Ca II Triplet Spectroscopy of Small Magellanic Cloud Red Giants. VI. Analysis of chemical properties of the Main Body

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1. INTRODUCTION

The Magellanic System (D’Onghia & Fox 2014) is one of the most rewarding nearby systems for the study of dwarf galaxies and the stellar populations that they host. It consists of the Small Magellanic Cloud (SMC), the Large Magellanic Cloud (LMC), the Bridge, the Magellanic Stream and the Leading Arm. The SMC and LMC are the closest pair of interacting galaxies to the Milky Way (MW) located at distances of $49.59 \pm 0.09$ kpc (Pietrzyński et al. 2019) and $62.44 \pm 0.47$ kpc (Graczyk et al. 2020), respectively. The Magellanic Clouds (MCs) are embedded within a diffuse structure of HI gas (Mathewson et al. 1974, Putman et al. 2003, Nidever et al. 2008, 2010) which has been interpreted by numerous works as the consequence of interaction either between SMC and LMC or among SMC, LMC and the MW (e.g., Diaz & Bekki 2011, 2012, Besla et al. 2012, 2016). There is some discussion in the literature as to whether MCs have been orbiting the MW (Gardiner & Noguchi 1996, Diaz & Bekki 2012), however the latest research based on the most accurate measurements of proper motions with the Hubble Space Telescope (HST) and Gaia, and updated LMC and
star clusters have proven historically to be excellent tracers of the chemical enrichment processes of the stellar populations of MCs (Besla et al. 2012; Zivick et al. 2018) and Niederhofer et al. (2021), suggest that this galaxy is being tidally disrupted by the LMC. Also, the current morphology of the SMC could be the consequence of a recent collision between the MCs (Besla et al. 2012, 2010; Besla et al. 2019; Gaia Collaboration et al. 2021; El Youssoufi et al. 2021; Piatek et al. 2008; Kallivayalil et al. 2013; Patel et al. 2017; Gaia Collaboration et al. 2018). Several studies have found evidence of tidal tails around the SMC and the LMC (Besla et al. 2007; Belokurov & Erkal 2018; Nieder et al. 2019; Gaia Collaboration et al. 2021; El Youssoufi et al. 2021; Dias et al. 2021). In particular, the complex patterns of velocities in the SMC found, for example, by Niederhofer et al. (2018) and Niederhofer et al. (2021), suggest that this galaxy is being tidally disrupted by the LMC. Also, the current morphology of the SMC could be the consequence of a recent collision between the MCs (Besla et al. 2012; Zivick et al. 2018).

Given such interactions, the star formation history and chemical enrichment processes of the stellar populations of a galaxy are of course affected (Whitmore et al. 1999; Da Costa & Krajnoviê 1991; Dopita et al. 1997; Parel & Tautvaisiene 1998). Their spatial, age and metallicity distributions and gradients present distinctive effects of the interaction processes (e.g., Cioni et al. 2009; Dobbie et al. 2014; Navak et al. 2016; Dias et al. 2016; Rubele et al. 2018; De Leo et al. 2020; Santos et al. 2020). SMC star clusters have proven historically to be excellent tracers of the chemical and dynamical history of this galaxy (e.g., Da Costa & Hatzidimitriou 1998; Glatt et al. 2010; Parisi et al. 2009, 2014, 2015; Perren et al. 2017; Piatti et al. 2018; Navak et al. 2018; Bitsakis et al. 2018; Narloch et al. 2021; Dias et al. 2021). However, despite the exhaustive study of the chemical properties of the SMC clusters, there is some controversy in the literature regarding the chemical evolution of this galaxy using those objects as tracers.

Several studies have shown that the field metallicity distribution (MD) is unimodal with a [Fe/H] maximum near -1 dex (e.g., Carrera et al. 2008; Parisi et al. 2010; Dobbie et al. 2014); Parisi et al. 2016; Choudhury et al. 2018, 2020). However, using a sample of 36 clusters homogeneously studied, Parisi et al. (2015) (hereafter P15) suggest that the MD could be bimodal with a probability of 86%. This probability drops drastically to 59% when the cluster sample increases significantly (Parisi et al. 2022, hereafter P22), but nevertheless, the sample shows a marked absence of clusters in the internal region with metallicity values typical of the SMC field.

Although there is agreement between most studies regarding the existence of a metallicity gradient (MG) in the SMC field (e.g., Carrera et al. 2008; Parisi et al. 2010; Dobbie et al. 2014); Parisi et al. 2016; Choudhury et al. 2018, 2020) it is not clear if the SMC clusters present such a gradient. Narloch et al. (2021) studied 35 clusters with Str€omgren photometry and they found that younger, more metal-rich star clusters are concentrated mainly towards the centre of the galaxy, while older, more metal-poor clusters are located further from the centre. However, studies based on CaII triplet (CaT) metallicities from Parisi et al. (2009) (hereafter P09), P15, Dias et al. (2022) (hereafter D22) and P22 find that although there is a tendency for the clusters to be more metal-poor as we move away from the centre of the galaxy up to 4°, the cluster MG is not statistically significant due to the large cluster metallicity dispersion in the internal region (~0.6 dex, P15, P22). To make things more interesting, employing the separation of SMC cluster samples into the different sky regions defined by Dias et al. (2016, 2021) hereafter D16, D21), we can see that the clusters belonging to the Northern Bridge appear to be the ones that best trace a V-shape in the MD (P22, D22) and the West Halo clusters could present a MG (D16, D22) but with some uncertainty (P22).

The mentioned metallicity dispersion, not only observed in spectroscopic studies but also in photometric ones (e.g., Perren et al. 2017; Narloch et al. 2021), is also evident in the analysed age-metallicity relationships (AMR) in which the models of chemical evolution proposed in the literature for the SMC do not reproduce the data in general (Da Costa & Hatzidimitriou 1998; Harris & Zaritsky 2004; Pagel & Tautvaisiene 1998; Carrera et al. 2008; Cignoni et al. 2013; Tsujimoto & Bekki 2009; Perren et al. 2017). Also, the V-shape present in the field and metallicity gradient (P15, P16, Bica et al. 2020, D16) is under discussion, specially in the outer region, where it is no clear that the gradient increases or remains constant (Parisi et al. 2016; Choudhury et al. 2020, P22, D22).

Galaxy-galaxy interactions are expected to mostly affect the outskirts of the SMC (Mayer et al. 2001), but D22 show that the SMC disruption due to tidal effects starts much further inside the SMC tidal radius (Dias et al. 2021). P22 also showed that all the components suggested by D21 present a minimum in metallicity as well as smaller metallicity dispersion near the projected tidal radius. Significantly different cluster chemical properties are displayed by samples inside vs. outside the tidal radius. The outer cluster system of the SMC is being systematically studied by the VISCACHA survey (Maia et al. 2019) with results that impose important constraints on dynamical models of the Magellanic Clouds (D21, D22). In this paper we focus our analysis in the internal region, where chemical evolution does not seem to follow a canonical behavior either.

We organize the paper as follows: In Section 2 we describe the cluster sample selection, observations and data reduction process. The measurement of radial velocities and equivalent width of the Ca II Triplet lines and the metallicity determination are presented in Section 3. Sections 4 and 5 are dedicated to the membership and metallicity analysis, respectively. Finally we summarize our results in Section 6.

2. OBSERVATIONS AND DATA REDUCTION

In order to increase the number of inner SMC star clusters homogeneously studied with the CaT technique, we have observed 6 clusters in the inner region of the SMC, which are spatially distributed as can be seen in Figure 1. The ellipses are defined in the plane of relative RA vs. relative DEC, with ratio $b/a=3.4$ and position angle $=45^\circ$ (Piatti et al. 2005; Dias et al. 2014). The semi-major axis $a$ of the ellipse coincident with the position of the cluster is used as the projected distance from the SMC center. We considered the semi-major axis $a = 3.4\,a$ as the division between the inner and outer regions of the SMC (D21), so our sample basically consists of clusters in the SMC Main Body (D16, D21, P22). Clusters were selected from Piatti (2011a, Piatti 2011b and Piatti et al. 2011). We have prioritized those clusters whose Color-Magnitude Diagram (CMD) show the most populated red giant branch (RGB), in order to maximize the number of suitable targets for the CaT technique. Although our whole sample has ages and metallicities previously determined from photometric techniques, in this work we provide more accurate spectroscopic
metallicities derived from the CaT technique as well as radial velocities (RVs). The cluster sample is presented in Table 1, which includes coordinates, projected distances and ages.

For each cluster, pre-images in the g and r filters had been previously obtained with the instrument Gemini/GMOS-S (programme GS-2014B-Q-78), from which the CMDs (g, g − r) were built. We selected RGB stars from the CMDs as spectroscopic targets. As an example, we show in Figure 3 the CMD for the cluster K 38. We marked the spectroscopic targets with large circles in the figure, following the color code related to our membership analysis (see the figure caption and Section 3 for details).

The spectroscopic data for the selected RGB stars consist of intermediate resolution infrared spectra obtained with GMOS-S (Hook et al. 2004), with the new Hamamatsu CCDs featuring enhanced red sensitivity (Gimeno et al. 2016) in MOS mode (programme GS-2016B-Q-17). It comprises more than 150 spectra of stars in the area of our SMC cluster sample. Observations of 4×900 sec exposure time and 2×2 binning were taken for each frame, using the R831 disperser and the CaT-G0333 filter. The four observations were taken in pairs centred on 8500 Å and 8550 Å for dithering. In average, 26 slits of 1 arcsec width were taken for each frame. For the cluster K 38 for which it was necessary to apply a shift of 3.4. Black ellipses correspond to semi-major axes of 2°, 4°, 6° and 10°. They are centred on the SMC, with PA = 45° and h/a = 1/2.

In order to reduce the spectra, we used the script developed by M. Angelo. First, we applied the bias and flat corrections, interpolated across the useless CCDs gap (GMOSAIC task), identified the spatial extension of each slitlet (GSCUT task), and cut and pasted the two-dimensional spectra in different FITS file extensions. Additionally, bad pixel masks have been applied. The wavelength solution for each individual spectrum has been obtained from GSWAVELENGTH task and differences in quantum efficiency between the 3 CCDs chips have been corrected with the GQECORR task. Afterwards, we used CRMEDIAN and FIXPIX to remove cosmic rays. We then ran the GTRANSFORM task, using arc spectra, to rectify the spectra and apply the appropriate wavelength solution. Finally, we extracted and combined the spectra of different central wavelengths, summing them.

In order to analyse if a zero point correction to our wavelength calibration was necessary, we measured in our spectra the centre of several bright sky lines with well known central wavelengths (Hamuschik 2003). When a non-negligible difference was found, we used SPECSHIFT to shift the spectra. In all cases corrections were smaller than 0.4 Å (∼ 14 km s⁻¹), except for the cluster K 38 for which it was necessary to apply a shift of 0.9 Å (∼ 32 km s⁻¹).

Finally, we ran the CONTINUUM task to normalize the spectra to the pseudo-continuum level (e.g., Vásquez et al. 2015). As an example, we show in Figure 3 two normalized spectra of RGB stars in two clusters with very similar evolutionary stages but different metallicities. The signal-to-noise ratio (SNR) for combined and normalized spectra range from 50 to 130.

3. STELLAR PARAMETERS DETERMINATION

3.1. Radial velocity and equivalent width measurements

The determination of target radial velocities (RVs) is crucial for cluster membership determination. They are also needed to perform the Doppler correction in order to measure equivalent widths (EW) of the three CaT lines in rest spectra.
correlation, which additionally corrects the observed RVs providing the heliocentric values. We obtained a typical RV error of \( \sim 0.08 \text{ Å} \).

As we describe in the next section, EWs of the CaT lines are used to determine the metallicity. Following the same procedure as in our previous work (e.g., P09, P15), the pseudo-continuum was fitted in a pair of continuum windows to shorter wavelengths of the corresponding line centre, using the line and continuum bandpasses from Armandroff & Zinn (1988). We fitted a Gaussian plus a Lorentzian function to each CaT line, with respect to the pseudo-continuum, and calculated the "pseudo-EW". As shown by Rutledge et al. (1997b) and Cole et al. (2004), this combined function takes into account adequately the contribution of the wings and the core of the line profile. We obtained a typical EW error of \( \sim 0.08 \text{ Å} \).

### 3.2. Metallicity determination

Many studies have calibrated the strength of the CaT lines with metallicity from integrated and individual spectra of RGB stars. In the case of individual stellar spectra, the technique requires the construction of the so-called CaT index as the sum of the EW of two or three CaT lines (\( \Sigma EW \)). Also, it is necessary to remove the effects of surface gravity and temperature on the \( \Sigma EW \) (Armandroff & Da Costa 1991; Olszewski et al. 1991), e.g. by using the difference in magnitudes, in a given filter, between the observed star and the horizontal branch or red clump. A detailed description of the different ways of building the CaT index and the filters used in the literature, as well as the available calibrations, can be found in Dias & Barbudo (2020) and references therein.

Usually, using the sum of the three CaT lines is the best choice because it takes into account the complete information. However, if the SNR is low, the faintest line adds mostly noise and increases the errors in metallicity, so that it is avoided in these cases, following an adequate calibration. In this work, most of the spectra have SNR between 50 and 130, which is high enough to produce good quality CaT lines in almost all cases.

Therefore we use the calibration including the three lines, as follows:

\[
\Sigma EW = EW_{5498} + EW_{8542} + EW_{8662}
\]  

(1)

In those cases in which the weakest line could not be well fit, we add the contribution of the two most intense lines and then performed the corresponding conversion according to equation 5 of DP20. We then calculated the reduced EW (\( W' \)) from:

\[
W' = \Sigma EW + \beta (g - g_{HB})
\]

(2)

where \((g - g_{HB})\) represents the difference between the magnitude of the star \((g)\) and the magnitude of the cluster’s horizontal branch/red clump \((g_{HB})\). By considering the magnitude difference, we not only remove the dependence of \( \Sigma EW \) with surface gravity and temperature, but also its dependence on cluster distance and interstellar reddening. We adopt a \( \beta \) value of \( 0.85 \pm 0.08 \) from DP20, which was calculated for filter g using as reference \( \beta_{CV} = 0.71 \) for the canonical V filter. We note that this value of \( \beta_{CV} \) is the same used in our previous works, therefore our measurements are on the same scale.

The \( g \) magnitudes were obtained from PSF photometry performed on the pre-images using the SKZ pipeline (Mauro et al. 2013; Mauro 2020). We then determined \( g_{HB} \) from the cluster CMD following the procedure detailed in DP20. Figure 4 shows the \( \Sigma EW \) as a function of \( g-g_{HB} \) for targets that resulted to be cluster members according to our membership analysis (see Section 4).

Finally, we calculated the metallicity of each observed star using the calibration derived by DP20,

\[
[Fe/H] = -2.917(\pm 0.116) + 0.353(\pm 0.020)W'
\]

(3)

### Table 1. Selected SMC cluster sample.

| Cluster     | RA (J2000.0) | DEC (J2000.0) | a         | Age (Gyr) |
|-------------|--------------|---------------|-----------|-----------|
| K38, L 57   | 0:57:49.5    | -73:25:23     | 1.363     | 3.0 ± 0.4 |
| HW 31, [RZ2005] 97 | 0:55:34.0    | -74:3:46      | 2.149     | 4.6 ± 0.3 |
| HW 41, [RZ2005] 125 | 1:00:33.6    | -71:27:13     | 1.769     | 5.6 ± 0.4 |
| HW 42       | 1:01:08.0    | -74:04:25     | 2.617     | ≈ 2.4^2   |
| L 3, ESO 28-13, OGLE-CL SMC 323 | 0:18:25.2    | -74:19:05     | 2.938     | 1.2 ± 0.3 |
| L 91, [RZ2005] 194 | 1:12:51.6    | -73:07:07     | 2.609     | 4.1 ± 0.3 |

References: Parisi et al. (2014), Bica et al. (2022, in prep.), Dias et al. (2014)
Fig. 4. Sum of the equivalent width of the three CaT lines against $g-g_{HB}$ for member stars of the six SMC clusters. Dashed lines represent lines of constant metallicity corresponding to $[\text{Fe/H}]= -0.5, -0.65, -0.80, -0.95, -1.10$ and $-1.25$ dex, from top to bottom.

As shown by DP20, their calibration is in excellent agreement with the one derived by Cole et al. (2004). Therefore, our metallicity values are on the same scale as our previous work, in which Cole’s calibration was used. We have obtained individual uncertainties in $[\text{Fe/H}]$ of typically ~0.2 dex.

Table 2 presents coordinates and measured values, with their respective errors, for all observed RGB stars. We have differentiated the cluster member stars from those belonging to their surrounding fields, according to our membership analysis (see section 4). Stars are labelled with the cluster name plus a number, which represents the aperture number in our program.

4. MEMBERSHIP ANALYSIS

In order to separate cluster members from SMC field stars, we followed the same procedure as in our previous work (see P09, P15 and P22 for more details). In summary, for each cluster, we first built the radial density profile using stellar counts from our photometry and adopting the cluster centre from Bica et al. (2020). The cluster radius is defined as the distance from the centre out to the level where the profile intersects the background density, but in some cases we adopted a smaller radius in order to maximize the probability of the selected stars to belong to the clusters (Figure 5). We assume the background level to be that at which the radial profile does not decrease significantly any further. The exception are the clusters HW 42 and K 38 for which the radial profile could not be constructed due to the low cluster overdensity with respect to the field. In these cases, the radius values from Bica et al. (2020) were adopted. We then analysed the targets RV and metallicity as a function of the distance from the cluster centre (Figure 6). Stars closer to the centre have a larger probability of being cluster members. It is also assumed that, in general, cluster members have smaller velocity dispersion and potentially different mean RV and metallicity compared to field stars. We adopted the RV and metallicity cuts of $\pm 10 \text{ km s}^{-1}$ and $\pm 0.2 \text{dex}$ (from C09, P15 and P22) around the mean value of the visually identified probable members candidates. The RV cuts are consistent with the intrinsic cluster RV dispersion and our mean RV error. The adopted metallicity cuts are representative of our mean metallicity error.

We consider as member stars those targets located closer to the cluster centre than the adopted radius and having RV and metallicity values inside the cuts (red symbols in Figure 6). In the figure, targets discarded as probable cluster members because of their distance, RV and metallicity values are represented with blue, cyan and green circles, respectively. The RV and metallicity cuts are shown with short dashed lines in Figure 6 while the adopted cluster radius is represented by the dotted line.

Finally, we checked the proper motions (PMs) of our targets, from the Gaia EDR3 (Gaia Collaboration et al. 2021) catalogue, in order to maximize the membership probability of our cluster member candidates. We use the PM to verify that the spectroscopic members have consistent PM values among them. None of the stars considered cluster members, according to the criteria described above, was discarded due to their PMs.

Using only member stars we calculated the simple mean RV and metallicity for each cluster. As a representative metallicity of the cluster surrounding fields, we calculated the median of nonmember stars metallicity values, as suggested by Dobbie et al. (2014b), Parisi et al. (2016). To determine the median field metallicities, we verified that the selected stars do not have RV and metallicity values close to the limits imposed by the adopted cuts nor were located close to the cluster radius ($\Delta r < 0.2 \text{ arcmin}$, $\Delta RV < 5 \text{ km s}^{-1}$ and $\Delta [\text{Fe/H}] < 0.1 \text{ dex}$). The results for both cluster and field stars are given in Table 3. The median metallicity for the field of L 3 is less reliable because the sample contains only three stars.

5. CHEMICAL PROPERTIES OF CLUSTER AND FIELD STARS

In order to perform a statistically more significant study of the SMC chemical history, we enlarged our cluster sample by adding 51 clusters having CaT metallicities de-
Table 2. Measured parameters for the observed RGB stars

| Star ID | RA (J2000.0) (h m s) | DEC (J2000.0) (° ′ ″) | RV (km s\(^{-1}\)) | \(g−g_\text{hbat}\) (mag) | \(Σ\)EW (Å) | \([Fe/H]\) (dex) | Cluster/Field |
|---------|---------------------|------------------------|---------------------|-------------------------|----------|-----------------|---------------|
| K 38-2  | 0:57:49.3           | -73:22:45              | 177.2 ± 4.2         | -1.56                   | 7.88 ± 0.13 | -0.60 ± 0.21    | F             |
| K 38-4  | 0:58:15.9           | -73:26:09              | 161.7 ± 2.8         | -1.57                   | 7.27 ± 0.09 | -0.82 ± 0.20    | F             |

Note: Full table is available online.

Table 3. Mean parameters for the selected SMC star clusters and their standard error of the mean.

| Cluster | n | RV (km s\(^{-1}\)) | \([Fe/H]\) (dex) | \(n_{\text{field}}\) | \([Fe/H]_{\text{field}}\) (σ) (dex) |
|---------|---|-------------------|------------------|---------------------|-------------------------------------|
| K 38    | 13| 84.0 ± 0.9        | -0.90 ± 0.02     | 18                  | -0.65 ± 0.04 (0.18)                  |
| HW 31   | 6 | 125.5 ± 3.4       | -0.89 ± 0.04     | 15                  | -1.12 ± 0.10 (0.37)                  |
| HW 41   | 7 | 143.6 ± 1.6       | -0.67 ± 0.05     | 14                  | -0.96 ± 0.10 (0.36)                  |
| HW 42   | 5 | 144.3 ± 2.0       | -0.58 ± 0.03     | 13                  | -0.95 ± 0.12 (0.42)                  |
| L 3     | 7 | 140.1 ± 3.4       | -0.90 ± 0.05     | 3                   | -0.75 ± 0.37 (0.33)                  |
| L 91    | 5 | 126.7 ± 1.8       | -0.90 ± 0.06     | 18                  | -1.01 ± 0.08 (0.35)                  |

Fig. 6. Membership analysis for the cluster K 38. The color code is the same as in Figure 2. Cluster radius is shown by the dotted vertical line and the dashed lines represent the adopted RV and metallicity cuts.

Out of the 7 clusters studied by DH98 we only included here NGC 121. For the rest of the DH98 cluster sample we adopt, for homogeneity, the values derived by P15 and P22, which are in excellent agreement with the CaT metallicities derived by DH98. P09, P15 and P22 employed data from the VLT-FORS2 whereas clusters studied in P22 and in this work were observed with Gemini-GMOS. The FORS2 and GMOS samples have two clusters in common (NGC 151 and K 8). The FORS2 metallicity of NGC 151 (P22) is in very good agreement with the GMOS metallicity (D22). In the case of K 8 both datasets (P15 and D22) have four stars in common with metallicities in agreement, one of them a cluster member. Therefore, we consider that the metallicities based on FORS2 and GMOS data are consistent. Then, our final sample includes 57 clusters with metallicities on the same scale spread over all SMC regions of which 37 are in the Main Body. Hence, the 6 GCs analysed in this work...
represents an increase in the inner SMC cluster sample by 16%.

In addition, we add to our field sample those studied by Parisi et al. (2010) and Parisi et al. (2016), hereafter P10 and P16. The fields studied in these two works (15 from P10 and 15 from P16) correspond to the fields surrounding the clusters studied in P09 and P15, respectively. Therefore we have a total of 36 SMC fields with homogeneously determined average metallicities.

5.1. Metallicity Distribution

In order to analyse the existence of bimodality in the MD, as suggested by P09 and P15, we applied the Gaussian Mixture Modeling test (GMM Muratov & Gnedin 2010) to the full sample. The MD of our cluster sample is shown in Figure 7 as well as the fits considering one (dashed line) or two (dotted lines) Gaussian functions. The results for the application of this algorithm are summarized in the first line of Table 4. In the table we list the sample, the peaks ($\mu$) and the $\sigma$ for the unimodal and bimodal fits, the p value (which is the probability of being wrong in rejecting unimodality), the bimodality probability given by the parametric bootstrap, the separation of the peaks of the fitted Gaussian functions (DD) and the kurtosis of the distribution (k). An indication of a bimodal distribution is given by a negative k value and $DD > 2$ (Ashman et al. 1994). As can be seen from the table we found a significantly lower probability (39%) than that obtained by P15 (86%) that the whole SMC cluster MD is bimodal, in agreement with P22 (59%).

Considering the different behavior observed for the chemical properties of clusters and field stars in the inner and outer regions, we decided to analyse their MDs separately. We divided our total cluster sample considering clusters inside and outside of $3.4^\circ$ and applied the GMM test to each of these two subsamples (Table 4). The internal and external MDs can be seen in Figures 8 and 9 respectively. As can be seen from the results included in the Table, while the outer MD presents a probability consistent with that found for the entire sample ($\sim 37\%$), the inner part shows a high probability of a bimodal MD ($\sim 95\%$). The inner MD analysis also shows a $DD$ greater than 2 and a negative kurtosis. This means that the possible bimodality in the internal region of the SMC is lost when we analyse the entire sample. The possible existence of bimodality in the inner region suggests the idea of two possible cluster populations coexisting towards the Main Body having a mean metallicity smaller and larger (-1.15 and -0.80 dex, respectively, see Table 4) than the typical mean metallicity of field stars ($\sim -1$, P16). In order to analyse if the bimodality distribution is an artifact of our sample missing clusters with $[\text{Fe/H}] < -1$ in the inner region, we performed an experiment generating random clusters with $[\text{Fe/H}]$ values scattered around -1 dex and with a dispersion of 0.1, and repeated the GMM test. The results show that we had to add 14 clusters (which represents an increase of 37% of the total sample) to bring the probability of bimodality down to 50%. Even in these cases, the DD and the kurtosis remain larger than 2 and negative, respectively. So, we consider that the probability of bimodality being an artifact is low. In the case of the outer MD analysis shows a $DD$ lower than 2 and a positive kurtosis. The metallicities of our extended field star sample clearly show a unimodal distribution (Figure 10), with a peak at -0.99, in agreement with previous works. Considering these results, we define two groups of clusters in the inner region, which we will call "metal-poor" and "metal-rich" clusters hereafter. The mean metallicities for the metal-rich and metal-poor clusters are -0.8 and -1.15 dex, respectively, corresponding to the peaks of the bimodal fit of the inner cluster MD (Table 4).

5.2. Metallicity Gradient

The behaviour of the cluster metallicity as a function of the projected distance to the SMC centre $a$ for our cluster sample can be seen in the upper panel of Figure 11. The field MG is shown for Article number, page 7 of 11
Table 4. Gaussian Mixture Modeling results.

| Sample | N  | Unimodal fit $\mu$ ($\sigma$) | Bimodal fit $\mu_1$ ($\sigma_1$); $\mu_2$ ($\sigma_2$) | p value | Bimodality probability Peaks separation kurtosis  |
|--------|----|-------------------------------|---------------------------------|--------|---------------------------------|
| All    | 57 | -0.913 (0.180)                | -0.830 (0.125); -1.106 (0.135) | 0.657  | 39.1% 2.83 ± 0.77 -0.356       |
| Inner  | 37 | -0.871 (0.173)                | -0.797 (0.105); -1.148 (0.061) | 0.051  | 95.3% 4.17 ± 0.40 -0.632       |
| Outer  | 20 | -0.991 (0.167)                | -0.959 (0.083); -1.031 (0.228) | 0.611  | 36.6% 1.91 ± 1.69 0.314        |

Fig. 9. Metallicity distribution of star clusters outside $a=3.4^{\circ}$. Solid, dotted and dashed lines show the same as in Figure 7.

Fig. 10. Metallicity distribution of field stars. Dashed line shows an unimodal fit.

Comparison in the middle panel of that Figure while the lower panel shows the difference between field and cluster metallicities. This last panel has been included to analyse P10 and P16's suggestion that most clusters are more metal-rich than the corresponding fields, which can be observed for the inner clusters in the figure. This implies that the metallicity gradient of the clusters is shifted with respect to that of the field towards higher metallicities, with the exception of clusters of the metal-poor group.

Following the analysis of our previous work, we determined from our extended samples the MGs in the inner and outer regions of the galaxy (solid lines in Fig. 11). We found values of $-0.08 \pm 0.04$ dex deg$^{-1}$ and $0.03 \pm 0.02$ dex deg$^{-1}$ for the inner and outer regions of the cluster sample, respectively. With respect to field stars, the linear fits give a MG of $-0.08 \pm 0.03$ dex deg$^{-1}$ for the inner part of the SMC and $0.05 \pm 0.02$ dex deg$^{-1}$ for the outer part. The inner field MG is in excellent agreement with the field MG found by other authors in that region also using CaT ($-0.075 \pm 0.011$ dex deg$^{-1}$ from Dobbie et al. 2014b and $-0.08 \pm 0.02$ dex deg$^{-1}$ from P16). The inner cluster MG found in this work is consistent with P15 ($-0.05 \pm 0.04$ dex deg$^{-1}$) considering errors, and it is in excellent agreement with P22 ($-0.08 \pm 0.04$ dex deg$^{-1}$). The inner cluster MG is also consistent with the inner field MG. Although these results apparently lead to the conclusion that cluster and field stars have the same MG, the dispersion for field stars considering median metallicities of field regions is very low in contrast to the high cluster metallicity dispersion, as can be clearly seen in Figure 11, particularly in the inner region.

P15 and P16 noted that two potential internal cluster groups are above and below the general field metallicity trend, which are now more clearly defined, as can be seen in Figure 11. These two potential groups correspond to the metal-poor and metal-rich cluster groups defined in the previous section. The mean metallicity and mean age values of the two groups, with their respective standard deviations, are $-1.15 \pm 0.06$ dex and $4.2 \pm 3.1$ Gyr for the metal-poor group, and $-0.8 \pm 0.10$ dex and $3.1 \pm 1.7$ Gyr for the metal-rich group.

We performed linear fits to the two internal groups separately (dashed lines in Figure 11, upper panel) yielding values for the MG of $-0.02 \pm 0.03$ dex deg$^{-1}$ and $-0.003 \pm 0.042$ dex deg$^{-1}$, for the metal-rich and metal-poor groups, respectively. Within the errors, the derived values are consistent with the absence of MG in the two potential internal groups. Therefore, the MG found for the inner clusters that is similar to that of the field stars, seems to be an artifact of the combination of two groups of clusters with a large spread in metallicity.

It is noticeable in Figures 8 and 11 that the inner SMC lacks clusters with [Fe/H] $\sim$ -1.0, whereas the outer clusters have metallicities around [Fe/H] $\sim$ -1.0. If we assume the existence of two groups of clusters with different origins in the inner region as real, then we can speculate in various ways. (1) Metal-rich clusters have formed in situ while the metal-poor clusters were accreted (Forbes et al. 2011), as observed in elliptical galaxies (e.g. Ennis et al. 2019; De Bortoli et al. 2020), although the accretion...
mainly affects the outer part; (2) Metal-poor and metal-rich gas formed clusters in the inner SMC whereas gas with intermediate metallicity formed clusters in the SMC outskirts; (3) The SMC experienced infalls of gas with different metallicities combined with inhomogeneous mixing of gas since its formation; the multiple encounters with the LMC would have triggered cluster formation by shock.

A completely different scenario to the existence of two inner populations is to postulate that the outer clusters were formed in the SMC during a continuous cluster formation with the interstellar medium chemical enrichment and inhomogeneous mixing, but the clusters with [Fe/H] ~ -1.0 that would be concentrated in a given inner region were moved outwards by interactions with the LMC. In any case, all of these possible explanations are speculative. Real distances as well as dynamical simulations must be carried out to test these or other possible scenarios.

5.3. Age-Metallicity Relation

In an effort to help constrain the chemical evolution of the SMC, we plot in Figure 12 the AMR for the full cluster sample which shows, as in our previous work, that none of available models of chemical evolution reproduce the data adequately. If the different regions of the SMC (D16,D21) are analysed separately, the AMR becomes somewhat clearer. The AMR of the Main Body, which is the region of interest of the present paper, is presented in Figure 13. In that figure we have distinguished with red and blue symbols clusters belonging to the metal-rich and metal-poor groups, respectively. We compare the observational data with different models of chemical evolution (see the caption of the figure for model references).

It is noticeable in Figure 13 that 21 of the 28 metal-rich clusters (75%) are concentrated at ages younger than 4.5 Gyr and none are older than about 6-7 Gyr, whereas metal-poor clusters cover a wider age range, although the number of metal-poor clusters is low. The age of ~ 6 Gyr corresponds approximately to the time where star formation was probably triggered by the infall to the SMC-LMC pair towards the Milky Way (e.g. Besla et al. 2012). It is interesting to note that the age distribution of the SMC clusters shows a peak at ~ 5 Gyr (Piatti et al. 2011; Parisi et al. 2014; Bica et al. 2020) which agrees with a peak in the fields SFR of log(t) = 9.7 from Rubele et al. (2018). On the other hand, while the clusters of the metal-rich group present a metallicity dispersion of ~ 0.4 dex, the clusters of the metal-poor group are found concentrated in a significantly smaller metallicity range (± 0.1 dex) around the previously calculated mean value of ~1.15 dex. The oldest clusters of the metal-rich group show a primordial constant metallicity of -0.86 ± 0.04 dex (without considering HW41, see text below) until 4-5 Gyr ago, showing a considerable subsequent chemical enrichment process which increased the metallicity considerably, at least for about half of the younger clusters. On the contrary, metal-poor cluster formation appears to have not undergone any chemical enrichment throughout the life of the SMC, which suggests a low efficient gas mixing for the metal-poor gas that kept forming clusters during the entire life of the SMC. The chemical evolution of the metal-rich group clusters would seem to be well represented by the Harris & Zaritsky (2004, H&Z) and Perren et al. (2017) models. Particularly interesting is the fact that the AMR proposed by H&Z was specifically derived from the Star Formation History (SFH) of 361 regions located in the main body of the SMC (4°× 4.5°). This finding supports the arguments of D16 that each region of the SMC should be analysed separately, possibly revealing specific pieces of the SMC chemical evolution history. This result also suggests a similar chemical evolution for field stars analysed by H&Z and and metal-rich star clusters analysed here in the SMC main body region.

One exception to this apparent match with the H&Z and Perren et al. (2017) models is the cluster HW 41 for which there is a large dispersion in the age determination that can be found in the literature (marked in Figure 13 with a rectangle). Piatti...
6. SUMMARY AND CONCLUSIONS

Using Ca II Triplet lines we have determined the mean RV and metallicity of 6 clusters and 6 fields in the SMC. We added another 51 clusters and 30 fields studied with the same technique and with metallicities on the same scale. We divided our samples in inner and outer regions considering the breakpoint derived by Dias et al. (2021) ($\delta = 3.4^\circ$). According to the definition of the Dias et al. (2016, 2021) and P22, the inner region corresponds to the SMC Main Body. Our main conclusions are the following:

- We find a high probability (95.3%) that the cluster MD is bimodal in the inner region but unimodal in the outer regions.
- Considering the bimodal MD in the inner region we define two cluster groups as metal-rich and metal-poor groups with mean metallicities of -0.80 and -1.15 dex, respectively.
- Outer cluster MD and field MD have coincident, unimodal peaks at -0.99 dex.

Cluster metallicity gradient (MG) is negative (-0.08±0.04 dex deg$^{-1}$) in the inner region but positive or null in the outer region (0.03±0.02 dex deg$^{-1}$), in agreement with the MG for field stars. However, linear fits for the metal-rich and metal-poor clusters separately are consistent with no MG. In the outer region field stars MG is significantly positive.

With our extended sample we continue to find the cluster metallicity gap in the Main Body at $\sim -1$, as suggested by P16.

- The Age-Metallicity Relation (AMR) in the inner region shows that the metal-rich clusters appear to follow the chemical enrichment of field stars by Harris & Zaritsky (2004) or the model proposed by Perren et al. (2017), but metal-poor clusters do not present any chemical enrichment.

In this work we present observational evidence that the chemical enrichment is complex in the SMC Main Body. Two cluster groups with potential different origins could be coexisting in the Main Body but more data with precise and homogeneous metallicities and distances are needed to corroborate not only the metallicity gap but also any possible projection effect. Dynamical simulations are required to understand possible different origins for the metal-rich and metal-poor cluster groups in the SMC Main Body.

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