THE CHEMICAL ENRICHMENT HISTORY OF THE SMALL MAGELLANIC CLOUD AND ITS GRADIENTS*

RICARDO CARRERA1,3, CARMEL GALLART1, ANTONIO Aparicio1,4, EDGARDO COSTA2, RENE A. MÉNDEZ2, AND NOELIA E. D. NOËL1

1 Instituto de Astrofísica de Canarias, Spain; ricarrera@iac.es, carme@iac.es
2 Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile

Received 2007 November 26; accepted 2008 June 17; published 2008 August 1

ABSTRACT

We present stellar metallicities derived from Ca triplet spectroscopy in over 350 red giant branch stars in 13 fields distributed in different positions in the Small Magellanic Cloud, ranging from ~1° to ~4° from its center. In the innermost fields, the average metallicity is [Fe/H] ~ −1. This value decreases when we move away from the center. This is the first detection of a spectroscopic metallicity gradient in this galaxy. We show that the metallicity gradient is related to an age gradient, in the sense that more metal-rich stars, which are also younger, are concentrated in the central regions of the galaxy.

Key words: galaxies: evolution – galaxies: individual (SMC) – galaxies: stellar content – Local Group – Magellanic Clouds

Online-only material: color figures, machine-readable and VO tables

1. INTRODUCTION

The chemical enrichment history of a galaxy is related to the origin and distribution of nuclear species in its stars and gas. The chemical elements are mainly produced by stars, which drive the enrichment of the interstellar medium by ejecting material containing the product of the stellar nucleosynthesis from which the new generations of stars are formed. In addition, gas flows also play an important role in chemical enrichment, diluting the products of the stellar nucleosynthesis with unenriched material from outside the galaxy, ejecting out metal-enriched gas through galactic winds, and mixing metals from one part of the system to another (e.g., bringing metal-rich gas into metal-poor regions). Thus, the study of the chemical evolution of galaxies involves understanding the spatial distribution and temporal evolution of various elements by taking into account the processes of star formation, the distribution of stars according to their masses and chemical compositions, and the final yields of various elements and detectable remnants of parent stars. Until recently, only the chemical enrichment history of the solar vicinity could be studied in detail. However, the modern multiobject spectrographers attached to the 8–10 m class telescopes allow us to study the chemical enrichment history of the nearest Local Group galaxies.

Because of their proximity, and the fact that they present a wide range of ages and metallicities, the Magellanic Clouds are attractive objects in which to study chemical enrichment histories. In a previous paper (Carrera et al. 2008, hereafter Paper III), we investigated the chemical enrichment history of the Large Magellanic Cloud (LMC). In this paper, we will focus on the study of the Small Magellanic Cloud (SMC). There are considerably less studies of the SMC as compared with the LMC, probably due to (a) its irregular appearance, with complex kinematics; (b) its distance, located further away than the LMC; and (c) its depth in the line of sight, which remains a subject of controversy.

Most of the information about the stellar populations of the SMC has been obtained from its cluster system (e.g., Da Costa & Hatzidimitriou 1998; Piatti et al. 2001, 2005). The cluster age distribution does not show the age gap observed in the LMC (Da Costa & Hatzidimitriou 1998; Mighell et al. 1998). From a sample of seven clusters older than 1 Gyr, Rich et al. (2000) suggest that star formation was stronger in two main episodes, one ~8 ± 2 Gyr ago and another ~2 ± 0.5 Gyr ago. However, there does not seem to be any age interval completely lacking in objects (Rafelski & Zaritsky 2005). There is only one old cluster, NGC 121, that is younger than most of the LMC globular clusters (Piatti et al. 2005). However, the SMC shows a significant old field population (Noël et al. 2007, hereafter Paper I).

To our knowledge, there are only four studies in which a detailed star formation history (SFH) of the SMC field population was derived (Dolphin et al. 2001; Harris & Zaritsky 2004; Chiosi & Vallenari 2007; N. E. D. Noël et al. 2008, in preparation). From a deep color–magnitude diagram (CMD), Dolphin et al. (2001) found that the star formation rate (SFR) in a small field in the periphery of this galaxy was relatively constant until about 2 Gyr ago, with no star formation occurring since then. However, this could be biased by the fact that their field was specifically chosen because it did not have young stars. Harris & Zaritsky (2004) studied a 4° × 4°5 field in the central region of the galaxy. From shallower CMDs, they found that the star formation in the SMC has had two main episodes: one that formed the oldest populations and lasted until 8.5 Gyr ago and a recent one that started around 3 Gyr ago. Recently, Chiosi & Vallenari (2007) derived the SFH in the fields around three SMC clusters, using deep Advanced Camera for Surveys (ACS) CMDs. The fields are located at ~0.8° in the southwest direction and ±0.2 and 0.4° to the east of the SMC center. They found a low rate of star formation until 6 Gyr ago and, since then, two main periods of enhanced star formation between 3 and 6 Gyr and at 300–400 Myr. N. E. D. Noël et al. (2008, in preparation) have also obtained accurate SFHs for the fields presented in this paper, using CMDs reaching the oldest main-sequence turnoffs with good photometric accuracy. They found two main episodes of star formation in all fields, one at old ages (~10 Gyr ago) and another one at intermediate ages (~5 Gyr ago), in addition
to young star formation in the wing fields. This result agrees with the conclusions obtained by Pagel & Tautvaisiene (1998) on the basis of chemical evolution models. They found that the abundances of some chemical elements are better reproduced when a model based on a SFR with two main bursts—one about 12 Gyr ago and another 4 Gyr ago—is considered.

Detailed determinations of chemical abundances exist only for the youngest population of the SMC (i.e., Hill et al. 1997; Venn 1999; Hunter et al. 2007), and its chemical enrichment history has been mainly determined from studies of its cluster system. The cluster age–metallicity relationship (AMR) has been obtained by Piatti et al. (2005) and Mighell et al. (1998), mainly from photometric indicators. An initial chemical enrichment has been found, followed by a period of relatively slow increase in the metal abundance. Clusters which are more metal-rich than [Fe/H] ≥ −1 are younger than 5 Gyr. Since then, the metallicity has again increased until now. On average, the SMC is more metal-poor than the LMC. The very recent work by Idiart et al. (2007), who have obtained chemical abundances in a sample of SMC planetary nebulae, has found a similar result, with the exception that the chemical enrichment episode at a very early epoch is not observed.

In the present work, we focus on obtaining stellar metallicities of individual red giant branch (RGB) stars in the field population of the SMC from Ca II triplet (hereafter CaT) spectroscopy. These stars have been selected in 13 fields distributed at different positions in the SMC ranging from ∼1° to ∼4° from its center. Deep photometry of these fields has been presented in Paper I. The procedure followed to select the targets is explained in Section 2. The data reduction is discussed in Section 3. The radial velocities of the stars in our sample are obtained in Section 4. In Section 5, we discuss the calculation of the CaT equivalent widths and the determination of metallicities. Section 6 presents the method used to derive ages for each star by combining information on their metallicity and position on the CMD. The analysis of the data is presented in Section 7. The metallicity distribution of each field and the possible presence of a metallicity gradient are discussed in Section 7.1. The derived AMRs for each field are presented in Section 7.2. The main results of this paper are discussed in Section 8.

2. TARGET SELECTION

In the framework of a large program to obtain proper motions, deep CMDs, and stellar metallicities in the SMC, we secured spectroscopy of stars in 13 fields spread about the galaxy body. The photometry of these fields, presented in Paper I and listed in Table 1, was obtained with a Tektronic 2048 × 2048 CCD detector attached to the Las Campanas Observatory (LCO) 100″ telescope, which covers a field size of 835 × 835. Following the notation described by Tinney et al. (1997), fields denoted by “qj” (followed by right ascension) are centered on quasars and were observed photometrically with the main objective of determining the absolute proper motion of the SMC (E. Costa et al. 2008, in preparation). Fields labeled “smc” were selected specifically to study their stellar populations by sampling a range of galactocentric radii at similar azimuth. The BR photometry of these fields is described in detail in Paper I, where the distribution of stellar populations of the SMC is discussed on the basis of CMDs. These observations have been complemented with observations in the J band in order to enable one to use the reduced equivalent width–metallicity (W ′−[Fe/H]) relationship derived in Carrera et al. (2007, hereafter Paper II) to obtain metallicities for individual RGB stars. I-band observations of “qj” fields were obtained with the same instrument and telescope as the BR photometry. The I images of “smc” fields were obtained with FORS2 at the Very Large Telescope (VLT) in an image mode and were also used for spectroscopic mask configuration of MXU@FORS2. Field qj0111 was observed with both telescopes in order to compare the photometric calibrations. The magnitudes obtained with each calibration differ by about ∼0.1 mag. This relatively large difference is mainly explained by the poor photometric calibration of the FORS2 images, which were not taken for photometric purposes. In any case, this error means a metallicity uncertainty of only ∼0.02 dex, a value smaller than the metallicity uncertainty itself (∼0.1 dex).

In each field, we selected stars in two windows of the CMD, which are plotted in Figure 1. In each region, the stars were ordered from the brightest to the faintest ones, regardless of their color. The resulting star list was used as input for the mask configuration task of the instrument. Stars in the box below the RGB tip were given higher priority, and only objects above the tip were observed when it was impossible to put the slit on a star of the lower region.

![Figure 1. CMD of the field qj0035 showing the RGB windows used to select the candidates to be observed spectroscopically.](image-url)
3. OBSERVATIONS AND DATA REDUCTION

The spectroscopic observations were carried on in service mode with the VLT Antu telescope, at Paranal Observatory (Chile), through program 074.B-0446. We used FORS2 in the MXU multiobject mode with grism 1028z + 29 and filter OG590 + 32 in order to eliminate residual orders. Slits with a length of 8′′ and a width of 1′′ were selected. With this setup, we were able to observe about 40 objects in each field (the final number depends on the spatial distribution of the selected stars). The slit length was selected with the purpose of shifting the stars along it in order to acquire two exposures of each field without superposition of the stellar spectra in each. This particular procedure allowed us to extract the spectra using the same method used in Paper II.

After bias subtraction, each image was flat-field corrected. Then, since each star is in a different position in the two images of the same field, we subtracted one from the other, obtaining a positive and a negative spectrum of the same star. With this procedure, the sky is subtracted in the same pixel in which the star has been observed, thus minimizing the effects of pixel-to-pixel sensitivity variations. Sky residuals due to temporal variation of the sky brightness were eliminated in the following step, in which the spectrum is extracted in the usual way and the remaining sky background is subtracted using the information on both sides of the stellar spectrum. In the next step, the spectra were wavelength calibrated and added to obtain the final spectrum. Finally, each spectrum was normalized by fitting a polynomial, excluding the strongest lines (such as the CaT lines). There is an uncertainty in the wavelength calibration when we tried to characterize this effect in the way described in Paper II, for the calibration clusters in the SMC fields and presented in Paper II. The resulting velocities can be affected by the fact that the stars might not have been positioned exactly in the center of the slit. The importance of this is described in detail in Paper II. However, in the case of the SMC, the stars were observed at a relatively large air mass (≥1.6) and with a seeing near to or larger than 1′′. Since the slit width was 1′′, the effect of the incorrect centering of the star on the slit was of little importance. In fact, when we tried to characterize this effect in the way described in Paper II, we found that its contribution to the resulting velocity is smaller than the uncertainty due to the wavelength calibration. For this reason, we did not take this effect into account in the final radial velocity. We considered as SMC members those stars with radial velocities in the range 50 ≤ Vr ≤ 250 km s⁻¹ (Harris & Zaritsky 2006).

5. CaT EQUIVALENT WIDTHS AND METALLICITY DETERMINATION

The metallicity of the RGB stars is obtained following the procedure described in Paper II. The equivalent width is the area of the line normalized to the local continuum within a line bandpass. The continuum is calculated from a linear fit to the mean value of the corresponding bandpasses. The line and continuum bandpasses used in this work are listed in Table 3. The line flux is calculated from the fit of its profile using a Gaussian plus a Lorentzian function. As discussed in Paper II, this function provides a better fit to the core and the wings of the strongest lines than other functions previously used. The CaT index, denoted as ΣCa, is defined as the sum of the equivalent widths of the three CaT lines. ΣCa and their uncertainties for each star observed are given in Table 2, together with their magnitudes and radial velocities. Two calibrations of the CaT as the metallicity indicator were obtained in Paper II based on I and V magnitudes. In this case, only I magnitudes are available for the SMC stars. The reduced equivalent width, W_r, for each star has been calculated using the slope obtained in Paper II for the calibration clusters in the M1-ΣCa plane.
Figure 2. Position in the $M_I - \Sigma_{Ca}$ plane of observed SMC stars in the eastern fields. Only stars with confirmed membership from their radial velocity are represented. The typical $\Sigma_{Ca}$ error is shown in the bottom right corner of each panel. Isometallicity lines, obtained from the relationship based on $M_I$ presented in Paper II, have been plotted for reference. The solid part of the line is the magnitude interval covered by the cluster stars used for the calibration (see Paper II). The dashed part is the region in which the calibration is extrapolated. Distances from the SMC optical center are given in the bottom right corner. The innermost field is on the left and the outermost one is on the right.

(A color version of this figure is available in the online journal.)

$(\beta_I = -0.611 \text{ Å mag}^{-1})$. To obtain the absolute magnitudes, we assumed a distance modulus of $(m-M)_0 = 18.9$ (see van den Bergh 1999) and reddenings listed in the last column of Table 1 (see Paper I for details). Also, in Paper II three different metallicity scales were used as reference. In this case, we used only the relationships obtained on the Carretta & Gratton (1997, hereafter CG97) metallicity scale, because it is the only one that uses homogeneous high-resolution metallicities of open and globular clusters and because the metallicities of the LMC stars in Paper III were also obtained in this way.

In brief, the metallicity for each star is given by

$$[\text{Fe/H}]_{\text{CG97}} = -2.95 + 0.38\Sigma_{Ca} + 0.23M_I.$$  (1)

In Figures 2–4, the positions of SMC stars (radial velocity members) in the $M_I - \Sigma_{Ca}$ plane for our eastern, western, and southern fields, are respectively shown. Solid lines indicate the magnitude range of the observed cluster stars used in Paper II to obtain the above relationship. Dashed lines show the region where the relationship is extrapolated.

The metallicity distribution of each field is shown in Figures 5–7 and will be discussed in Section 7.1.

6. DETERMINATION OF STELLAR AGES

The position of the RGB on the CMD suffers from age–metallicity degeneracy. However, when the metallicity is obtained in an alternative way, as in this case from spectroscopy, this age–metallicity degeneracy can be broken, and ages can be derived from the position of the stars in the CMD. In Paper III, a polynomial relationship was computed to derive stellar ages from their metallicities and positions in the CMD. For that purpose, synthetic CMDs computed with IAC-star (Aparicio & Gallart 2004) with the overshooting BaSTI (Pietrinferni et al. 2004) and Padova (Girardi et al. 2002) stellar evolution models as input were used. As is explained in Paper III, differences between both models in the resulting ages are negligible for our purpose, since we are not interested in an accurate determination of ages. For simplicity, as in Paper III, we used only the relationship obtained from the BaSTI stellar models. The aforementioned relation was obtained for $(V - I)$ and $M_V$. Since $V$ magnitudes are unavailable for our sample of SMC stars, we computed a new relationship for $B$, $R$, and $I$ magnitudes. In this case, we selected $(B - I)$ instead of $(B - R)$ because the

Figure 3. The same as Figure 2, for the western fields. They are ordered from the innermost field (top left) to the outermost one (bottom right).

(A color version of this figure is available in the online journal.)
former is much more sensitive to small changes in the stellar metallicity and age. We followed the same procedure as in Paper III. First, we used the same synthetic CMD used in Paper III,\(^5\) which was computed with a constant SFR between 0 and 13 Gyr and with a chemical law such that any star can have any metallicity between $-2.3$ and $+0.5$ dex. In this CMD, we only selected stars in the same region below the tip of the RGB in which the observed

\(^5\) During the referee process of this paper, the authors of the BaSTI models discovered a problem in the calculation of models in the mass range $1.1-2.5 \, M_\odot$ (\(\sim 1-4\) Gyr) (see http://albione.oa-teramo.inaf.it). Even though the differences between the new and old models were unlikely to affect our results in any substantial way, we recalculated Equation (2) using a synthetic CMD computed with the updated model set. All the results shown are derived from this new relationship. We have verified that the differences are indeed minor and that, therefore, the results on the LMC on Paper III, obtained using the faulty models, can be trusted nevertheless.
ones were mainly chosen. We did not consider the brightest asymptotic giant branch (AGB) stars due to the uncertainty of their parameters as predicted by stellar evolution models. Following the same statistical procedure described in Paper III, we checked which polynomial combinations of magnitude $M_I$, color $(B-I)$, and metallicity $[\text{Fe}/\text{H}]$ best represented the age of the stars in this synthetic CMD. In order to minimize the $\sigma$ and to improve the correlation coefficient, different linear, quadratic, and cubic terms of each observed magnitude have been added. We have checked whether $M_I$ or $M_B$ magnitudes improve the relationship. Similar results are obtained for both magnitudes, so we choose the first because metallicities were calculated from it. The final polynomial form adopted is

$$\log(\text{age}) = a + b(B-I) + cM_I + d[\text{Fe}/\text{H}] + f(B-I)^2 + g[\text{Fe}/\text{H}]^2.$$  

(2)

The best-fit coefficients are listed in Table 4.

In order to estimate the age uncertainty when this relationship is used to compute stellar ages, we performed a Monte Carlo test as in Paper III. The goal of the test is to check how the ages obtained change when the input parameters are modified. The test consists of computing, for each synthetic star, several age values for stochastically varying $[\text{Fe}/\text{H}]$, $(B-I)$, and $M_I$ according to a Gaussian probability distribution of the corresponding $\sigma$ ($\sigma_{[\text{Fe}/\text{H}]} \sim 0.15$ dex, $\sigma_{(B-I)} \sim 0.001$, and $\sigma_{M_I} \sim 0.001$). The $\sigma$ value of the ages obtained provides an estimation of the age error when Equation (2) is used. The values obtained for the considered age intervals are shown in Figure 8. The age uncertainty increases for older ages.

It is also necessary to check how well Equation (2) reproduces the age of a real stellar system. Following the same steps as in Paper III, we choose the cluster stars used in Paper II for the calibration of the CaT as the metallicity indicator. For these stars, we knew their $(B-I)$ color and $M_I$ magnitudes, so we could compute their metallicity in the same way as the metallicity of the SMC stars was computed (see Section 5). We then used these observational magnitudes as input for Equation (2), obtaining an age for each cluster star. The cluster age was computed as the mean of the ages of its member stars. In Figure 9, the age computed for each cluster has been plotted versus its reference value. As in Paper III, ages younger than 10 Gyr are well recovered. However, the relationship saturates for ages larger than 10 Gyr.
Figure 9. Ages derived from Equation (2) for the cluster sample presented in Paper II, plotted against the reference values. The solid line corresponds to the one-to-one relation.

7. ANALYSIS

7.1. Metallicity Distribution

Metallicity distributions are shown in Figures 5–7 for eastern, western, and southern SMC regions respectively. We have fitted a Gaussian to obtain the mean metallicity and metallicity dispersion of each of them. These values are listed in columns 3 and 4 of Table 5. The fields are ordered by their distance to the center, which is shown in column 2. Fields in different regions are indicated by different font types: eastern fields in regular type, western fields in boldface, and southern fields in italics. Mean metallicities are very close to $[\text{Fe/H}] \sim -1$ in all fields within $r \lesssim 2.5$ from the SMC center. A similar value is observed for the southern fields up to $r \lesssim 3^\circ$ (qj0047 and smc0049).

Note that the SMC isopleths of intermediate-age and old stars are elongated in the northeast–southwest direction ($\text{PA} = 45^\circ$; Cioni et al. 2000) and that a radius of $3^\circ$ in the southern direction corresponds to approximately the same isopleth at radius $2.5^\circ$ in the eastern and western directions. For the outermost fields, qj0033 in the west, and qj0102 and qj0053 in the south, the mean value is clearly more metal-poor than the others. However, these are also the fields where less stars are observed and, therefore, where the determination of the mean metallicity has the largest uncertainty.

The fact that the mean metallicity decreases when we move away from the center implies that there is a metallicity gradient in the SMC. This gradient is clearer when we compute the percentage of stars in different metallicity bins, values also listed in Table 5 (columns 5 and 6). For the western and southern fields, the percentage of stars more metal-poor than $[\text{Fe/H}] = -1$ increases when we move away from the center. This is not observed in the eastern fields because they are almost at the same distance from the center. This is the first time that a spectroscopic metallicity gradient has been reported in SMC stellar populations. The detection of this gradient has been possible because we have covered a large radius range, up to $4^\circ$ from the SMC center.

7.2. Age–Metallicity Relationships

From a purely phenomenological point of view, there are two main ways to account for the mean metallicity gradient found in the previous section. One possibility is that chemical enrichment has proceeded more slowly toward the SMC periphery, in such a way that coeval stars would be more metal-poor when we move away from the center. This seems to be the case of spiral galaxies, like the Milky Way, where the observed abundance gradients may be explained by radial variations of the relation between the SFR and the amount of infalling gas (e.g., Prantzos & Boissier 2000; Chiappini et al. 2001). The situation would be complicated in dwarf galaxies by the probable existence of galactic winds that originated in supernova explosions (e.g., Romano et al. 2006), which are able to remove a large amount of metals from the interstellar medium. An example of this is the outside-in scenario proposed by Pipino et al. (2006) in the context of the formation and evolution of elliptical galaxies.

In this scenario, the outskirts develop efficient galactic winds earlier than the central region, which forms stars for a longer period. An alternative scenario is that the stellar AMR (i.e., the law of chemical enrichment as a function of time) has been the same everywhere in the SMC. As a result, the average metallicity of coeval stars would be the same in all fields and the metallicity gradient would be related to an age gradient. A mixture of both scenarios is also possible.

To investigate the nature of the gradient, we have therefore calculated the AMR for each field. They are plotted in Figures 10–12 for fields situated to the east, west, and south, respectively. Note that the uncertainty in age is much larger than in metallicity. However, since we are interested in the global behavior and not in obtaining individual stellar ages, the age determinations are still valid. Since the procedure to obtain the age saturates for values older than 10 Gyr, we can only be confident that the oldest stars have an age $\gtrsim 10$ Gyr. For these, we assume an age of 12.9 Gyr, which is the age of the oldest cluster in the Milky Way (NGC 6426, Salaris & Weiss 2002). Regarding the youngest stars, in the region of the CMD where we selected the observed stars, and according to the stellar evolution models, we do not expect to find stars younger than $\sim 0.8$ Gyr. However, Equation (2) can formally compute ages younger than this value. Because the age determination uncertainty for these young stars is $\sim 1$ Gyr, in order to avoid this contradiction we assign them an age of 0.8 Gyr. The inset panels show the age distribution of the observed stars, with and without taking into account the age uncertainty (solid line and histogram, respectively). To obtain the first one, we assumed that the age of each star is represented by a Gaussian probability distribution on the age axis, with a mean value equal to the age calculated for this given star and $\sigma$ equal to the age uncertainty. The area of each of these distributions is unity. In the case of stars near the edges, the wings of the distribution may extend further than the limits. We have proceeded in the same way as described in Paper III, cutting off the wings outside the assumed limits (0.8 and 12.9 Gyr) and rescaling the rest of the distribution so that the area remains unity.

All the AMR plotted in Figures 10–12 show a rapid chemical enrichment at a very early epoch. Even though in some fields we have not observed enough old stars to sample this part of the AMR, note that 12 Gyr ago all fields have reached $[\text{Fe/H}] \sim -1.4$ to $-1.0$. This initial chemical enrichment was followed by a period of very slow metallicity evolution until
around 3 Gyr ago. Then, the galaxy started another period of chemical enrichment, which is observed in the innermost fields, which are, however, the only ones where we observed enough young stars to sample this part of the AMR. For a given age, the mean metallicity of the stars in fields qj0111, qj0112, and smc0057 seems to be slightly more metal-poor than those of other fields. The uncertainties in age determination could account for the observed differences. In all cases, however, the mean metallicity is similar to that of the other fields at similar galactocentric radii. The field AMRs obtained in this work are similar to those for clusters (the reader should take into account that differences in the metallicity scales exist among different works), although there is only one cluster older than 10 Gyr (see Figure 13) and for planetary nebulae, with the exception that in these objects the chemical enrichment episode is not observed at a very early epoch (see Figure 6 of Idiart et al. 2007).

It does not seem that there was a period in which the galaxy has not formed stars, in agreement with the result found in Paper I (Figures 10–12, inset panels). For eastern fields, located in the wing, most of the observed stars have ages younger than 8 Gyr, but there is also a significant number of objects older than 10 Gyr. At a given galactocentric distance, eastern fields show a large number of young stars (≤3 Gyr) compared with the western ones, as discussed in Paper I. For the western and southern fields, the fraction of intermediate-age stars, which are also more metal-rich, decreases as we move away from the center, although the average metallicity in each age bin is similar. This indicates the presence of an age gradient in the galaxy, which may be the origin of the metallicity one. It is noticeable that for the most external fields, qj0033 and qj0053, we find a predominantly old and metal-poor stellar population.

We can statistically check the hypothesis that the AMR is independent of the position in the SMC. To do so, we have combined the measurements on the 13 fields to obtain a global AMR and compared it with that of each field. To do so, we have divided the age range into six intervals (age < 1.5 Gyr, 1.5–3.5 Gyr, 3.5–5.5 Gyr, 5.5–8.5 Gyr, 8.5–11 Gyr, >11 Gyr). We have computed the dispersion and mean metallicity in each age bin, and listed the results in Table 6. With these data, we have performed a χ² test as follows:

$$\chi^2 = \sum_{i=1}^{6} \frac{(Z_{\text{field}}^i - Z_{\text{global}}^i)^2}{\sigma_i^2}$$

(3)

where $\sigma_i^2$ is the squared sum of the uncertainties in the age bin $i$ of each field and the global AMR. The result is shown in column 8 of Table 6. All fields, except qj0047 and smc0033, have values of $\chi^2 < 1$. The discrepancy in fields qj0047 and smc0033 may be due to small number statistics: there are only two stars younger than 11 Gyr in field qj0047 and three in smc0033. Values of $\chi^2 < 1$ mean that the observed AMR for each field is the same as the global one with a confidence of

Figure 10. Age–metallicity relationships for the eastern SMC fields in our sample. Inset panels show the age distribution computed by taking (solid line) and by not taking (histogram) into account the age determination uncertainties. The top panels show the age error in each age interval (see Figure 8). The right panel shows the metallicity uncertainty in each metallicity bin.

(A color version of this figure is available in the online journal.)

Figure 11. The same as Figure 10, for the western fields.

(A color version of this figure is available in the online journal.)
90% (95% in most cases). From these results, we may conclude that the hypothesis that the AMR is independent of position is correct within the uncertainty.

8. SUMMARY AND DISCUSSION

Using CaT spectroscopy, we have derived stellar metallicities for a large sample of RGB field stars in 13 regions of the SMC situated at different galactocentric distances and position angles. We have found a radial metallicity gradient, which is most evident for those fields situated toward the south, where we covered a large galactocentric radius. For a given galactocentric distance, the mean metallicities for fields situated at different position angles are very similar. The inner fields have a mean metallicity of $[\text{Fe/H}] \sim -1$, which is similar to that of the cluster metallicity distribution.

We have obtained the AMR of each field from the combination of metallicities, derived from CaT spectroscopy, and the position of stars in the CMD. All fields have similar AMRs, which are also similar to the clustered one (Piatti et al. 2005). All show a rapid initial increase of metallicity, followed by a very slow chemical enrichment period. A new relatively fast
A chemical enrichment episode is observed in the last few Gyrs in the fields within ~2° of the center with enough young stars to sample it. From information on the AMRs, we conclude that coeval stars have the same metallicity everywhere in the SMC. The observed metallicity gradient is therefore related to an age gradient, because the youngest stars, which are also the most metal-rich, are concentrated in the central regions of the galaxy.

In a forthcoming paper we will try to reproduce the observed AMR with chemical evolution models using accurate SFRs, as a function of time, which are being derived by our group in each field (Noël et al. 2008, in preparation).

A.A., C.G., N.E. D.N. and R.C. acknowledge the support from the Spanish Ministry of Science and Technology (Plan Nacional de Investigación Científica, Desarrollo e Investigación Tecnológica, AYA2004-06343). R.C. also acknowledges the funds by the Spanish Ministry of Science and Technology under the MEC/Fullbright postdoctoral fellowship program. E.C. and R.E.M. acknowledge support from the Fondo Nacional de Investigación Científica y Tecnológica (proyecto no. 1050718, Fondecyt) and from the Chilean Centro de Astrofísica FONDAP No. 15010003. This work has made use of the IAC-STAR Synthetic CMD computation code. IAC-STAR is supported and maintained by the computer division of the Instituto de Astrofísica de Canarias.

Facilities: VLT(FORS2).

REFERENCES

Aparicio, A., & Gallart, C. 2004, A&A, 128, 1465
Carrera, R., Gallart, C., Hardy, E., Aparicio, A., & Zinn, R. 2008, AJ, 135, 836 (Paper III)
Carrera, R., Gallart, C., Pancino, E., & Zinn, R. 2007, AJ, 134, 1298 (Paper II)
Carretta, E., & Gratton, R. G. 1997, A&AS, 121, 95 (CG97)
Chiappini, C., Matteucci, F., & Romano, D. 2001, ApJ, 554, 1044
Chiosi, C., & Vallenari, A. 2007, A&A, 466, 165
Cioni, M. R. L., Habing, H. J., & Israel, F. P. 2000, A&A, 358, L9
Da Costa, G. S., & Hatzidimitriou, D. 1998, AJ, 115, 1934
Dolphin, A. E., Walker, A. R., Hodge, P. W., Mateo, M., Olszewski, E. W., Schommer, R. A., & Suntzeff, N. B. 2001, ApJ, 562, 303
Gallart, C., Martinez-Delgado, D., Gomez-Pellejos, M. A., & Mateo, M. 2001, AJ, 121, 2572
Girardi, L., Bertelli, G., Bressan, A., Chiosi, C., Groenewegen, M. A. T., Marigo, P., Salasnich, B., & Weiss, A. 2002, A&A, 391, 195
Harris, J., & Zaritsky, D. 2004, AJ, 127, 1531
Harris, J., & Zaritsky, D. 2006, AJ, 131, 2514
Hill, V. 1999, A&A, 345, 430
Hill, V., Barbuy, B., & Spithe, M. 1997, A&A, 323, 461
Hunter, I., Dufon, P. L., Smartt, S. J., Ryans, R. S. I., Evans, C. J., Lennon, D. J., Trudle, C., Hubeny, I., & Lanz, T. 2007, A&A, 466, 277
Idiart, T. P., Maciel, W. J., & Costa, R. D. D. 2007, A&A, 472, 101
Mighell, K. J., Sarajedini, A., & French, R. S. 1998, AJ, 116, 2395
Noel, N. E. D., Gallart, C., Costa, E., & Mendez, R. A. 2007, AJ, 133, 2037 (Paper I)
Pagel, B. E. J., & Tautvaisiene, G. 1998, MNRAS, 299, 535
Piatti, A. E., Santos, J. F. C., Clariá, J. J., Bica, E., Sarajedini, A., & Geisler, D. 2001, MNRAS, 325, 792
Piatti, A. E., Sarajedini, A., Geisler, D., Gallart, C., & Wischnjewsky, M. 2007, MNRAS, 382, 1202
Piatti, A. E., Sarajedini, A., Geisler, D., Seguel, J., & Clark, D. 2005, MNRAS, 358, 1215
Pietrinferni, A., Cassisi, S., Salaris, M., & Castelli, F. 2004, ApJ, 612, 168
Pipino, A., Matteucci, F., & Chiappini, C. 2006, ApJ, 638, 739
Prantzos, N., & Boissier, S. 2000, MNRAS, 313, 338
Rafelski, M., & Zaritsky, D. 2005, AJ, 129, 2701
Rich, R. M., Shara, M., Fall, S. M., & Zurek, D. 2000, AJ, 119, 197
Romano, D., Tosi, M., & Matteucci, F. 2006, MNRAS, 365, 759
Salaris, M., & Weiss, A. 2002, A&A, 388, 492
Suntzeff, N. B., Friek, E., Klemola, A., Kraft, R. P., & Graham, J. A. 1986, AJ, 91, 275
Tinney, C. G., Da Costa, G. S., & Zinnecker, H. 1997, MNRAS, 285, 111
Toney, J., & Davis, M. 1979, AJ, 84, 1511
van den Bergh, S. 1999, A&A Rev., 9, 273
Venn, K. A. 1999, ApJ, 518, 405