

OLD MAIN-SEQUENCE TURNOFF PHOTOMETRY IN THE SMALL MAGELLANIC CLOUD. II. STAR FORMATION HISTORY AND ITS SPATIAL GRADIENTS

NOELIA E. D. NOËL^{1,4}, ANTONIO APARICIO², CARME GALLART¹, SEBASTIÁN L. HIDALGO¹, EDGARDO COSTA³, AND
RENÉ A. MÉNDEZ³

¹ Instituto de Astrofísica de Canarias & Departamento de Astrofísica, Universidad de La Laguna, 38200 La Laguna, Tenerife, Canary Islands, Spain; noelia@roe.ac.uk, carme@iac.es, shidalgo@iac.es

² Departamento de Astrofísica, Universidad de La Laguna & Instituto de Astrofísica de Canarias, 38200 La Laguna, Tenerife, Canary Islands, Spain; antapaj@iac.es

³ Universidad de Chile, Departamento de Astronomía, Casilla 36-D, Santiago, Chile; costa@das.uchile.cl, rmendez@das.uchile.cl

Received 2009 July 15; accepted 2009 September 22; published 2009 October 20

ABSTRACT

We present a quantitative analysis of the star formation history (SFH) of 12 fields in the Small Magellanic Cloud (SMC) based on unprecedented deep $[(B - R), R]$ color–magnitude diagrams (CMDs). Our fields reach down to the oldest main-sequence turnoff with a high photometric accuracy, which is vital for obtaining accurate SFHs, particularly at intermediate and old ages. We use the IAC-pop code to obtain the SFH, using synthetic CMDs generated with IAC-star. We obtain the SFH as a function $\psi(t, z)$ of age and metallicity. We also consider several auxiliary functions: the initial mass function (IMF), $\phi(m)$, and a function accounting for the frequency and relative mass distribution of binary stars, $\beta(f, q)$. We find that there are several main periods of enhancement of star formation: a young one peaked at ~ 0.2 – 0.5 Gyr old, only present in the eastern and in the central-most fields; two at intermediate ages present in all fields: a conspicuous one peaked at ~ 4 – 5 Gyr, and a less significant one peaked at ~ 1.5 – 2.5 ; and an old one, peaked at ~ 10 Gyr in all fields but the western ones. In the western fields, this old enhancement splits into two, one peaked at ~ 8 Gyr old and another at ~ 12 Gyr old. This “two-enhancement” zone is unaffected by our choice of stellar evolutionary library but more data covering other fields of the SMC are necessary in order to ascertain its significance. Correlation between star formation rate enhancements and SMC–Milky Way encounters is not clear. Some correlation could exist with encounters taken from the orbit determination of Kallivayalil et al. But our results would also fit in a first pericenter passage scenario like the one claimed by Besla et al. For SMC–Large Magellanic Cloud encounters, we find a correlation only for the most recent encounter ~ 0.2 Gyr ago. This coincides with the youngest $\psi(t)$ enhancement peaked at these ages in our eastern fields. The population younger than 1 Gyr represents $\sim 7\%$ – 12% of the total $\psi(t)$ in our fields of the wing area. This is not an exceptional increment as compared with the average $\psi(t)$ but is very significant in the sense that these eastern fields are the only ones of this study in which star formation is currently going on. There is also a strong dichotomy between east/southeast and west in the current irregular shape of the SMC. We find that this dichotomy is produced by the youngest population and began ~ 1.0 Gyr ago or later. The age of the old population is similar at all radii and at all azimuth, and we constrain the age of this oldest population to be more than ~ 12 Gyr. We do not find yet a region dominated by a true, old, Milky-Way-like, halo at 4.5 kpc from the SMC center, indicating either that this old stellar halo does not exist in the SMC or that its contribution to the stellar populations, at the galactocentric distances of our outermost field, is negligible. Finally, we derive the age–metallicity relation and find that, in all fields, the metallicity increased continuously from early epochs until the present. This is in good agreement with the results from the Ca II triplet, a completely independent method, constituting an external consistency proof of IAC-pop in determining the chemical enrichment law.

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

Online-only material: color figures

1. INTRODUCTION

The Local Group dwarf galaxies provide a unique laboratory for studying and testing galaxy formation theories and cosmology. Their close proximity allows individual stars to be resolved, giving accurate kinematics (see, e.g., Walker et al. 2006; Costa et al. 2009), photometry (see, e.g., Noël et al. 2007), and spectroscopy (e.g., Carrera et al. 2008b). Their stellar populations can be characterized in detail and their star formation histories (SFHs) derived (e.g., Gallart et al. 1999). Their extended edges can be compared with cosmological predictions to give

useful constraints (e.g., Noël & Gallart 2007), and their large mass-to-light ratios can be used, through dynamical modeling, to place constraints on the nature of dark matter (e.g., Kleyna et al. 2001).

Containing stars born over the whole lifetime of a galaxy, the color–magnitude diagram (CMD) is a fossil record of the SFH. For the Milky Way satellites, it is possible to obtain accurate SFHs, from CMDs reaching the oldest main-sequence (MS) turnoffs, using ground-based telescopes. Reaching the oldest MS turnoffs is vital for breaking the age–metallicity degeneracy and properly characterizing the intermediate-age and old population (see Gallart et al. 2005). The Magellanic Clouds (MCs), our nearest irregular satellites, provide an ideal environment for this work. In this paper, we focus on the Small

⁴ Current address: Institute for Astronomy, Royal Observatory, University of Edinburgh, UK.

Magellanic Cloud (SMC). It has been historically neglected in favor of its larger neighbor, the Large Magellanic Cloud (LMC). However, recently there has been growing interest in the SMC as a result of new proper motion measurements—which constrain the past orbital motions of the MCs (Costa et al. 2009; Kallivayalil et al. 2006; Piatek et al. 2008). These indicate that it may have a different origin to the LMC (see, e.g., Bekki et al. 2004). If true, this would imply that its SFH, evolution, and structure could differ significantly from that of the LMC.

The SMC lies at a distance of 61.1 kpc from the Sun (Westerlund 1997; Storm et al. 2004; Hilditch et al. 2005; Keller & Wood 2006), has a mass interior to 3 kpc of $M_{\text{SMC}} \sim 3 \times 10^9 M_{\odot}$ (Harris & Zaritsky 2006), a high fraction of H I ($M_{\text{H I}} \sim 4 \times 10^8 M_{\odot}$; Stanimirovic et al. 1999), a luminosity of $6 \times 10^8 L_{\odot}$ in the V band (de Vaucouleurs et al. 1991), and a current metallicity of $\sim 1/5$ solar (Dufour 1975; Peimbert & Torres-Peimbert 1976; Dufour & Harlow 1977; Peimbert et al. 2000). The SMC is actively forming stars at a global rate of $0.05 M_{\odot} \text{ yr}^{-1}$ (Wilke et al. 2004), and is populated by well-studied H II regions and star clusters of all ages (e.g., Massey 2002; Rafelski & Zaritsky 2005; Chiosi et al. 2006; Bica et al. 2008; Piatti et al. 2008; Glatt et al. 2008).

1.1. The SMC Stellar Content from Field Stars: Summary from Previous Work

The most comprehensive study of the SFH of the SMC to date was presented by Harris & Zaritsky (2004).⁵ They derived the global SFH of the SMC, based *UBVI* catalog that includes over 6 million SMC stars. They used the StarFISH package (Harris & Zaritsky 2001) to determine the global SFH of the SMC, derived by summing the star formation rate (SFR) over all 351 subregions and using three different metallicities. They found that there was a significant epoch of star formation up to 8.4 Gyr ago when $\sim 50\%$ of the stars were formed, followed by a long quiescent period in the range $3 \text{ Gyr} \leq \text{age} \leq 8.4 \text{ Gyr}$, and a more or less continuous period of star formation starting 3 Gyr ago and extending to the present. They also found three peaks in the SFR, at 2–3 Gyr, at 400 Myr, and 60 Myr ago.

While global studies of the SMC like Harris & Zaritsky (2004) are invaluable in aiding our understanding of the evolution of the SMC, their CMDs do not go deep enough to derive the full SFH from the information on the MS ($B \sim 22$, corresponding to stars younger than ~ 3 Gyr old on the MS). Obtaining CMDs reaching the oldest MS turnoff is essential in order to properly constrain the intermediate-age and old population (e.g., see Paper I and Gallart et al. 2005, for a review). Going deep usually means sacrificing the available field of view, so such studies are very complementary to galaxy-wide surveys like Harris & Zaritsky (2004). To our knowledge, the papers which have presented CMDs reaching the oldest MS turnoffs so far, studying small fields of view are: Dolphin et al. (2001), McCumber et al. (2005), Chiosi & Vallenari (2007), and Sabbi et al. (2009). Dolphin et al. (2001) presented a combination of *Hubble Space Telescope* (*HST*) and ground-based *V* and *I* images of an SMC field situated 2° northeast of NGC 121. Using the ground-based CMD (for statistical reasons), with the Girardi et al. (2000) models, they

quantitatively determined the SFH for that field and found a broadly peaked SFH, with the largest SFR occurring between 5 and 8 Gyr ago, and some small amount of star formation going on since a very early epoch and down to ~ 2 Gyr ago. McCumber et al. (2005) analyzed the stellar populations of an SMC field located in the wing area with observations from the *HST* WFPC2. They compared the luminosity function from their observed CMD with those obtained from two different model CMDs, one with constant $\psi(t)$ and another with bursts of star formation at ~ 2 and ~ 8 Gyr. They concluded that the population appears to have formed largely in a quasi-continuous mode, with a main period of star formation between 4 and 12 Gyr ago and a very prominent recent star formation event producing bright stars as young as 100 ± 10 Myr. Using deep CMDs obtained with the Advanced Camera for Surveys (ACS), Chiosi & Vallenari (2007) retrieved the SFH of three fields around SMC clusters. The fields are located at galactocentric distances of ~ 0.22 kpc and ~ 0.45 kpc toward the east, and at ~ 0.9 kpc in the southern direction. Chiosi & Vallenari (2007) found two main episodes in the SFR, at 300–400 Myr and between 3 Gyr and 6 Gyr. They also found that the SFR was low until ~ 6 Gyr ago, when few stars were formed.

Finally, Sabbi et al. (2009) present very deep data (the deepest so far) from the ACS at the *HST* of six fields distributed within the bar, wing, and external body of the galaxy. They provide only a qualitative discussion of the stellar population based mainly on isochrone superposition which is enough to indicate that stars of all ages are present in the galaxy, including very old ones (older than 10 Gyr) and that intermediate-age stars are a very significant component of the stellar population.

1.2. The Stellar Populations of the Outer Reaches of the SMC: Summary of Previous Work

Photometric studies of the outer SMC began with the pioneering work of Gardiner & Hatzidimitriou (1992). With a rather shallow photometry (reaching the horizontal branch (HB) level at $R \sim 20$ mag), they mainly gave information about the young populations (age ≤ 2 Gyr). From their CMDs and contour plots of the surface distribution of MS stars with $(B - R) < 0.1$ and $R < 20$, they noticed the almost complete absence of bright MS stars in the northwestern part, while a considerable bright MS population was present in the eastern and southern area. With the aid of luminosity functions, they found that youngest populations (< 0.6 Gyr in age) are concentrated toward the center of the SMC and in the “wing”⁶ region. Using an index defined as the difference between the median color ($B - R$) of the red clump (RC) and the color of the red giant branch (RGB) at the level of the HB, the authors inferred that the bulk of the field population has a median age around 10–12 Gyr.

More recently, Harris (2007) presented the SFH of the young inter-Cloud population along the ridgeline of the H I gas that forms the Magellanic Bridge and found an intermediate-age and old population at $4^{\circ}.4$ and $4^{\circ}.9$ from the SMC center in that direction, but only a young population belonging to the SMC at $6^{\circ}.4$ (~ 7.2 kpc). At the same time, Noël & Gallart (2007) presented the analysis of three SMC fields located in the southern outskirts of the SMC. They found the first evidence of intermediate-age and old stars belonging to the SMC at $5^{\circ}.8$ (6.5 kpc) from the SMC center. These studies together suggest that the SMC is more extended than previously thought.

⁵ Many other recent studies have also made valuable contributions. For example, Cioni et al. (2006) compared the k magnitude distribution of the SMC asymptotic giant branch stars obtained from DENIS and Two Micron All Sky Survey data with theoretical distributions. They found that the SMC is on average 7–8 Gyr old, but that there are older stars present at its periphery, while younger stars are located toward the LMC.

⁶ The wing is located in the eastern side of the SMC, facing the LMC.

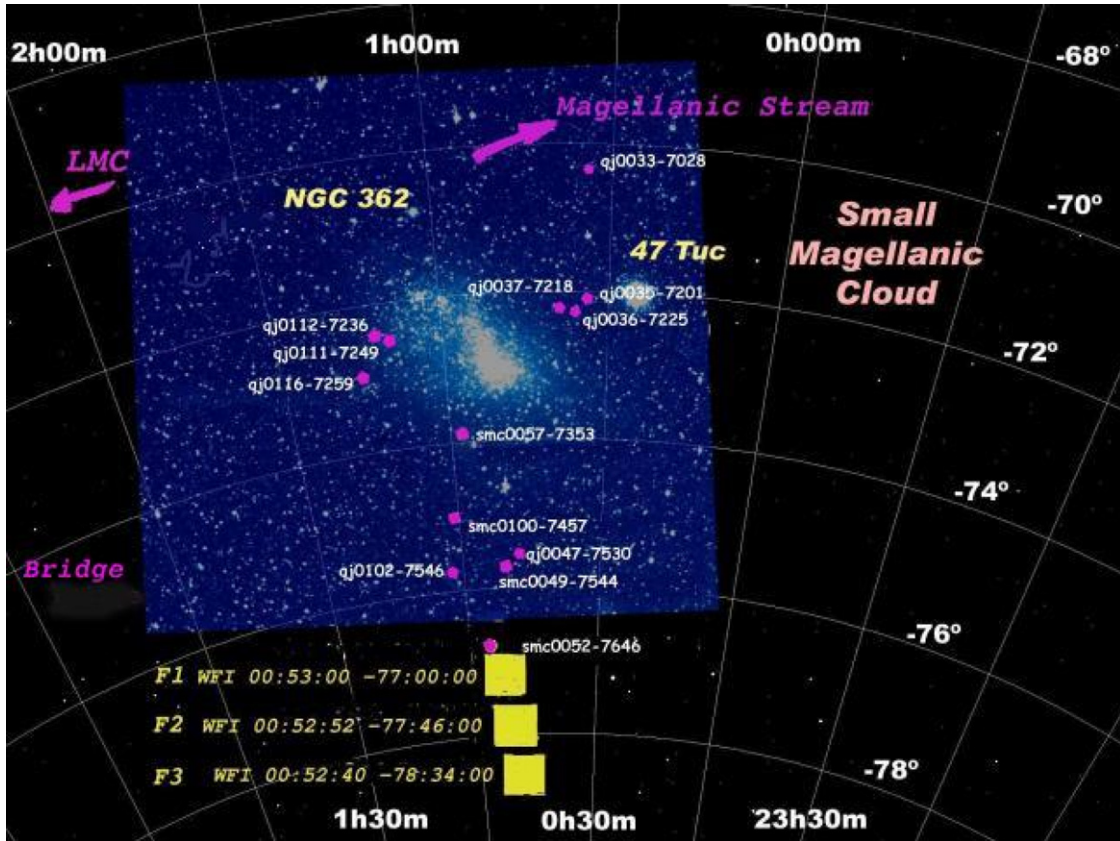


Figure 1. Spatial distribution of our SMC fields. The large squares show the $34' \times 33'$ fields analyzed in Noël & Gallart (2007). The small symbols represent the fields analyzed here and in Paper I.

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

1.3. Context of the Present Work

In Paper I, we presented the isochrones and color functions analysis of 12 unprecedented deep *BR*-based SMC CMDs corresponding to fields ranging from $\sim 1^\circ$ (~ 1.1 kpc) to $\sim 4^\circ$ (~ 4.5 kpc) from the SMC center. The fields are distributed in different parts of the SMC, avoiding the central area (see Figure 1). Each field reaches down to the old MS turnoffs, allowing for a good characterization of the intermediate-age and old population in these areas. The western fields contain very few stars younger than ~ 3 Gyr, while the fields located toward the east—the wing region—show very active current star formation. The presence of considerable amounts of young population in the eastern fields and lack thereof in the western ones is in good correspondence with the existence or absence of large amounts of H I at the corresponding locations (Stanimirović et al. 1999). A significant intermediate-age population is present in all of our fields.

In this paper, we extend the analysis presented in Paper I and obtain quantitative SFHs of all the analyzed fields using the IAC-pop code (Aparicio & Hidalgo 2009). IAC-pop allows us to compare the observed CMD with synthetic CMDs generated using IAC-star (Aparicio & Gallart 2004). To compute the synthetic CMDs, suitable stellar evolution libraries and ingredients were adopted.

The SFH of the SMC as derived from CMDs that reach the oldest MS turnoffs allows us to address several important questions: (1) what is the age distribution of the old and intermediate-age population?; (2) are there spatial differences in the composition of this underlying population?; and (3) shallower studies inform us about the young population, but does

this young population reflect an exceptional increase of the star formation at the present time with respect to the average SFR?

This paper is organized as follows. In Section 2, we briefly summarize the characteristics of the SMC data. In Section 3, we explain the procedure we followed to quantitatively retrieve the SFH. In Section 4, we discuss the ingredients of our models, such as the input stellar evolution models, the initial mass function (IMF), the characteristics of the binary star population, and the parameterization of the SFH, among others. In Section 5, we present the detailed SFH of our SMC fields. Finally, in Section 6, we discuss our results and present our conclusions.

2. THE SMC DATA

B- and *R*-band images of 12 $8'.85 \times 8'.85$ SMC fields were obtained throughout a four-year campaign (2001–2004) using the 100-inch telescope at Las Campanas Observatory (see Figure 1). Photometry of the stars in all the SMC fields was obtained using the set of DAOPHOT, ALLSTAR, and ALLFRAME programs (Stetson 1994) and the final photometry was calibrated to the Johnson–Cousins system. A total of 215,121 stars down to $R \sim 24$ were kept, with small photometric errors ($\sigma \leq 0.15$, $\text{CHI} \leq 2.5$, and $-0.6 \leq \text{SHARP} \leq 0.6$). See Paper I for a complete description of the data reduction and photometry.

3. DERIVING THE SFH OF A STELLAR SYSTEM

The first step in accurately determining the SFH of a stellar system is a deep CMD reaching the oldest MS turnoffs. The advantage of this is twofold: (1) stellar evolution models are

more accurate along the MS than for more advanced stellar evolutionary phases such as the RGB or the HB, where the corresponding physics is more complicated or uncertain; and (2) stars are less densely packed on the MS than in the RGB or HB, which contain stars of very different ages in a small interval of color and/or magnitude, and suffer from important age–metallicity degeneracies. The SFH is composed of several pieces of information. We adopt here the approach of Aparicio & Hidalgo (2009), which can be sketched as follows: since time and metallicity are the most important variables in the problem, we define the SFH as a function $\psi(t, z)$ such that $\psi(t, z) dt dz$ is the number of stars formed at time t' in the interval $t < t' \leq t + dt$ and with metallicity z' in the interval $z < z' \leq z + dz$. Where necessary, the function $\psi(t)$ —defined as an integral over metallicity of $\psi(t, z)$ —and the function $\psi(z)$ —defined as an integral over time of $\psi(t, z)$ —will be used to represent the time-dependent SFH and metallicity-dependent SFH, respectively. There are also several other functions and parameters related to the SFH that we will consider here as auxiliary: the IMF, $\phi(m)$, and a function accounting for the frequency, f , and relative mass distribution, q , of binary stars, $\beta(f, q)$, are the main ones. Other parameters affecting the solution of $\psi(t, z)$ are the distance and reddening (including differential reddening) adopted. For a detailed discussion, see Aparicio & Hidalgo (2009) and Hidalgo et al. (2009).

An important limitation on the information that can be retrieved from the empirical data is produced by observational effects. These include all the factors affecting and distorting the CMD, namely the signal-to-noise limitations, the defects of the detector, and the crowding and blending between stars. The consequences are a loss of stars, changes in measured stellar colors and magnitudes, and external errors, which are usually larger and more difficult to control than internal ones (Aparicio & Gallart 1995). A realistic simulation of observational effects in the synthetic CMDs is necessary in order to obtain an accurate solution for $\psi(t, z)$. In our case, it was performed on a star-by-star basis, using an empirical approach that makes no assumption about the nature of the errors or about their propagation (Aparicio & Gallart 1995). The process is fully described in Aparicio & Hidalgo (2009).

The procedure followed to find the SFH is similar to that described in Hidalgo et al. (2009). The SFH is derived through a comparison of the distribution of stars in the observed CMD with that of a model CMD, using the IAC-pop code (Aparicio & Hidalgo 2009). A single *global* synthetic CMD was generated using the IAC-star code for each input set (stellar evolution and bolometric correction libraries, IMF, and binarity; see Section 4 for details). Observational effects were simulated in the global synthetic CMD as discussed above. The synthetic stars were distributed in an array of *partial models*, ψ_i , each containing stars within small intervals of age and metallicity. Then, a set of boxes was defined in the CMDs. An array, M_i^j , containing the number of stars from partial model i populating box j is computed. The same operation is made in the observed CMD, producing a vector, O^j , containing the number of observed stars in box j . This step defines the parameterization of the CMD.

Any SFH (with the restriction in time and metallicity resolution imposed by the partial models) can be written as

$$\psi(t, z) = A \sum_i \alpha_i \psi_i, \quad (1)$$

where $\alpha_i \geq 0$ and A is a scaling constant. The associated

distribution of stars in the defined boxes is

$$M^j = A \sum_i \alpha_i M_i^j. \quad (2)$$

In this way, any synthetic SFH and CMD can be formally extracted from the single initial global synthetic CMD. M_i can now be compared with O^j using a merit function. A reduced Mighell χ^2 (Mighell 1999), $\chi_v^2 = \chi^2/\nu$ is used, where $\nu = k - l$ is the number of degrees of freedom, k is the number of boxes used to parameterize the CMD, and l is the number of partial models ($l = n \times m$, where n and m are the numbers of age and metallicity intervals, respectively). Minimization of χ_v^2 with respect to the α_i coefficients provides the best solution for $\psi(t)$.

4. RETRIEVING THE SFHS FOR THE SMC FIELDS

We used IAC-pop (Aparicio & Hidalgo 2009) to obtain the SFH, $\psi(t, z)$, in our SMC fields. The global synthetic CMD used by IAC-pop is computed by IAC-star with the following input. It comprises 10^6 stars with ages and metallicities uniformly distributed over the full interval of variation of $\psi(t, z)$ in time and metallicity. This represents a constant SFR as a function of time with equally probable metallicity, within a given range, for each age. The age range considered was between 13 Gyr ago⁷ and now. We assumed a low metallicity bound $z_i = 0.0001$, since it is compatible with the CMD and is the lowest metallicity allowed by the models. The high metallicity bound was taken from the H II region observations (Dufour 1984; see below and Table 3). For the stellar evolution libraries, we used the overshooting BaSTI (Pietrinferni et al. 2004, 2006; see also Cordier et al. 2007) and Padua (summarized in Bertelli et al. 1994). Bolometric corrections from Castelli & Kurucz (2004) were adopted. Kroupa’s revised IMF⁸ $\phi(m)$, was used (Kroupa et al. 2003). It is not possible to uniquely determine the binary fraction, but we explored the consequences of their presence in the CMDs of the SMC. Only in binaries with mass ratios q close to unity would the secondary have a substantial effect on the combined luminosity of the system. For this reason, in our final models we have considered mass ratios in the interval $0.7 \leq q \leq 1.0$ (see Gallart et al. 1999, for details). After testing different binary fractions, we found that, in general, the $\psi(t, z)$ is not significantly affected by changes in $\beta(f, q)$. In our final models, we adopted a 30% of binary fraction. Finally, observational errors were simulated as mentioned in Section 3. We used a distance modulus of $(m - M)_0 = 18.9$ and the reddening values given in Table 1 (see Paper I for details on the reddening determinations).

Several global synthetic CMDs were obtained using the two mentioned stellar evolution libraries and different binary fractions. Each model CMD was divided into partial models, using the age–metallicity pairs defined in Tables 2, 3, and 4. In Table 2, the name of each set of age intervals is shown together with the corresponding age sampling. Three different sets were used in order to address how the SFH is affected by changes in such age intervals. In Table 3, the name of each set of metallicity intervals is shown together with the corresponding metallicity

⁷ The results from the *WMAP* (Spergel et al. 2003) imply that the age of the universe is 13.7 ± 0.2 Gyr. The first stars started forming ~ 0.4 Gyr after the beginning of the universe. With the current most commonly accepted distance scale for globular clusters (Carretta et al. 2000), the age of the oldest globular cluster in the Milky Way, derived using up to date stellar evolution models, is in good agreement with the age of the universe (Marín-Franch et al. 2009).

⁸ $m^{-1.3}$ for $0.1 \leq m/M_\odot < 0.5$ and $m^{-2.3}$ for $0.5 \leq m/M_\odot < 100$.

Table 1
Reddening Values

Field	$E(B - V)$
smc0057	0.09
qj0037	0.07
qj0036	0.07
qj0111	0.09
qj0112	0.09
qj0116	0.08
smc0100	0.05
qj0047	0.05
qj0033	0.03
smc0049	0.06
qj0102	0.05
smc0053	0.06

Table 2
Age Intervals

Model	Age Intervals (Gyr)
Age-1	0.0 0.5 1.0 2.0 3.0 4.0 5.0 7.0 9.0 11.0 13.0
Age-2	0.0 0.2 0.5 1.1 1.8 2.7 3.9 5.4 7.2 9.0 11.0 13.0
Age-3	0.0 0.1 0.2 0.5 1.0 1.9 2.7 3.3 4.1 5.0 6.0 7.1 9.0 10.7 13.0

sampling. The two different sets of metallicity intervals were chosen according to the stellar population present in each field. In those fields in which there is a considerable amount of young stars (eastern fields and the two southern ones closest to the center), the metal-1 set of intervals from Table 3 was used (which reaches higher metallicities), while in those in which the recent star formation is negligible, metal-2 from Table 3 was used. Table 4 defines the combination of intervals of age and metallicity used for each field. The first column gives the number of simple populations; the second and third columns denote the number of age and metallicity intervals, respectively; and in the fourth column, the corresponding field names are listed. The age intervals are defined such that they are larger towards older ages. This is because older stars are more densely packed in the CMD and the isochrones become closer together as they get older, while stars have higher photometric errors at fainter magnitudes. By choosing these intervals of age for the partial models, we are introducing an upper limit to the resolution in age of $\psi(t)$.

The next step was the parameterization of the data. Instead of using a uniform grid, it is better to use one in which the box size is different across the CMD. We call this “à la carte”

parameterization (see Hidalgo et al. 2009). In this way, regions for which stellar positions as a function of mass, age, and metallicity, as provided by the stellar evolution theory, are better known, are sampled with smaller boxes, so receiving a larger weight in the solution searching. We performed several tests using different “à la carte” parameterizations. Figure 2 shows some examples of the parameterizations we performed and their corresponding solutions for $\psi(t, z)$ for field smc0057. As seen from the figures, the different SFHs are very similar and the resulting $\chi^2_{v,\min}$ are very good in all cases, implying that the parameterization is not significantly affecting the solution. We kept the “à la carte” parameterization shown in Figure 3(a), which has small boxes in the regions in which the stellar evolutionary phases are well known (MS), and larger boxes in the regions of the CMD in which stars in more advanced phases are located. The solution for the $\psi(t, z)$ in field smc0057 is shown in Figure 3(b). Error bars have been computed as the dispersion of 20 solutions with $\chi^2_v = \chi^2_{v,\min} + 1$, where $\chi^2_{v,\min}$ is the solution shown in this figure. These error bars are only indicative, while the actual dispersion of the three solutions (see Aparicio & Hidalgo 2009) shown in Figure 3(b) is a more realistic representation of the solution uncertainties.

For all fields, we retrieved the SFH using both stellar evolution libraries as inputs of IAC-star: BaSTI and Padua. The results are presented in Section 5.

4.1. Testing the Pipeline: Recovering the SFH of “Mock” Galaxies

Several tests of IAC-pop are discussed by Aparicio & Hidalgo (2009) and Hidalgo et al. (2009). We have performed some more tests for our particular case, setting out to recover the SFH of two “mock” galaxies, generated using the IAC-star code. One mock galaxy assumed a constant SFR, $\psi(t) = 1$, and a metallicity law suitable for our SMC fields (the “SMC-mock”; see below and Carrera et al. 2008a). The other (the “metal-mock”) assumed the same $\psi(t)$ but a different metallicity law, in order to investigate if the assumption of such law affects the results. In both cases, 5×10^5 stars were considered. We simulated observational errors for each synthetic population as described in Section 3. Errors from the observed field qj0116 were used for the simulation since it is a typical “wing” field, with a fairly large amount of stars. The same test was performed simulating observational errors from other fields, obtaining similar results.

Different subsamples were extracted randomly from SMC-mock, and $\psi(t)$ was recovered for each of them using a global

Table 3
Metallicity Intervals

Model	Metallicity Intervals
Metal-1	0.0001 0.0003 0.0006 0.001 0.0015 0.002 0.003 0.004 0.005 0.006 0.008 0.01 0.015 0.02
Metal-2	0.0001 0.0003 0.0006 0.001 0.0015 0.002 0.003 0.004 0.006 0.008

Table 4
Age–Metallicity Pairs

N. Simple Pops.	N. Age Int.	N. Metallicity Int.	Fields
90	10	9	qj0047, smc0049, qj0102, smc0053, qj0033, qj0036, qj0037
99	11	9	qj0047, smc0049, qj0102, smc0053, qj0033, qj0036, qj0037
126	14	9	qj0047, smc0049, qj0102, smc0053, qj0033, qj0036, qj0037
130	10	13	smc0057, smc0100, qj0111, qj0112, qj0116
143	11	13	smc0057, smc0100, qj0111, qj0112, qj0116
182	14	13	smc0057, smc0100, qj0111, qj0112, qj0116

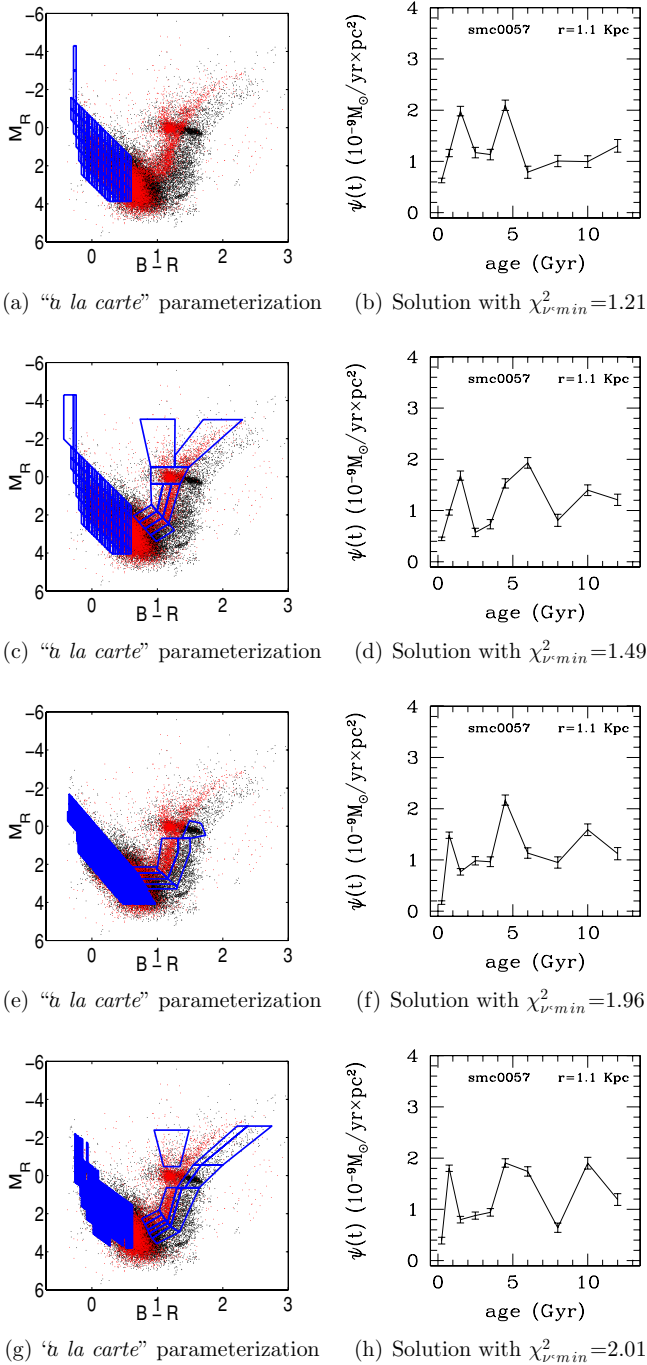


Figure 2. Left panels show some examples of the parameterizations we performed on the observed (red) and model (black) CMDs computed using the BaSTI library. The corresponding solutions are shown in the panels on the right. Error bars have been computed as the dispersion of 20 solutions with $\chi^2_v = \chi^2_{v,min} + 1$, where $\chi^2_{v,min}$ is the solution shown in this figure. These error bars are only indicative.

synthetic CMD with 10^6 stars computed assuming exactly the same inputs of binarity, IMF, stellar evolution library, and bolometric corrections as the SMC-mock. The metallicity distribution of the global synthetic CMD was assumed equally probable between $z = 0.0001$ and $z = 0.02$, for the whole age interval. The resultant $\psi(t)$ are displayed in Figure 4. Note that they deviate from the input $\psi(t) = 1$ by up to 25%, showing “wiggles” with similar patterns in the different subsamples, indicating that the effect is a systematic error, rather

than a random one. While it is difficult to ascertain where the origin of this systematic trend is, it is worth noting that this effect is not caused by the crowding present in the different fields. This is illustrated in Figure 5. It shows similar trends as the ones in Figure 4 for the SFH derived for SMC-mock (for the age interval age-1 from Table 2) after simulating in the latter the observational effects from three fields located at different galactocentric distances: the central-most field, smc0057 (located at ~ 1.1 kpc), the outermost one (at ~ 4.5 kpc), and field smc0049, located at an intermediate distance from the SMC center (at ~ 3.3 kpc).

Final solutions must be corrected from the former systematic effects. Since we cannot assure that the effects are fully reproducible, we have obtained the systematic signature for each field following the procedure described above but simulating the observational effects of the field into the SMC-mock. The SFH obtained for the observed field is then divided by the corresponding systematic signature to obtain the final adopted solution.

To test if such a correction really improves the solutions, we performed a new test, now using a third mock galaxy with a $\psi(t)$ similar to the solutions found for our real SMC fields. The results are shown in Figure 6, in which the input $\psi(t)$ for the mock galaxy is represented by the solid line. The solution $\psi(t)$ for such mock galaxy is represented by the dashed lines in the figure. It differs from the input $\psi(t)$ in a similar way as seen in Figure 4. The corrected $\psi(t)$ (after dividing the solutions by the one shown in Figure 4) is in excellent agreement with the input $\psi(t)$ (dotted line).

5. THE SFH OF THE SMC FIELDS

In order to reduce sampling problems associated with age binning, we obtained three different solutions for the SFH, $\psi(t, z)$ (see Aparicio & Hidalgo 2009), of each field, using three different age-binning sets (see Table 2). The adopted solution will be the average of the three. As an example, Figure 7 shows the three solutions obtained with the BaSTI library for field smc0057 together with the adopted solution, the age–metallicity relation and the observed CMD. The left panel shows the three-dimensional population boxes (Hodge 1989) of the three solutions, where $\psi(t, z)$ is represented as a function of age and metallicity. Here, the volume of each bar over the age–metallicity plane gives the mass that has been transformed into stars within the corresponding age–metallicity interval. The adopted solution (right medium panel) is obtained as a cubic spline fit to the three individual solutions after correcting for the systematic errors discussed above. Horizontal bars in this panel are not error bars, but show the time intervals considered. As in Figure 3, error bars (vertical) are only indicative, while the actual dispersion of the three solutions (see Aparicio & Hidalgo 2009) should be considered a more realistic representation of the solution uncertainties. The age–metallicity relations shown in the bottom panel have been obtained as the average metallicity of the stars in each age interval for the three individual solutions.

The solutions obtained using the Padua library are similar to the ones obtained using the BaSTI library. Figures 8 and 9 show a summary of the results obtained for $\psi(t)$ for all fields using BaSTI and Padua, respectively. Unless otherwise stated, from now on our discussion will use the results obtained using the BaSTI library. Our conclusions are unchanged if we use the results from the Padua library.

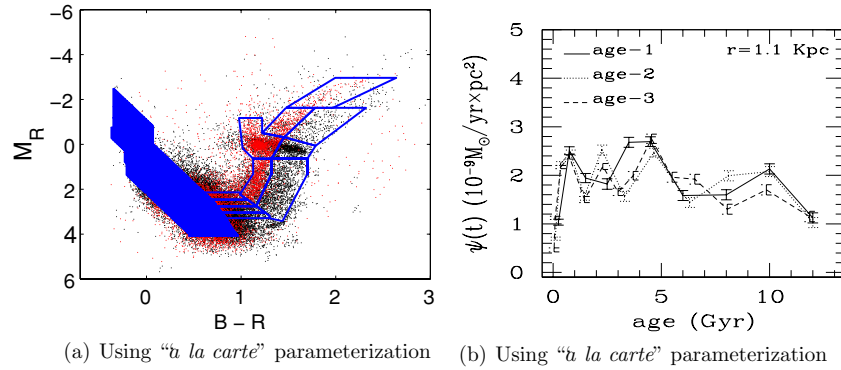


Figure 3. Panel (a) shows the final set of boxes used to obtain the $\psi(t, z)$ of our SMC fields. The final solution is shown in Panel (b) for three different age binnings. Error bars have been computed as the dispersion of 20 solutions with $\chi^2_v = \chi^2_{v,\min} + 1$, where $\chi^2_{v,\min}$ is the solution shown in this figure. These error bars are only indicative.

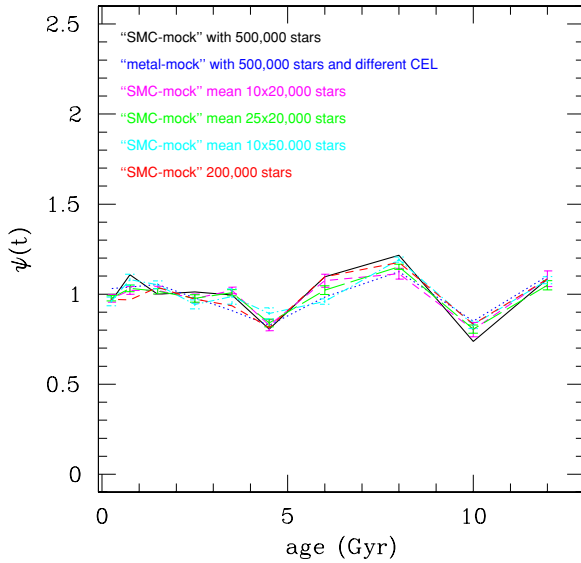


Figure 4. Solution for the SFH of several samples of the “SMC-mock” and “metal-mock” synthetic populations are shown. See the text for an explanation of the input $\psi(t)$ and metallicity laws. In the case of the mean SFHs the errors are defined as $\sigma/(N-1)^{1/2}$, where σ^2 is the variance of the solutions and N is their number. See the text for details.

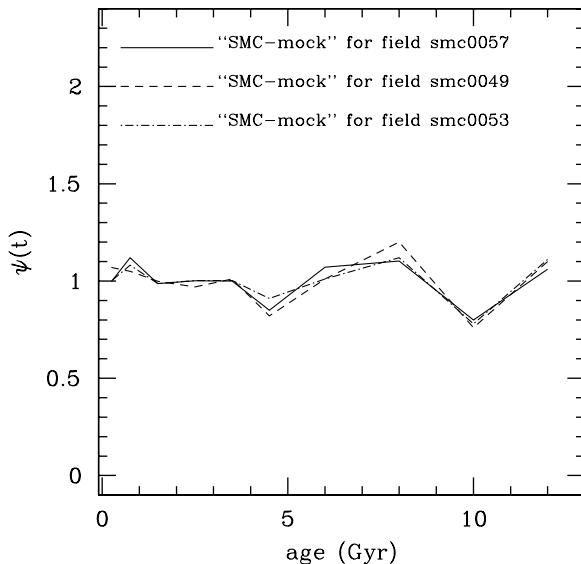


Figure 5. SMC-mock SFHs obtained simulating the observational errors for three SMC fields located at different galactocentric distances: smc0057 (at ~ 1.1 kpc), smc0049 (at ~ 3.3 kpc), and smc0053 (at ~ 4.5 kpc).

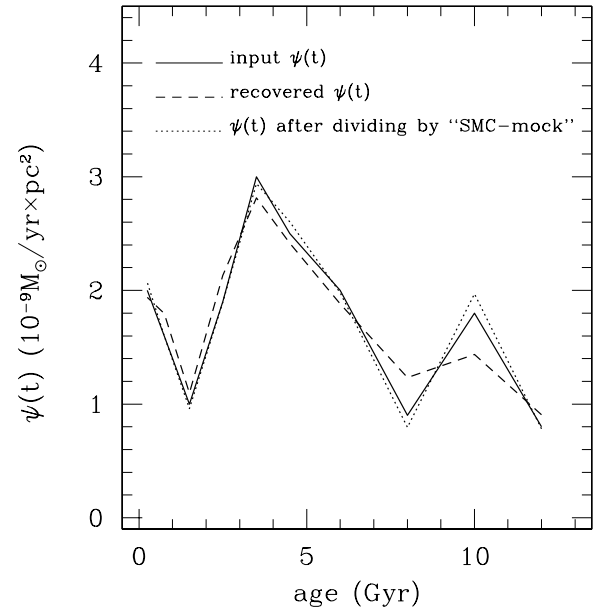
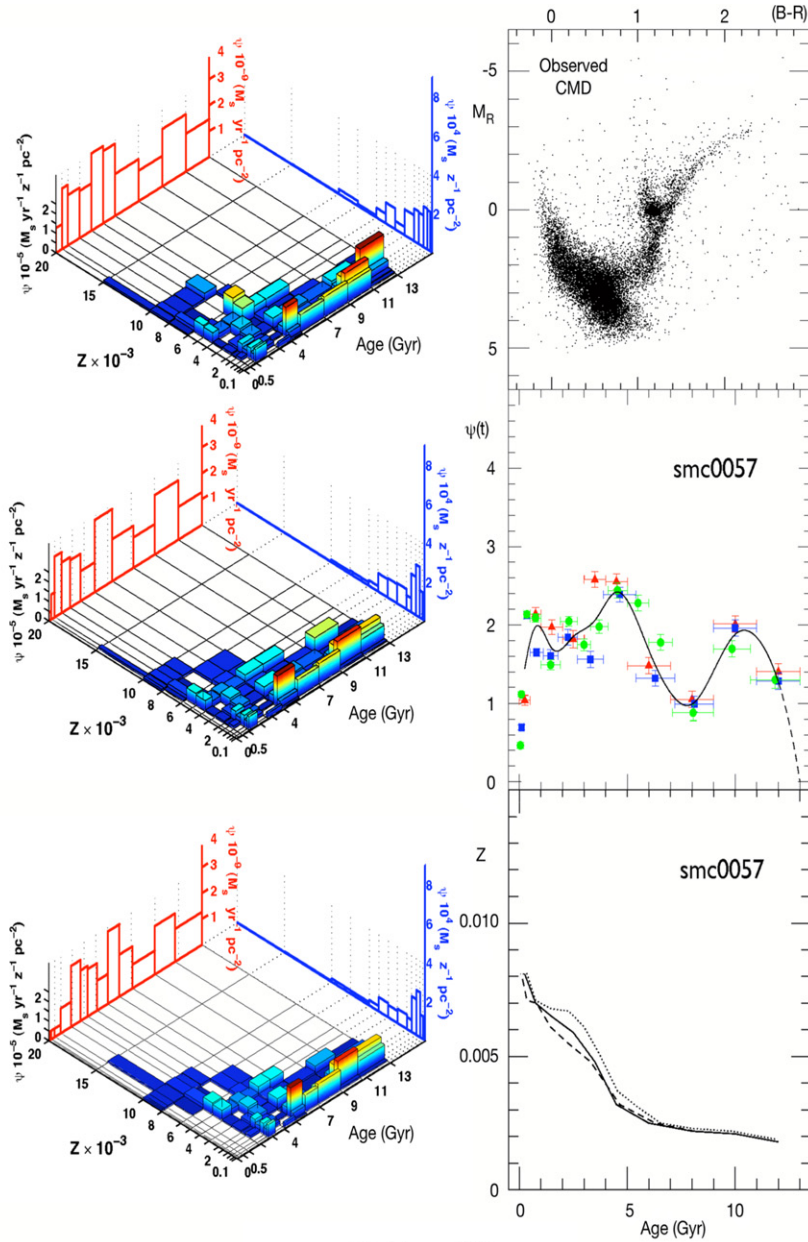


Figure 6. Input, recovered, and solution $\psi(t)$ for a mock galaxy with similar characteristics to the $\psi(t)$ obtained for the SMC fields.

5.1. Main Characteristics of the $\psi(t)$ Solutions for Our SMC Fields

As seen from Figure 8, the eastern fields and the central-most field, smc0057—located in the south—show significant recent star formation. In particular, the eastern fields show a recent enhancement from ~ 2 Gyr ago until the present, while smc0057 shows a recent peak of star formation ~ 1 Gyr ago, which seems to be mostly extinguished at the present time. This is in agreement with the characteristics derived for the stellar populations in the Magellanic Bridge (Harris 2007) and in other positions in the wing area of the SMC (see, for example, Irwin et al. 1990; McCumber et al. 2005; Chiosi & Vallenari 2007, among others). These $\psi(t)$ enhancements at young ages in the eastern fields and in smc0057 are not seen in other fields located at similar galactocentric distances. The three eastern fields are located in regions of large amount of H I, unlike the rest of our fields, including smc0057.

A conspicuous intermediate-age enhancement has its peak between ~ 4 and ~ 5 Gyr ago in all fields. In addition, there is a small ~ 2 – 2.5 Gyr old enhancement in the southern and western fields. Finally, a $\psi(t)$ enhancement at old ages peaks at ~ 10 Gyr old in the eastern and southern fields, which seems to be “split”



(a) Field smc0057

Figure 7. Solution obtained for field smc0057 is shown as an example of the solutions obtained for all the fields studied. Left panel: three-dimensional representations of the three solutions for the SFH as a function of age and metallicity, $\psi(t, z)$. Right panel: observed CMDs (top), the solutions for the SFH depending on time only, $\psi(t)$ (middle) and corresponding age–metallicity relations (bottom). Each of the individual $\psi(t)$ solutions were corrected from the systematic errors discussed in Section 4.1 and are represented by a different symbol and color: red triangles are for age-1, blue squares are for age-2, and green circles are for age-3. Horizontal tracks are not error bars but show the age interval associated with each point. Vertical error bars shown for $\psi(t)$ have been calculated as the dispersion of 20 solutions with $\chi^2_v = \chi^2_{v,\min} + 1$, where $\chi^2_{v,\min}$ is that of the solution shown in the figure. These error bars are only indicative of the internal precision. A more realistic estimate of the errors is obtained from the dispersion between the solutions for the three age-binning sets. They were combined by fitting a cubic spline, which is adopted as the final solution. Since we have not a constraint on $\psi(t)$ at 13 Gyr old, the end point of our spline fit has been arbitrarily chosen zero. In this way, a good agreement between the integrated SFH under the spline fit and those of the measured SFHs for the three age binning is obtained.

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

into two, at ~ 8 and ~ 12 Gyr old, in the western fields. Note that most of the above features remain unchanged when using the Padua stellar evolution library, as seen in Figure 9.

5.2. Global Bursts and Phase Mixing in the SMC

Phase mixing in a galaxy occurs when stars initially close in space—for example, stars formed in a star-forming region—spread out over time because they have slightly different energies and angular momenta. Stars are said to be fully phase mixed if there is no memory left that they were born close

together. The rate at which stars phase mix depends on the gravitational potential, on the initial proximity of the stars, and on their orbits. As a consequence of the latter, perfectly circular orbits will never mix in radius, while perfectly radial orbits never mix in angle.

The presence of the enhancement at ~ 4 – 5 Gyr old in all the SMC fields, together with the large variations found for ages younger than ~ 1.5 – 2 Gyr old, would suggest that the phase mixing time in the SMC is between ~ 2 and ~ 4 Gyr. However, we also find evidences for spatial variations at older

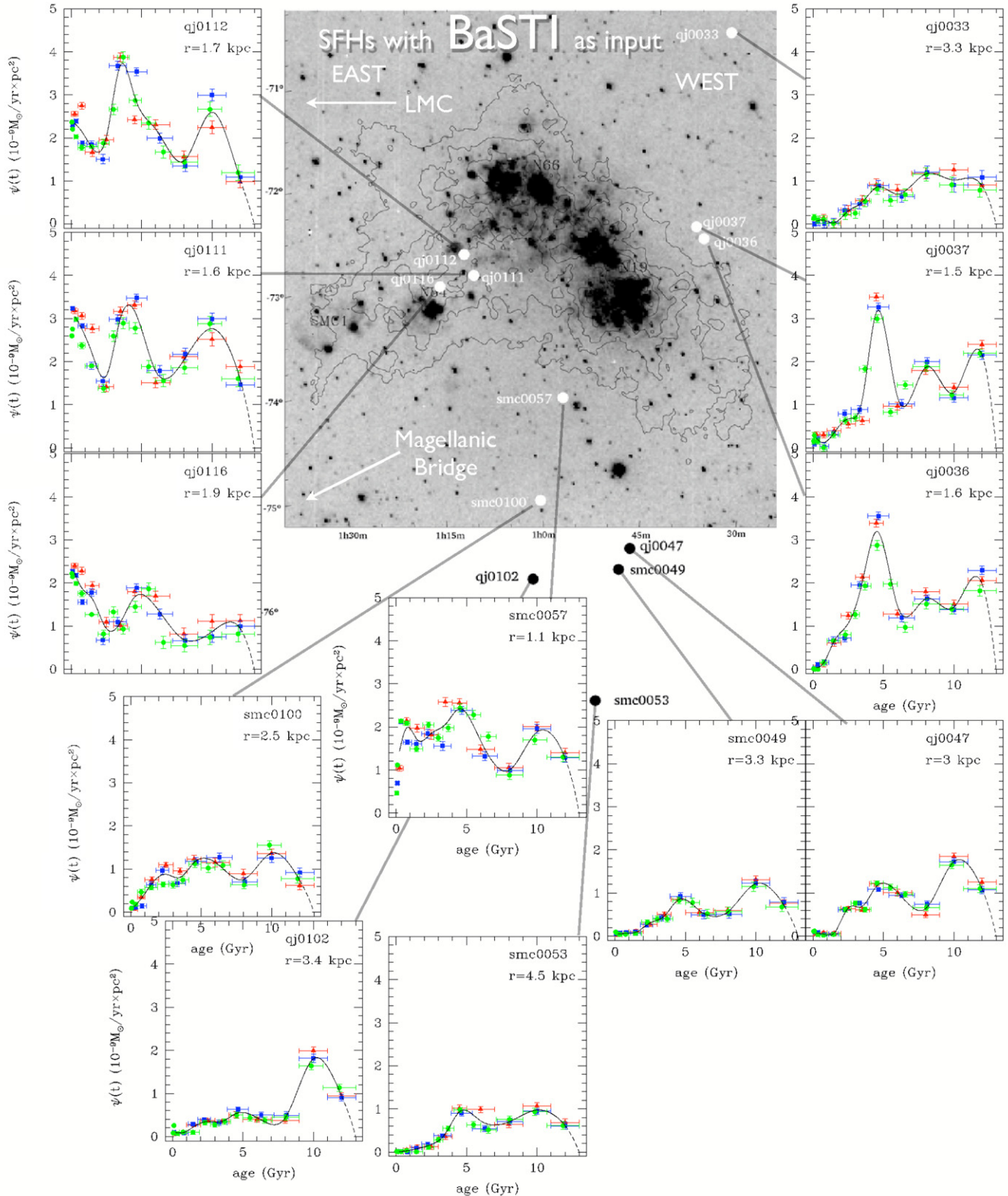


Figure 8. Derived SFHs of our SMC fields. BaSTI stellar evolution library was used as the input of IAC-star. Each solution box shows the same kind of information as Figure 7, right-medium panel. North is top and east is to the left. See the text for details.

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

ages: the western fields present two $\psi(t)$ enhancements at ~ 8 and ~ 12 Gyr old, while in the rest of the fields there is a single old enhancement occurring ~ 10 Gyr ago. This could imply that stars in the SMC take a Hubble time or more to phase

mix. However, solutions are noisier and time resolution is worst for older ages, for which this conclusion must be taken very cautiously until more accurate and precise data, sampling a larger area are available.

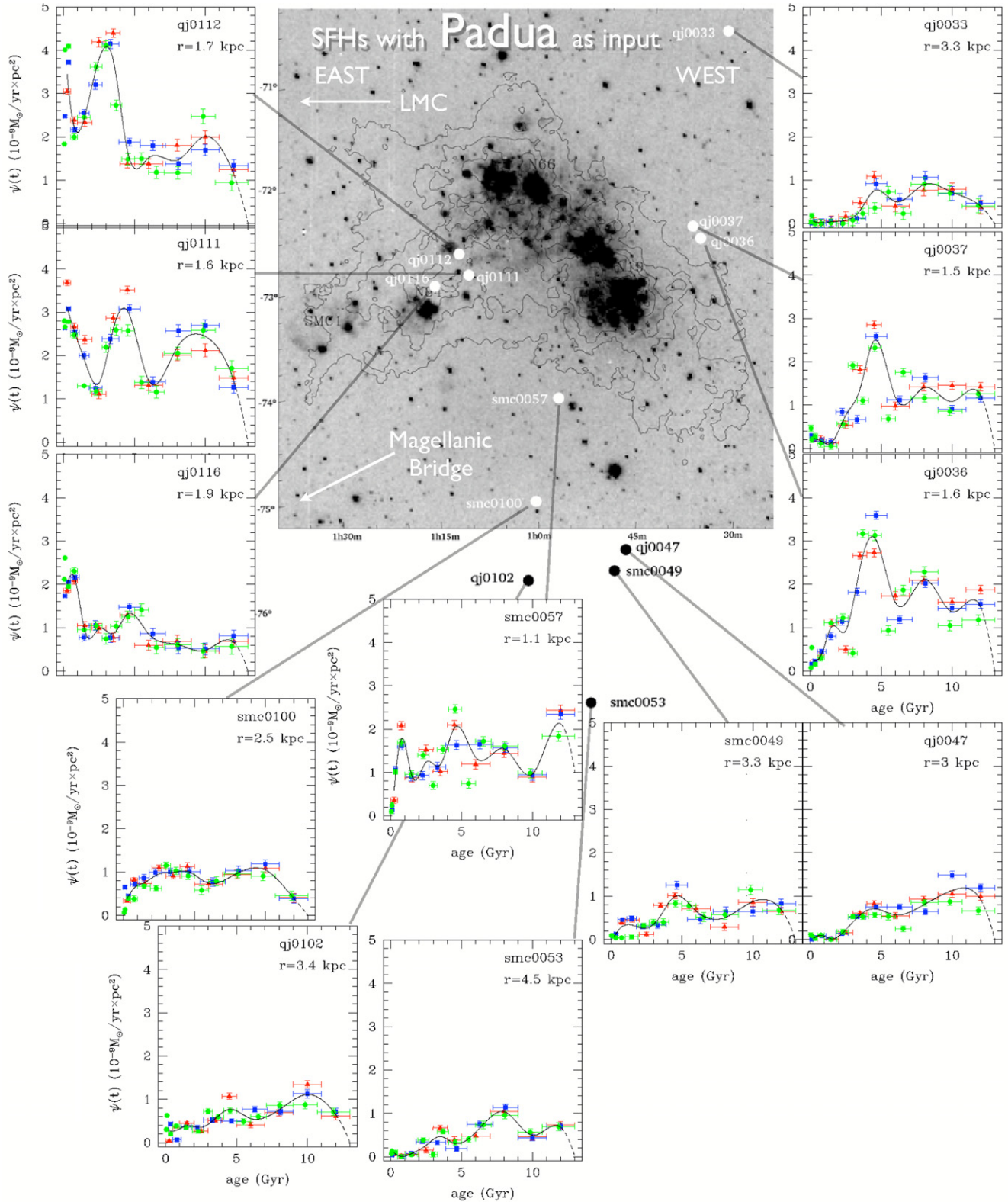


Figure 9. Same as Figure 8 but using Padua stellar evolution library as the input of IAC-star. Note that the main characteristics seen in Figure 8 are impervious to the change of stellar evolution library.

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

5.3. Spatial Distribution of the Stellar Populations in our SMC Fields

One of the most intriguing issues regarding the SMC evolution is the age and distribution of its oldest stars. In order to

shed light into this, we calculated the age at the fifth percentile of $\psi(t)$ in each of our SMC fields. This is the age by which the normalized integral of $\psi(t)$ is 0.05. In other words, it represents the age by which 5% of the total ever born stars were formed in each field and is also indicative of the time at which

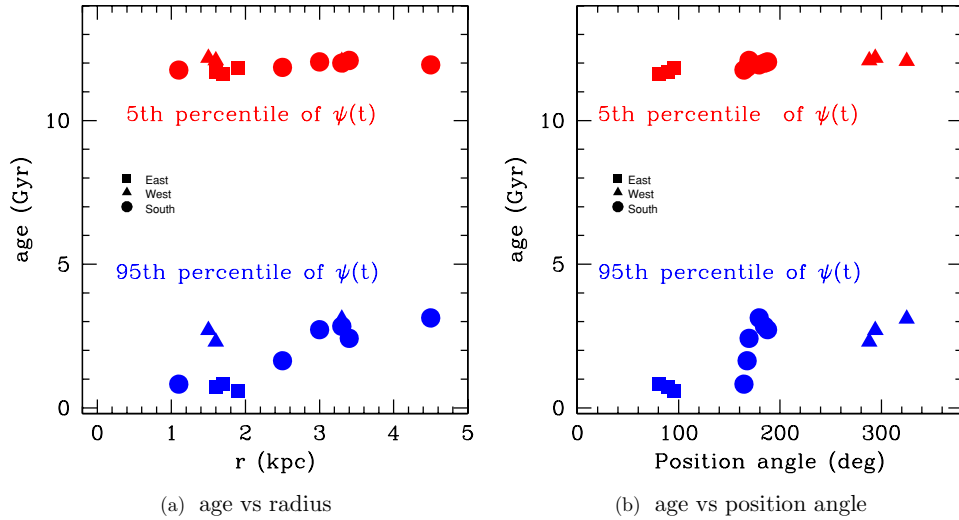


Figure 10. Age at the 5th and at the 95th percentiles of $\psi(t)$ for each of our SMC fields are represented as a function of radius and position angle. See the text for details.

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

the star formation started. It is plotted in Figure 10 and presents a flat distribution at ~ 12 Gyr (slope 0.064 ± 0.015 Gyr kpc^{-1}). This shows that the age of the oldest population in all our SMC fields is essentially the same, independently of the galactocentric distance or the position angle. In addition, we constrain the age of such oldest population to be more than ~ 12 Gyr. This is in agreement with the recent age determination of the oldest globular cluster in the SMC, NGC 121 (Glatt et al. 2008). Our results are also in good agreement with those of Dolphin et al. (2001) who, for an isolated field located in the northwestern part of the SMC, found that $14\% \pm 5\%$ of the star formation took place before 11 Gyr ago.

Another important—and controversial—fact regarding Local Group dwarf galaxies in general and the SMC in particular, is the composition of the outer extended stellar populations and if these galaxies hold a true, old, Milky-Way-like stellar halo (see Aparicio & Hidalgo 2009; Stinson et al. 2009). To study this, the age of the 95th percentile of $\psi(t)$ for all the SMC fields studied is helpful. It is representative—and an upper limit—of the age of the youngest stellar population. It is plotted in Figure 10 and shows a smooth slope as a function of the galactocentric radius and a clear step at position angle $\sim 190^\circ$, the latter indicating an east–west dichotomy. The behavior of the 95th percentile age as a function of the galactocentric distance, including the fact that it is ~ 3 Gyr at ~ 4 – 5 kpc from the SMC center, points out that, at such distance, we did not yet reach a region dominated by a true, old, Milky-Way-like, stellar halo, since in such halo-dominated region, the 95th percentile and the 5th percentile ages should be similar. Our results are in agreement with Noël & Gallart (2007) who found that up to ~ 6.5 kpc from the SMC center, the galaxy is composed by both, intermediate-age and old population. In summary, our results indicate that either a true, old, Milky-Way-like, stellar halo does not exist in the SMC or that, if it exists, its contribution to the stellar population is negligible at ~ 4.5 kpc from the galactic center.

5.4. On the Possible Correlation Between the $\psi(t)$ Enhancements and the SMC–LMC/SMC–MW Pericenter Passages

In the pioneering work from Murai & Fujimoto (1980), the authors claimed that the existence of the Magellanic Bridge

and the inter-Clouds region are partly explained if the SMC closely approached the LMC around 0.2 Gyr ago. Since then, the orbits of the MCs were studied in detail by many authors, through numerical simulations and proper motion studies (see Gardiner et al. 1994; Bekki & Chiba 2005; Kallivayalil et al. 2006; Besla et al. 2007, among others). All models reproduce a pericenter passage between the MCs around ~ 0.2 Gyr ago. Coincidentally, enhancements of star formation are found at these ages in both galaxies, particularly in the area in which they are facing each other, i.e., the eastern, wing area in the SMC and the west part in the LMC (see, for example, Irwin et al. 1990). Given the low temporal sampling of our SMC SFHs for the youngest ages, we cannot probe if the dichotomy east/southeast–west actually began ~ 0.2 Gyr ago. However, the steep behavior of the $\psi(t)$ 95th percentile age shown in Figure 10 indicates that the dichotomy appeared at an age smaller than ~ 1 Gyr ago. This population younger than 1 Gyr old represents $\sim 7\%$ – 12% of the total $\psi(t)$ in the wing area. This does not reflect an exceptional increment in the present star formation as compared with the average $\psi(t)$ but it is very significant in the sense that these eastern fields are the only ones in which star formation is currently going on.

Besides this youngest episode, authors such as Bekki et al. (2004), Bekki & Chiba (2005), and Harris & Zaritsky (2004) have claimed that the episodes of enhancement in the SFR along the SMC life could be related with earlier pericenter passages between the SMC and the LMC and/or between the SMC and the Milky Way, while Besla et al. (2007) have concluded that the MCs are likely to be in their first pericenter passage about the Milky Way or on a highly eccentric, bound orbit. To explore this, the $\psi(t)$ enhancements in our SFHs are quantified in Figure 11, in which the intensity of each $\psi(t)$ enhancement as a function of radius (panel a), position angle (panel b), and age for all the fields are represented, together with the pericenter passages of the SMC with respect to the Milky Way or the LMC, as predicted by different authors. The intensity of each $\psi(t)$ enhancement is defined as the area under a Gaussian function fitted to the elevation in the spline fit shown in Figure 8.

Although unclear, there may be a correlation between the SMC–Milky Way encounters given by Kallivayalil et al. (2006) (solid arrows) and the enhancements in $\psi(t)$ we found at ~ 2.5 Gyr ago, ~ 4.75 Gyr ago, and ~ 8 Gyr ago. In the

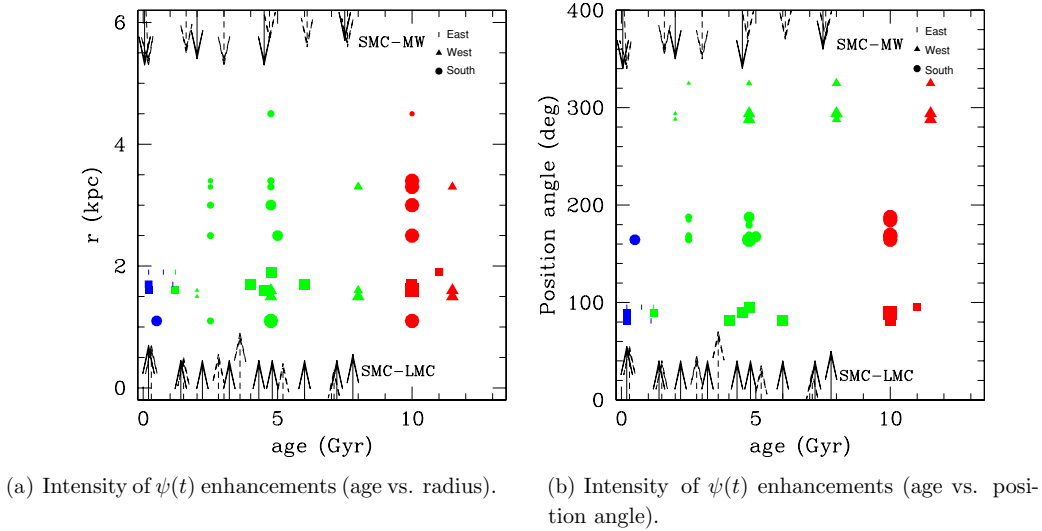


Figure 11. Intensity of the $\psi(t)$ enhancements together with pericenter passages of the SMC. The size of the symbols depends on the intensity of the enhancement, obtained as the integral of a Gaussian fitted to the elevations in Figure 8. The bottom arrows indicate the pericenter passages with the LMC, while the top arrows show the encounters with the Milky Way. Solid-lined arrows represent data from Kallivayalil et al. (2006), and dashed-lined ones are data obtained from Bekki & Chiba (2005). The size of the arrows represents the intensity of the encounter. Note that some enhancements are hidden behind larger ones. See the text for details.

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

case of pericenter passages between the LMC and the SMC, there only seems to be a coincidence between the most recent encounter ~ 0.2 Gyr ago and the youngest $\psi(t)$ enhancement peaked at these ages in our eastern fields. In the other cases, for the published orbits, we see no clear correlation between the pericenter passages and the observed enhancements in our derived SFHs. All in all, the lack of a clear correlation between computed passages and SFH could be a support to Besla et al. (2007) results including that indicating that the SMC is in its first pericenter passage about the Milky Way.

5.5. Comparison with Other Works

Since our eastern and western fields, as well as two of our southern ones, overlap the regions from Harris & Zaritsky (2004), we superimposed our SFHs with the ones they obtained as seen in Figure 12. In each case, the SFHs found by Harris & Zaritsky (2004) are shown as dashed lines. Harris & Zaritsky (2004) used the starFISH code with the following inputs: a subset of the Padua isochrones for three different metallicities ($Z = 0.001$, $Z = 0.004$, $Z = 0.008$) without interpolation, a power law with Salpeter slope for the IMF, and a 50% binary fraction with secondary masses drawn randomly from the IMF. We averaged the SFR from Harris & Zaritsky (2004) in the last 0.2 Gyr into only one age bin to fit the age resolution we adopted for the youngest population. We also added up the SFR given by Harris & Zaritsky (2004) for each of their three metallicities. Harris & Zaritsky (2004) cover a larger area in the region of our western fields qj0036 and qj0037, so the solution they give includes both of our fields. We compare the Harris & Zaritsky (2004) solution with ours obtained using the Padua stellar evolution library. With the exception of field qj0033, there is a general disagreement at intermediate ages in all fields, for which Harris & Zaritsky (2004) find either total or quasi-total quiescence during a time interval of ~ 2 Gyr at ages in which we find significant star formation. In the western fields, Harris & Zaritsky (2004) find a peak at around 4.5 Gyr ago which is coincident with the one we find.

In order to understand the disagreement between our SFHs and the ones obtained by Harris & Zaritsky (2004), it should

be noted that their photometry is shallower and, therefore, the ability to reliably constrain the intermediate-age to old star formation is reduced. Also, their method to derive the SFH is coarser than the one used in this paper; for example, no interpolation in metallicity is performed and so the simple populations are restricted to the metallicities provided in the stellar evolution set.

Our SFH solutions for the western fields agree quite well with the SFH presented by Dolphin et al. (2001) (using Girardi et al. 2000 models) for a northwestern field located near NGC 121. They find a broadly peaked star formation between 5 and 8 Gyr ago and that the star formation almost stopped around 2 Gyr ago.

The $\psi(t)$ enhancement peaked at ~ 4 –5 Gyr old is in good agreement with the episodes found by Chiosi & Vallenari (2007) between 3 and 6 Gyr ago for three fields located around the SMC clusters K 29, NGC 290, and NGC 265.

Finally, estimates by Sabbi et al. (2009) are broadly consistent with our results, although we have to wait for the results of the detailed, quantitative analysis of the SFH that these authors are carrying on.

5.6. The Chemical Enrichment History

In the computation of the SFH, IAC-pop also provides the age–metallicity relation, which is plotted in the horizontal planes of Figure 7, left panel. To more clearly show this metallicity law, we determined the average metallicity of stars formed at each age interval, using the following relation (see Section 3):

$$Z(t) = \frac{\sum z_i \psi_i(t)}{\sum \psi_i(t)}. \quad (3)$$

We adopted $Z_{\odot} = 0.02$ and assumed $[\text{Fe}/\text{H}] = \log(Z/Z_{\odot})$ in order to convert from Z metallicities to $[\text{Fe}/\text{H}]$ values. The age–metallicity relations computed in this way for the eastern, western, and southern fields are shown in Figure 13 together with the age–metallicity relation found by Carrera et al. (2008a) (see their Table 6) using Ca II triplet spectroscopy of RGB stars from the same fields. The $\pm 1\sigma$ dispersion of the stellar

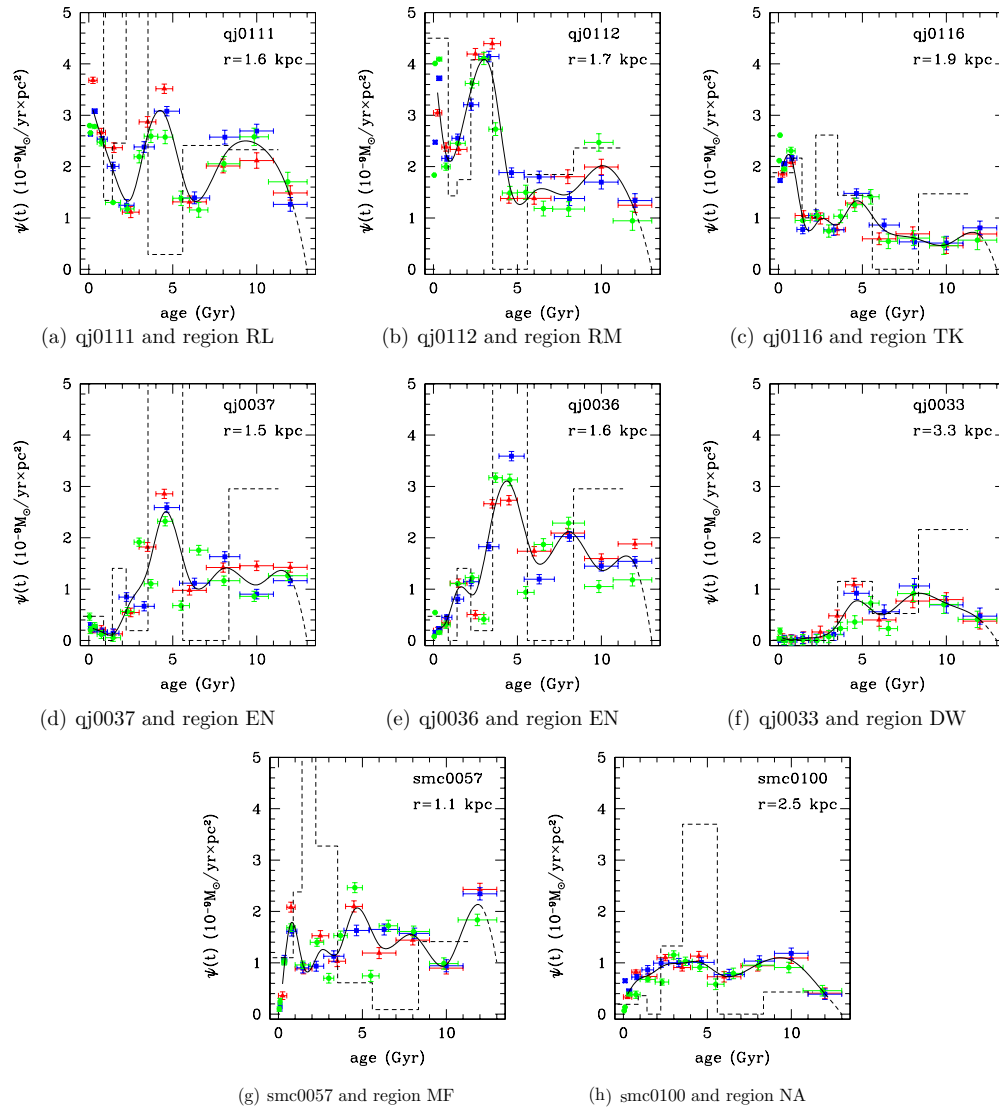


Figure 12. Comparison of the SFHs obtained in this work using the Padua stellar evolution library as input in IAC-star (see Figure 9) and the ones obtained by Harris & Zaritsky (2004; dashed lines) for the overlapping fields. See the text for details.

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

metallicity distribution as a function of age as derived in this paper, and the metallicity dispersion of the CaT metallicities in each age bin, from Carrera et al. (2008a) have also been represented.

The age–metallicity relations in all regions show a continuously increasing metallicity from an early epoch until now. For the southern fields, there is an excellent agreement with the findings of Carrera et al. (2008a). The agreement is also good in the case of the eastern and western fields, with small differences for ages older than 5 Gyr, for which we find a lower metallicity in the west and a higher metallicity in the east than those of Carrera et al. (2008a) but still within the dispersion intervals. These results, taken together, are an important test of IAC-pop because they show, for the first time, the external consistency of the code in determining the chemical enrichment law.

Tsujimoto & Bekki (2009) claim that a dip is detected in the [Fe/H]–age relation in the SMC and that would be related with a major merging event occurred some 7.5 Gyr ago. We have to mention that such dipping is not visible in the age–metallicity relations derived in our analysis.

6. DISCUSSION AND CONCLUSIONS

We have presented a detailed study of the SFH of 12 fields located in the SMC, based on a set of $[(B - R), R]$ CMDs that reach the oldest MS turnoffs ($M_R \sim 3.5$). The spatial distribution of the fields, located at different galactocentric distances and azimuths, makes it possible to distinguish the stellar content in the wing area and in the “undisturbed” parts toward the western and southern regions of the SMC (see Figure 1), and to study possible stellar population variations with galactocentric radius. We used the IAC-star and IAC-pop codes to obtain the SFH, $\psi(t, z)$. The results of this analysis allow us to accurately constrain the parameter space defining the SFHs of the 12 SMC fields. The fact that the main characteristics of $\psi(t, z)$ are unchanged for different combinations of parameters, including different stellar evolution libraries, indicates that our solutions for the SFHs are robust. In addition, common patterns, which vary smoothly with position, appear in most fields. As final inputs for IAC-star/IAC-pop, we used the BaSTI (Pietrinferni et al. 2004) and Padua (Bertelli et al. 1994) stellar evolution

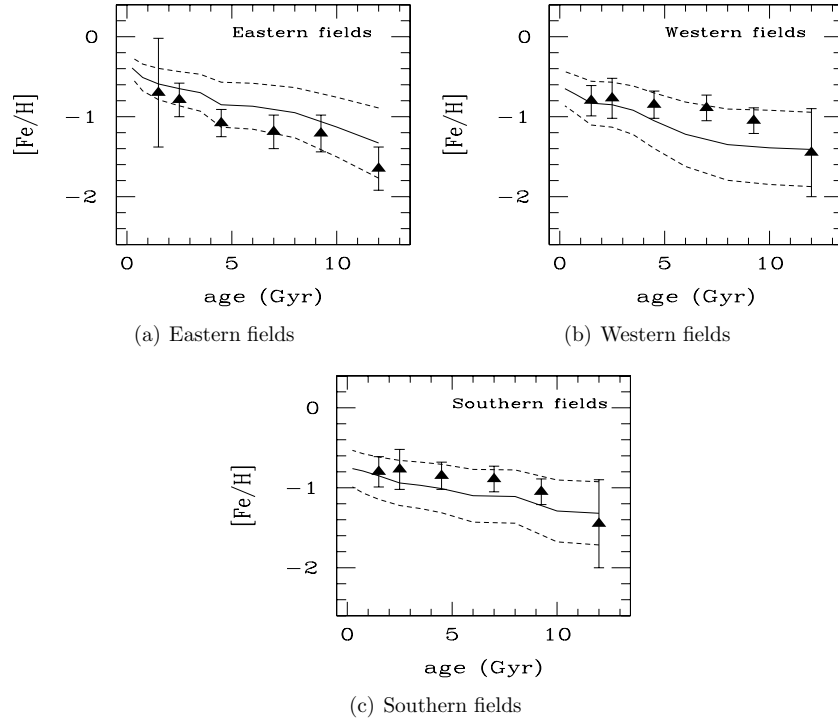


Figure 13. Averaged age–metallicity relations ($[\text{Fe}/\text{H}]$ as a function of age) for the eastern, western, and southern fields are shown with a solid line. The dotted lines represent the $\pm 1\sigma$ interval of the stellar metallicity distribution. The triangles represent the age–metallicity relations found by Carrera et al. (2008a, see their Table 6).

libraries, the bolometric corrections from Castelli & Kurucz (2004), the Kroupa’s revised IMF (Kroupa et al. 2003), and 30% of binaries with a mass ratio $q \gtrsim 0.7$. All the $\psi(t, z)$ solutions have $\chi^2_{v, \min} < 2$.

In the retrieved SFHs of our SMC fields, we found the following. There are four main episodes of enhancement in $\psi(t)$: one at young ages, only present in the eastern fields (the ones facing the LMC) and in the central-most one (located in the south), peaked at ~ 0.2 – 0.5 Gyr ago; two at intermediate ages, a conspicuous one peaked at ~ 4 – 5 Gyr old in all fields and a less significant one peaked at ~ 1.5 – 2.5 Gyr old in all fields; and one at old ages, with the peak at ~ 10 Gyr old in all but the western fields, in which this old enhancement is split into two at ~ 8 Gyr old and at ~ 12 Gyr old. There are smaller enhancements and variations from field to field that are less significant.

The fact that all fields present a $\psi(t)$ enhancement at ~ 4 – 5 Gyr old could mean that, at this age, there was a global episode of star formation in the SMC. Alternatively, this episode could have been produced in a particular region of the SMC and then the stars could have spread all over the galaxy. This, together with the large variations for ages younger than ~ 1.5 – 2 Gyr old, may suggest that the phase mixing time in the SMC is of the order of such ~ 2 – 4 Gyr. However, we also find evidence for variations at old ages, since the $\psi(t)$ enhancement at 10 Gyr old in the east and in the south seems split in two at ~ 8 and ~ 12 Gyr old in the western fields. If these differences at old ages are robust features, they could imply that stars in the SMC take a Hubble time or more to phase mix. However, this result needs further observational confirmation to be accepted. In particular, it will be interesting to determine the SFHs over larger areas at different azimuths in order to confirm or reject the existence of this “two-enhancements zone” and to constrain its spatial limits.

The eastern fields are located in a region of high H I concentration (see Figure 8). We found that the young population present in this wing area in the last 1 Gyr represents between

$\sim 7\%$ and 12% of the total stars found in it. This indicates that, although the young population does not reflect an exceptional increase of the star formation at the present time with respect to the average $\psi(t)$, this increase is important in global terms since this wing area is the only part of our study in which there is active and conspicuous star formation presently going on.⁹

The young $\psi(t)$ enhancement may have been triggered by a close encounter between the SMC and the LMC at these ages, as indicated by studies of the MC orbits, both from numerical simulations and proper motions (Murai & Fujimoto 1980; Gardiner et al. 1994; Bekki & Chiba 2005; Kallivayalil et al. 2006; Besla et al. 2007 among others). Given the low temporal sampling of our SMC SFHs for youngest ages, we cannot probe if the dichotomy east/southeast–west actually began ~ 0.2 Gyr ago. However, the step behavior of the $\psi(t)$ 95th percentile age shown in Figure 10 indicates that the dichotomy appeared at an age smaller than ~ 1 Gyr ago.

A correlation may exist between past $\psi(t)$ enhancements and the perigalactic encounters between the SMC and the Milky Way for the orbits given by Kallivayalil et al. (2006). But this correlation is unclear and there is nothing against the MCs are in their first perigalactic passage, as claimed by Besla et al. (2007). On another side, with the exception of the young $\psi(t)$ enhancement in the eastern fields, we do not find any clear correlation between $\psi(t)$ enhancements and the pericenter passages between the SMC and the LMC as computed by Bekki & Chiba (2005) and Kallivayalil et al. (2006).

The flat distribution at ~ 12 Gyr old of the age at the 5th percentile of $\psi(t)$ indicates that the age of the oldest population is remarkably similar in all fields at all radii and at all azimuths and constrains the age of the oldest stars in our SMC fields to be more than 12 Gyr. This is also seen in other Local Group

⁹ It is worth reminding that the highest current star formation activity is in the central, bar region of the galaxy, not studied here, where several, strong H II regions are located.

galaxies, such as Phoenix, a smaller and non-interacting galaxy (see Hidalgo et al. 2009).

We did not reach a region dominated by an old, Milky-Way-like, stellar halo at 4.5 kpc from the SMC center. This indicates that either such true, old, stellar halo does not exist in the SMC or that if it exists, its contribution to the stellar population is negligible at ~ 4.5 kpc. These results are in agreement with Noël & Gallart (2007) who found no signs of a predominantly old stellar component at ~ 6.5 kpc from the SMC center.

Finally, from our SFH solutions, we also retrieved a chemical enrichment history for our SMC fields. On average, all fields show a continuously increasing chemical enrichment from an early epoch until now. Our derived age–metallicity relations are in good agreement with the findings of Carrera et al. (2008a) using the Ca II triplet. This is an external consistency proof of IAC-pop in determining the chemical enrichment law.

We are very grateful to Mike Beasley, Ricardo Carrera, Santi Cassisi, Gary Da Costa, Ken Freeman, and Matteo Monelli for interesting comments and illuminating discussions. We also thank Justin I. Read for many very useful comments and discussions which improved this manuscript in its early stages. This work has been founded by the Instituto de Astrofísica de Canarias (P3-94) and by the Ministry of Education and Research of the Kingdom of Spain (AYA2004-06343 and AYA2007-67913). E.C. and R.A.M. acknowledge support by the Fondo Nacional de Investigación Científica y Tecnológica (No. 1050718, Fondecyt) and by the Chilean Centro de Astrofísica FONDAP (No. 15010003). This project has made generous use of the 10% Chilean time, and continuous support from the CNTAC and Las Campanas staff is greatly appreciated. N.E.D.N. acknowledges the hospitality of the astrophysics group at Zürich University.

REFERENCES

- Aparicio, A., & Gallart, C. 1995, *AJ*, **110**, 2105
Aparicio, A., & Gallart, C. 2004, *AJ*, **128**, 1465
Aparicio, A., & Hidalgo, S. L. 2009, *AJ*, **138**, 558
Bekki, K., & Chiba, M. 2005, *ApJ*, **625**, L107
Bekki, K., Couch, W. J., Beasley, M. A., Forbes, D. A., Chiba, M., & Da Costa, G. S. 2004, *ApJ*, **610**, L93
Bertelli, G., Bressan, A., Chiosi, C., Fagotto, F., & Nasi, E. 1994, *A&AS*, **106**, 275
Besla, G., Kallivayalil, N., Hernquist, L., Robertson, B., Cox, T. J., van der Marel, R., & Alcock, C. 2007, *ApJ*, **668**, 949
Bica, E., Bonatto, C., Dutra, C. M., & Santos, J. F. C., Jr. 2008, *MNRAS*, **389**, 678
Carrera, R., Gallart, C., Aparicio, A., Costa, E., Méndez, R. A., & Noël, N. E. D. 2008a, *AJ*, **136**, 1039
Carrera, R., Gallart, C., Hardy, E., Aparicio, A., & Zinn, R. 2008b, *AJ*, **135**, 836
Carretta, E., Gratton, R. G., Clementini, G., & Fusi Pecci, F. 2000, *ApJ*, **533**, 215
Castelli, F., & Kurucz, R. L. 2004, in IAU Symp. 210, *Modelling of Stellar Atmospheres*, ed. N. Pistukov et al. (Dordrecht: Kluwer), 20
Chiosi, E., & Vallenari, A. 2007, *A&A*, **466**, 165
Chiosi, E., Vallenari, A., Held, E. V., Rizzi, L., & Moretti, A. 2006, *A&A*, **452**, 179
Cioni, M.-R. L., Girardi, L., Marigo, P., & Habing, H. J. 2006, *A&A*, **452**, 195
Cordier, D., Pietrinferni, A., Cassisi, S., & Salaris, M. 2007, *AJ*, **133**, 468
Costa, E., Méndez, R., Pedreros, M., Moyano, M., Gallart, C., Noël, N., Baume, G., & Carraro, G. 2009, *AJ*, **137**, 4339
de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. G., Buta, R. J., Paturel, G., & Fouque, P. 1991, *Third Reference Catalogue of Bright Galaxies* (Berlin: Springer)
Dolphin, A. E., Walker, A. R., Hodge, P. W., Mateo, M., Olszewski, E. W., Schommer, R. A., & Suntzeff, N. B. 2001, *ApJ*, **562**, 303
Dufour, R. J. 1975, *ApJ*, **195**, 315
Dufour, R. J. 1984, in IAU Symp. 108, *Structure and Evolution of the Magellanic Clouds*, ed. S. van den Bergh & K. S. de Boer (Dordrecht: Reidel), 353
Dufour, R. J., & Harlow, W. V. 1977, *ApJ*, **216**, 706
Gallart, C., Freedman, W. L., Aparicio, A., & Bertelli, G. 1999, *AJ*, **118**, 2245
Gallart, C., Zoccali, M., & Aparicio, A. 2005, *ARA&A*, **43**, 10
Gardiner, L. T., & Hatzidimitriou, D. 1992, *MNRAS*, **257**, 195
Gardiner, L. T., Sawa, T., & Fujimoto, M. 1994, *MNRAS*, **266**, 567
Girardi, L., Bressan, A., Bertelli, G., & Chiosi, C. 2000, *A&AS*, **141**, 371
Glatt, K., et al. 2008, *AJ*, **135**, 1106
Harris, J. 2007, *ApJ*, **658**, 345
Harris, J., & Zaritsky, D. 2001, *ApJS*, **136**, 25
Harris, J., & Zaritsky, D. 2004, *AJ*, **127**, 1531
Harris, J., & Zaritsky, D. 2006, *AJ*, **131**, 2514
Hidalgo, S. L., Aparicio, A., Martínez-Delgado, D., & Gallart, C. 2009, *ApJ*, **705**, 704
Hilditch, R. W., Howarth, I. D., & Harries, T. J. 2005, *MNRAS*, **357**, 304
Hodge, P. 1989, *ARA&A*, **27**, 139
Irwin, M. J., Demers, S., & Kunkel, W. E. 1990, *AJ*, **99**, 191
Kallivayalil, N., van der Marel, R. P., & Alcock, C. 2006, *ApJ*, **652**, 1213
Keller, S. C., & Wood, P. R. 2006, *ApJ*, **642**, 834
Kleyna, J. T., Wilkinson, M. I., Evans, N. W., & Gilmore, G. 2001, *ApJ*, **563**, L115
Kroupa, P., Bouvier, J., Duchne, G., & Moraux, E. 2003, *MNRAS*, **346**, 354
Marín-Franch, A., et al. 2009, *ApJ*, **694**, 1498
Massey, P. 2002, *ApJS*, **141**, 81
McCumber, M. P., Garnett, D. R., & Dufour, R. J. 2005, *AJ*, **130**, 1083
Mighell, K. J. 1999, *ApJ*, **518**, 380
Murai, T., & Fujimoto, M. 1980, *PASJ*, **32**, 581
Noël, N. E. D., & Gallart, C. 2007, *ApJ*, **665**, L23
Noël, N. E. D., Gallart, C., Costa, E., & Méndez, R. A. 2007, *AJ*, **133**, 2037 (Paper I)
Peimbert, M., Peimbert, A., & Ruiz, M. T. 2000, *ApJ*, **541**, 688
Peimbert, M., & Torres-Peimbert, S. 1976, *ApJ*, **203**, 581
Piatek, S., Pryor, C., & Olszewski, E. W. 2008, *AJ*, **135**, 1024
Piatti, A. E., Geisler, D., Sarajedini, A., Gallart, C., & Wischnjewsky, M. 2008, *MNRAS*, **389**, 429
Pietrinferni, A., Cassisi, S., Salaris, M., & Castelli, F. 2004, *ApJ*, **612**, 168
Pietrinferni, A., Cassisi, S., Salaris, M., & Castelli, F. 2006, *ApJ*, **642**, 797
Rafelski, M., & Zaritsky, D. 2005, *AJ*, **129**, 2701
Sabbie, E., et al. 2009, *ApJ*, **703**, 721
Spergel, D. N., et al. 2003, *ApJS*, **148**, 175
Stanimirović, S., Staveley-Smith, L., Dickey, J. M., Sault, R. J., & Snowden, S. L. 1999, *MNRAS*, **302**, 417
Stetson, P. B. 1994, *PASP*, **106**, 250
Stinson, G. S., Dalcanton, J. J., Quinn, T., Gogarten, S. M., Kaufmann, T., & Wadley, J. 2009, *MNRAS*, **395**, 1455
Storm, J., Carney, B. W., Gieren, W. P., Fouqué, P., Latham, D. W., & Fry, A. M. 2004, *A&A*, **415**, 531
Tsujimoto, T., & Bekki, K. 2009, *ApJ*, **700**, L69
Walker, M. G., Mateo, M., Olszewski, E. W., Pal, J. K., Sen, B., & Woodroffe, M. 2006, *ApJ*, **642**, L41
Westerlund, B. E. 1997, *The Magellanic Clouds* (Cambridge: Cambridge Univ. Press)
Wilke, K., Klaas, U., Lemke, D., Mattila, K., Stickel, M., & Haas, M. 2004, *A&A*, **414**, 69