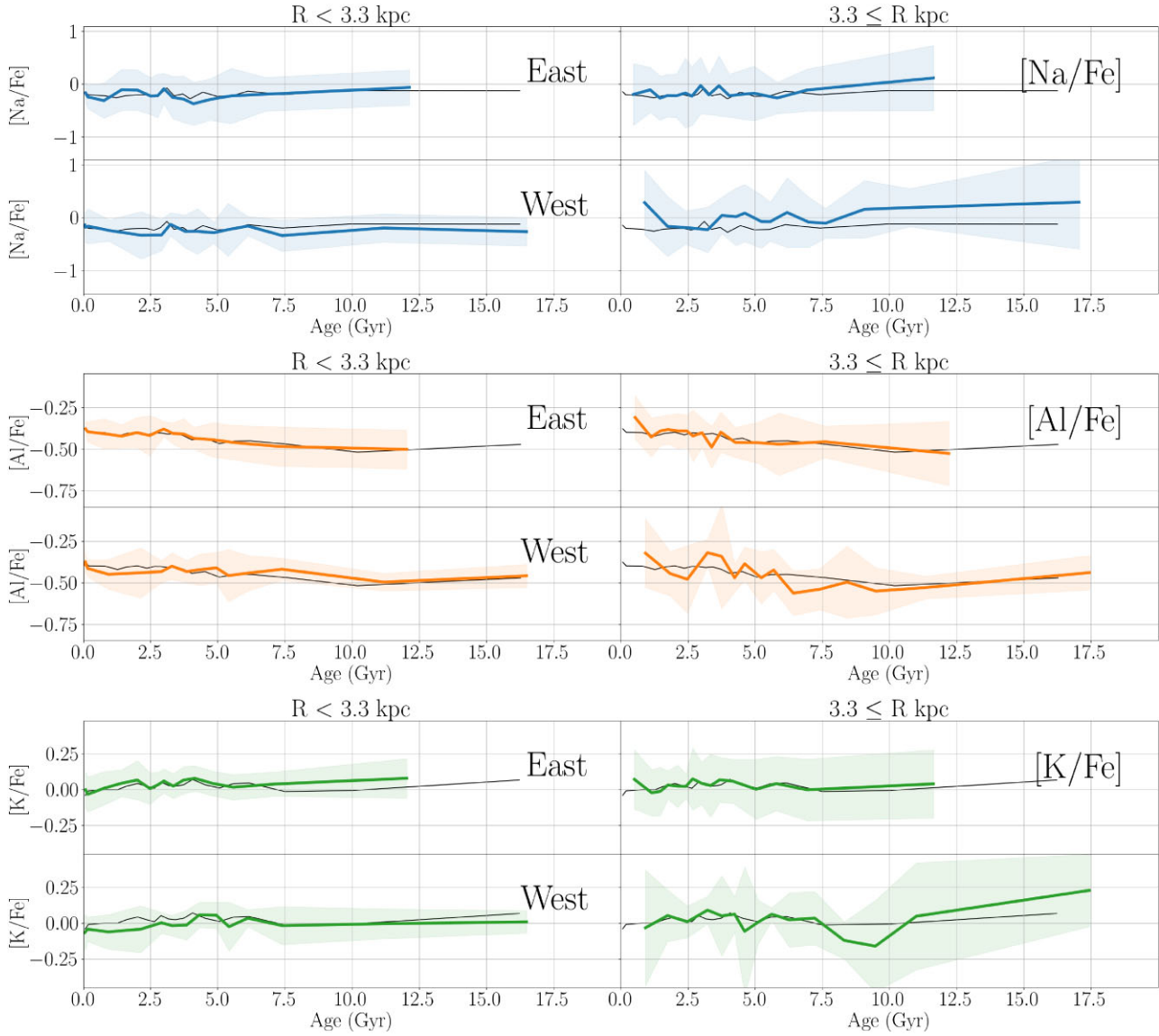


Figure D3. The age-[X/Fe] trends for the SMC for the odd-Z abundances. Like many of the other groups of elements, the odd-Z age-[X/Fe] trends are fat. The iron peak elements are mostly fat in the SMC.

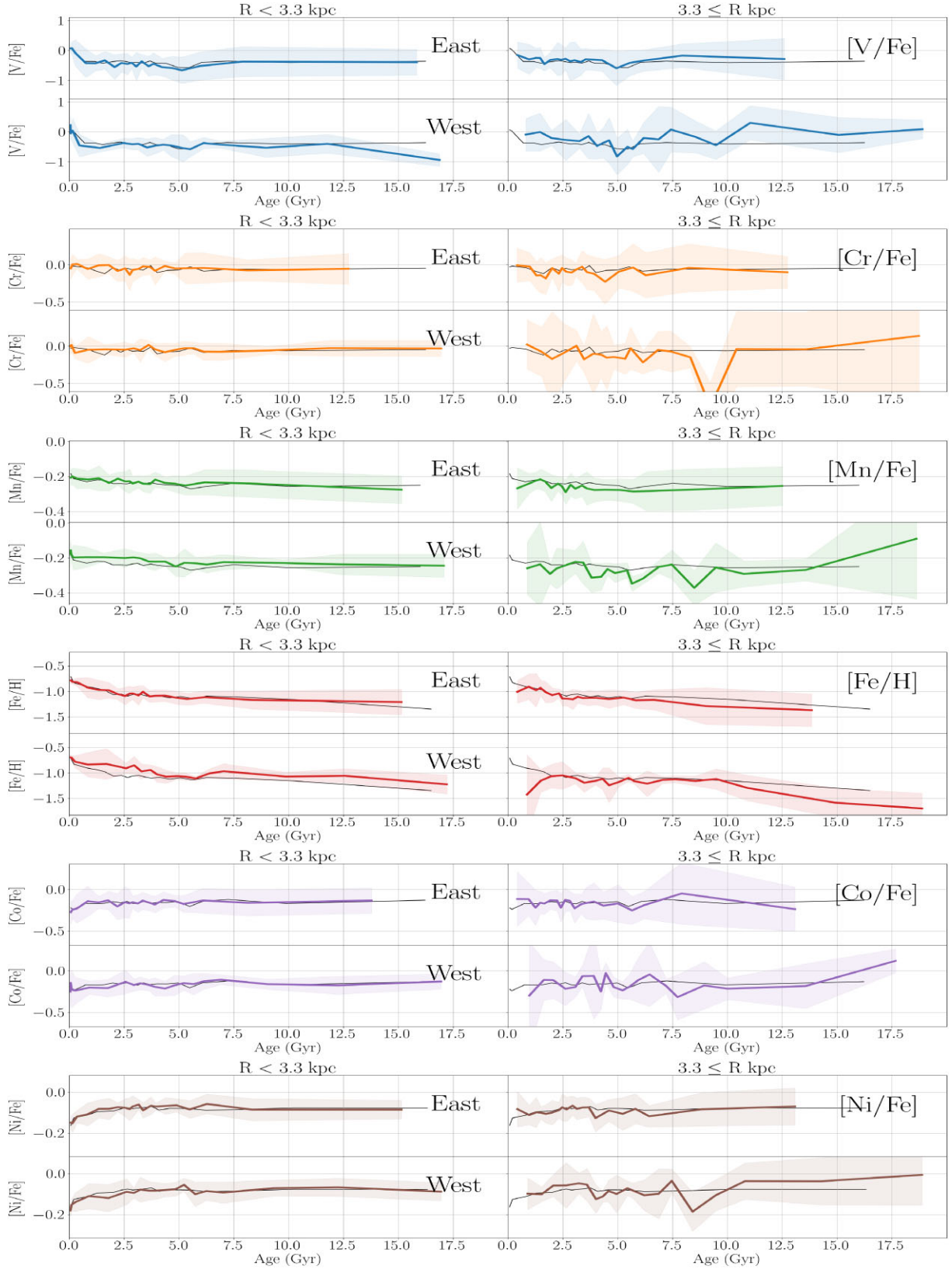


Figure D4. The age-[X/Fe] trends for the SMC for the individual iron peak abundances. Much like for the other age-[X/Fe] trends these are flat. There is, however, an increase in $[V/Fe]$ and a decrease in $[Ni/Fe]$ for the youngest stars. The age-[Fe/H] trends reveals a steady increase in $[Fe/H]$ over time with a slight ramp up in the last 2.5 Gyr.

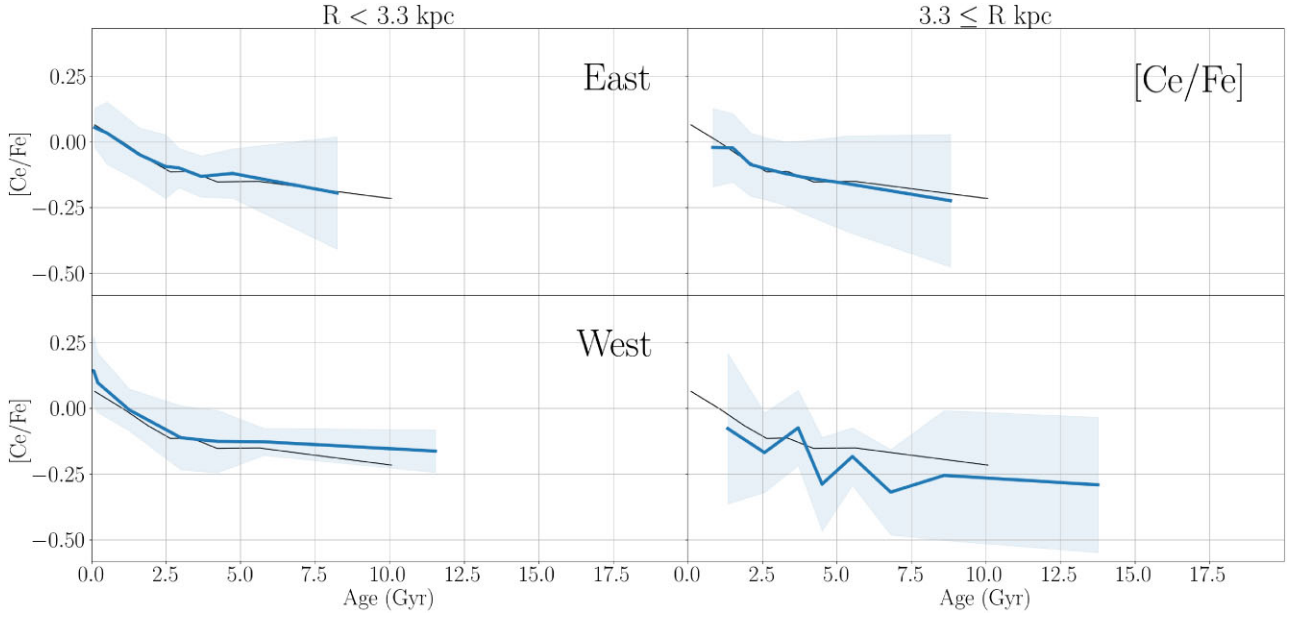


Figure D5. The age–[Ce/Fe] trend for the SMC for the neutron capture element cerium. Even with the lower number of stars with good [Ce/Fe], there has been an increase in the last few Gyr.

APPENDIX E: COMPARING TO THE LMC AND MW EXTRA PLOTS

Plots comparing the SMC, LMC, and Milky Way that do not appear in the main body of the paper.

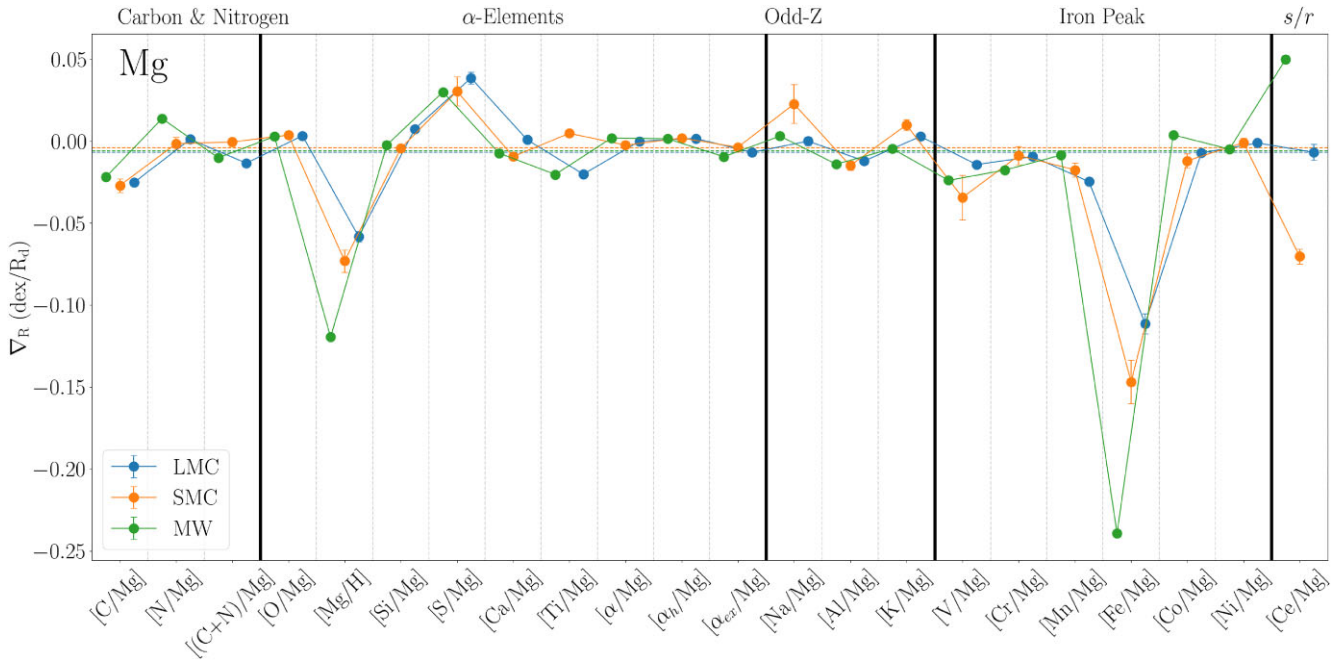


Figure E1. The same as Fig. 11, but for the [X/Mg] gradients only. The median gradient value all three galaxies is quite similar and around 0.0 dex/ R_d . For the SMC the median [X/Mg] gradient is -0.004 ± 0.001 dex/ R_d , for the LMC the median [X/Mg] gradient is -0.007 ± 0.001 dex/ R_d , and for the MW the median gradient is -0.006 ± 0.001 dex/ R_d . The [Fe/Mg] gradient shows a separation between the dwarf galaxies and the MW.

This paper has been typeset from a $\text{\LaTeX}$ file prepared by the author.