The Ages of Stars
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The star formation history of the Magellanic Clouds

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Abstract. The star formation history of the Magellanic Clouds, including the old and intermediate-age star formation events, can be studied reliably and in detail through color-magnitude diagrams reaching the oldest main sequence turnoffs. This paper reviews our current understanding of the Magellanic Clouds' star formation histories and discusses the impact of this information on general studies of galaxy formation and evolution.

Keywords. galaxies: formation and evolution; galaxies: individual (LMC, SMC); Magellanic Clouds

1. Introduction

The Magellanic Clouds (MCs) are close enough for the oldest main sequence turnoffs (MSTO) in the color-magnitude diagram (CMD)s of their resolved stars to be easily reachable from the ground, or using the HST in the case of the most crowded fields. This allows us to obtain accurate and detailed determinations of their spatially resolved star formation histories (SFH) which, in turn, will provide important information about some important aspects of galaxy formation and evolution. For example:

(i) The MCs are intermediate in size between the large spirals such as M31 or the Milky Way, and dwarf galaxies. In addition, they may have originated independently of the Milky Way system (D'Onghia & Lake 2008; Besla *et al.* 2007). Therefore, they can offer insight into the important question: does the onset of star formation in a galaxy depend on galaxy mass, type or environment?

(ii) The MCs appear to be an interacting system, both with each other and with the Milky Way. The combination of their detailed SFHs with knowledge of their past orbits can provide key information on how interactions affect the SFH of a galaxy.

(iii) Stellar clusters are often used as a proxy for the SFH of a galaxy. The MCs, where very accurate cluster ages and the field SFH can be obtained, are ideal places to test this common assumption.

(iv) Stellar population gradients are often inferred from the integrated light of distant galaxies, but their nature is difficult to ascertain (e.g. Taylor *et al.* 2005). The stellar population gradients in the MCs (e.g. Gallart *et al.* 2008) can be understood once the SFH is determined in representative portions of each galaxy, and this can provide insight into the nature of population gradients in galaxies in general.

The determination of accurate SFHs in representative portions of both MCs is necessary to properly approach the above issues. However, the amount of information published so far is actually quite limited, particularly as compared with that available about other aspects of the MCs. The huge size in the sky of both galaxies and the relatively (in comparison) small field of view of current optical detectors have certainly played a role in this situation. Most published MC CMDs reaching the oldest MSTO have been obtained using the WFPC2 or the ACS on board the HST, which implies a tiny field of view. In very crowded areas, the use of the HST is mandatory, but for less crowded regions excellent CMDs, comparable to the HST ones, can be obtained from the ground using 2–4m class telescopes (e.g. Gallart *et al.* 2008; Noël *et al.* 2007; see Figure 1). This produces well populated CMDs which allow us to overcome small number statistics problems at all ages. In this paper, we will review the existing literature on the SFH of the MCs, and present some ongoing work by our group on the same matter. We will preferentially discuss SFH determinations based on CMDs reaching the oldest MSTOs.

2. The LMC

2.1. *The cluster formation history*

Deep CMDs obtained with the WFPC2 confirmed the true old nature of a sample of candidate old clusters in the LMC (Olsen *et al.* 1998; Johnson *et al.* 1999; see also: Brocato *et al.* 1996 for earlier, high quality ground based CMDs of some of these clusters; Mackey & Gilmore 2004 for ACS data of three more additional old clusters). These works concluded that clusters as old as the old Milky Way globulars exist in the LMC, and that the age spread among them is actually very small. In contrast with the Milky Way, a type of populous young and intermediate-age clusters exists in the LMC in large numbers (Da Costa 1991), but careful searches have found only one cluster (ESO 121-SC03; Mackey *et al.* 2006) in the so-called LMC "age gap" (Geisler *et al.* 1997), which extends from $\simeq$ 4 to 13 Gyr ago.

2.2. *The field star formation history*

The published LMC field SFHs obtained from CMDs reaching the oldest MSTO are based on WFPC2 observations. In the case of bar fields, the CMDs are relatively well populated (e.g. Holtzman *et al.* 1999; Olsen 1999; Smecker-Hane *et al.* 2002), and yield relatively consistent SFHs, with star formation rate depressed from $\simeq$ 10 to 6 Gyr ago and somewhat increased or bursty in the last couple Gyr. Due to the small field of view, the WFPC2 disk CMDs are very sparsely populated (Holtzman *et al.* 1999; Javiel *et al.* 2005; Smecker-Hane *et al.* 2002 tried to overcome this problem by mosaicking 10 WFPC2 fields in a disk field located $\simeq 1.7^\circ$ southwest of the LMC center). While the corresponding SFHs present field-to-field variations, particularly at the young side, the general trend is, in contrast to the cluster age distribution, a relatively flat star formation rate as a function of time, with mild enhancements in the last few Gyr, but star formation not always continuing to the present time. While the scatter in the field SFH results could be related to small number statistics in the CMDs, the variations at young ages may be related to an actual gradient in the stellar populations present across the LMC disk, as discussed in Gallart *et al.* (2008).

We have undertaken a major project aimed at deriving the SFH of the LMC and its gradients using CMDs obtained with ground-based wide field imagers such as MOSAIC II at the CTIO 4m and WFI at the ESO 2.2 m. These CMDs are well populated and reach the oldest MSTO with good photometric precision. In this paper, we will discuss results for four fields located from 2.3° to 7.1° from the LMC center.

Figure 1 shows the $[(V-I)_0, M_I]$ CMDs of the four LMC fields. The number of stars observed with good quality photometry down to $M_I \lesssim 4$ in each field—in order

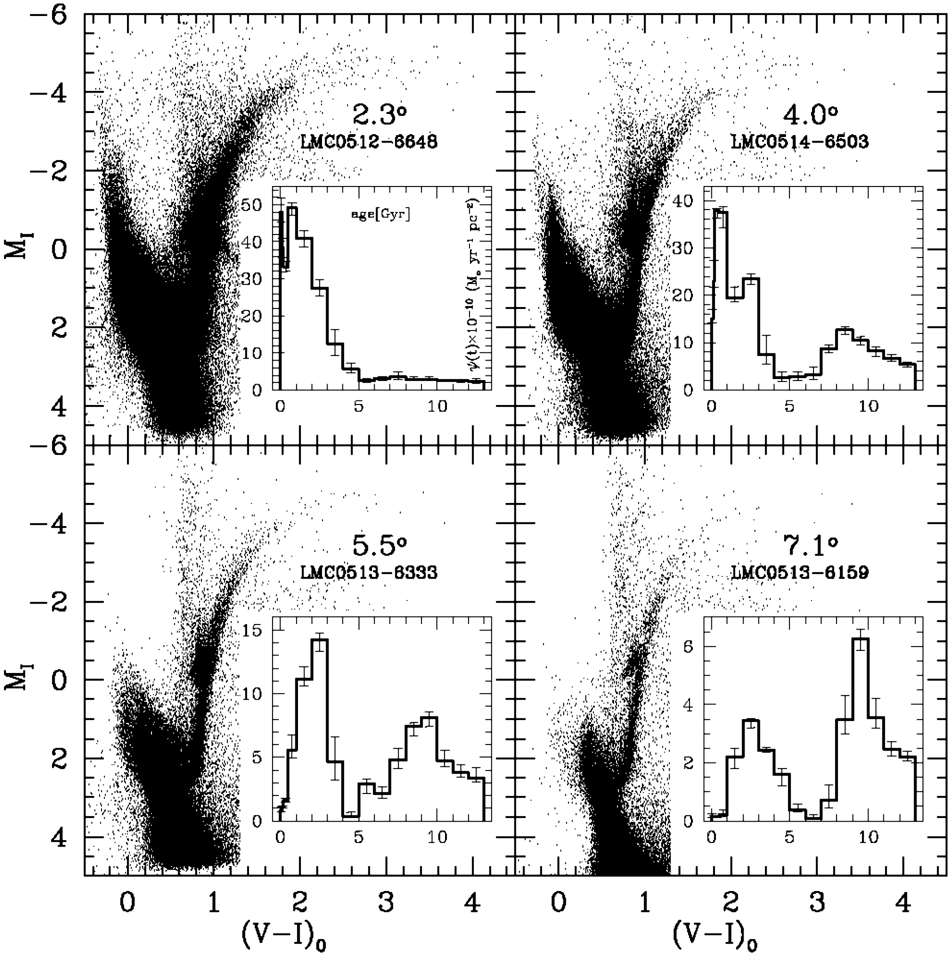

Figure 1. $[(V-I)_0, M_I]$ CMDs for the four LMC fields discussed in this paper. A distance modulus $(m-M)_0 = 18.5$ and E(B-V)=0.10, 0.05, 0.037 and 0.026 magnitudes, for the innermost to the outermost field respectively, have been assumed. The insets show the SFH projected on the $(\psi(t), t)$ plane (the age in Gyr refers to stellar ages or look-back time). We have assumed the Kroupa (2002) IMF, a 40% or binary stars with mass ratios $q \geqslant 0.5$. The BaSTI stellar evolution library (Pietrinferni *et al.* 2004) has been used as input to IAC-STAR to compute the synthetic CMDs.

of increasing galactocentric distances—are 300 000, 214 000, 86 000 and 39 000 respectively. All the CMDs reach the oldest MSTO ($M_I \simeq 3.0$) with good photometric precision and completeness fractions over 75% (except for the innermost field, in which crowding is severe). The two innermost fields show CMDs with a prominent, bright main sequence and a well populated red clump, typical of a population which has had on-going star formation from $\simeq$13 Gyr ago to the present time. The two outermost fields clearly show a fainter main sequence termination, indicating a SFH recently truncated or sharply decreasing. No extended horizontal branch is observed in any of the fields, but all fields host a number of stars redder than the RGB tip, which are candidate AGB stars.

To quantitatively derive the SFH, we have used the IAC-STAR, IAC-POP and MINNIAC codes (Aparicio & Gallart 2004; Aparicio & Hidalgo 2008; Hidalgo *et al.* 2008,

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in preparation) to compute synthetic CMDs and compare the distribution of stars in the observed and synthetic CMDs, obtaining the best solution through χ^2 minimization (see the references above and Meschin *et al.* (2008) for details on the synthetic CMD technique and our particular implementation of it). Preliminary solutions for each field are shown in Figure 1. We are in the process of testing their robustness and dependence on variations of some of the input parameters, such as the binary fraction, the IMF, or the distance modulus and reddening adopted. We believe, however, that the present solutions provide a reasonable description of the main features characterizing the LMC SFH at different galactocentric radii.

Some coherent features, together with systematic variations of the SFH among fields, are noticeable. In all fields, local maxima of the star formation rate as a function of time, $\psi(t)$, are found around $\simeq$ 3-4 and 8-10 Gyr ago, with relatively low star formation activity in the approximate age interval $\simeq$ 4-7 Gyr ago. The ratio between the amount of star formation younger and older than the age of the minimum $\psi(t)$ decreases toward the outer part of the galaxy, thus the population is on average older there. Star formation in all fields seems to have started around 13 Gyr ago. The youngest age in each field showing a substantial amount of star formation gradually increases with galactocentric radius, from 2.3° to 7.1°. In particular, in the fields at 2.3°and 4.0°, star formation goes on to ages younger than 1 Gyr; however, only in the innermost field the star formation continues vigorously to the present time.

The age gradient in the youngest LMC population is correlated with the HI column density as measured by Staveley-Smith *et al.* (2003): the two innermost fields are located at $\simeq$ 0.7 Kpc on either side of $R_{H\alpha}$, LMC0512-6648 on the local maximum of the azimuthally averaged HI column density with $\simeq 1.63 \times 10^{21}\,\mathrm{cm}^{-2}$ (close to the HI threshold for star formation; Skillman 1987) and LMC0514-6503 where the azimuthally averaged HI column density is only $\simeq 5 \times 10^{20}\,\mathrm{cm}^{-2}$. Finally, the two outermost fields are close to the HI radius considered by Staveley-Smith *et al.* to be at an HI density of $10^{20}\,\mathrm{cm}^{-2}$. The outermost field, LMC0513-6159, is approximately halfway to the tidal radius (van der Marel *et al.* 2002). If the youngest stars in each field were formed *in situ*, we are observing an outside-in quenching of the star formation at recent times ($\simeq$ 1.5 Gyr), possibly implying a decrease in size of the HI disk able to form stars. Alternatively, star formation may have been confined to the central $\simeq$ 3–4 Kpc, where gas resides (or is accreted to), and stars then migrate outwards (e.g. Roškar *et al.* 2008). In fact, it is expected that both star-formation sites and stars migrate across the LMC disk due to tidal interactions with the Milky Way and the SMC (e.g. Bekki & Chiba 2005). Of course, a combination of the two scenarios is also possible.

3. The SMC

3.1. *The cluster formation history*

No clusters as old as the Milky Way globulars are known in the SMC. Its oldest cluster, NGC121, has been shown to be $\simeq$ 2-3 Gyr younger than the oldest galactic globular clusters (Glatt *et al.* 2008a). Unlike the LMC, the SMC contains a fair amount of intermediate-age populous clusters (Glatt *et al.* 2008b; Piatti *et al.* 2008) and young clusters (Pietrzynski & Udalski 1999; Chiosi *et al.* 2006).

3.2. *The field star formation history*

Three studies have presented SFHs derived from CMDs reaching the oldest MSTOs: McCumber *et al.* (2005) and Chiosi & Vallenari (2007) studied small HST fields located toward the east near the SMC center and find a SFH with a conspicuous increase in the rate of star formation at ages younger than $\simeq$ 1 Gyr ago, together with star formation ongoing, with varying intensities, for the rest of the galaxy's lifetime. Dolphin *et al.* (2001) derived the SFH for a field located $\simeq 2°$ northwest from the SMC center and found a broadly peaked SFH, with the largest star formation rate occurring between 5 and 8 Gyr ago, and some small amount of star formation going on since a very early epoch and down to $\simeq$ 2 Gyr ago.

Harris & Zaritsky (2004) derived a global SFH for the SMC based on the Magellanic Clouds Photometric Survey (Zaritsky *et al.* 1997) UBVI catalog that includes over 6 million SMC stars. They concluded that there was a significant epoch of star formation up to 8.4 Gyr ago when $\simeq$ 50% of the SMC stars were formed, followed by a long quiescent period in the range 3–8.4 Gyr ago, and a approximately continuous period of star formation (somewhat peaked at 2-3 Gyr, 400 Myr and 60 Myr ago) starting 3 Gyr ago and extending to the present time. However, this study, which is often taken as a reference on the SMC SFH, is based on CMDs that are not deep enough to derive the full SFH from the information on the main sequence (the CMDs reach B$\simeq$ 22 mag., which corresponds to main sequence stars younger that $\simeq$ 3 Gyr old). Therefore, while this dataset and many studies derived from it are invaluable for the study of the central region of the SMC, we believe that deeper data are necessary to derive a detailed and reliable old and intermediate-age SFH.

We have also undertaken a project (see Noël *et al.* 2007) to derive the SMC SFH, using observations obtained with the LCO 2.5m telescope. These yield CMDs reaching the oldest MSTO, of similar quality to the LMC ones shown in Figure 1, in twelve $8.8' \times 8.8'$ fields. They range from 1.3° to 4.0° from the center of the SMC and have different position angles: three fields are located to the west of the SMC center, three to the east and six to the south. Noël *et al.* (2008, in preparation; Noël 2008) have derived the SFHs for these fields, which are reproduced in Figure 2.

In each panel showing the SFH of a given field, three solutions obtained with three different age binnings have been represented, together with a spline fit to them, which we will adopt as the final SFH (see the Figure caption for additional details on underlying parameters such stellar evolution models used, IMF and binary stars adopted in these solutions). It can be seen that common patterns, which vary smoothly with position, appear in most fields: there are four episodes of enhanced star formation rate: i) one at young ages, only present in the eastern fields and in the most central one located to the south, peaked at 0.2–0.5 Gyr ago; ii) two at intermediate ages: a conspicuous one peaked at 4–5 Gyr ago in all fields, and a less significant one peaked at 1.5–2.5 Gyr ago. Finally, iii) an enhancement at old ages, between $\simeq$ 8 and 12 Gyr old (the exact time varying among fields).

This spatially resolved SFH shows, for the first time, that the underlying spheroidally distributed population in the SMC (Zaritsky *et al.* 2000; Cioni, Habing & Israel 2000) is actually quite homogeneously composed of stars of a wide range of ages, from $\simeq$ 2-13 Gyr ago. In fact, the intermediate age star formation rate is relatively high out to large galactocentric distances (at least 4.5 kpc from the center, in field smc0053), in agreement with Noël & Gallart (2007). They also show that the young star formation event that is responsible for the irregular appearance of the SMC and the formation of the Magellanic Bridge (Harris 2007), does not represent, at least at galactocentric radius over $\simeq 1.5°$, an exceptional increase over the mean star formation rate.

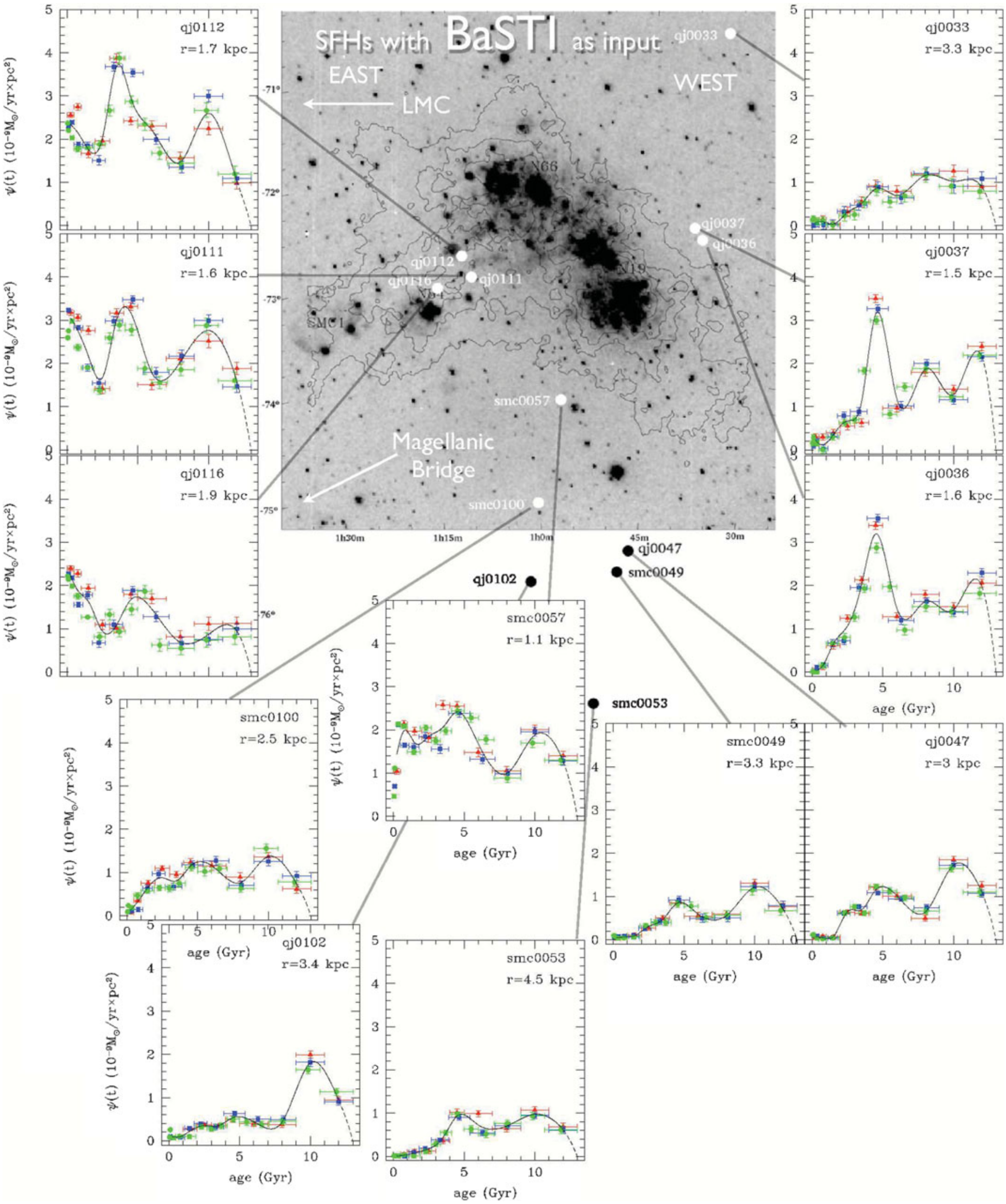

Figure 2. The derived SFHs of our SMC fields, projected on the $(\psi(t), t)$ plane (the age in Gyr refers to stellar ages or look-back time). The BaSTI stellar evolution library (Pietrinferni *et al.* 2004), with the bolometric corrections from Castelli & Kurucz (2003), was used as input of IAC-star. The Kroupa (2002) IMF was used. We assumed that 30% of the stars in the galaxy are binaries with q$\geqslant$0.7. A distance modulus $(m - M)_0 = 18.9$ and a reddening according to Schlegel *et al.* (1998; except for the innermost fields, where the reddening was estimated from the CMD itself, see Noël et a. 2007 for details) were adopted. Each solution shows the SFH obtained for three age binnings. Each point carries a vertical error bar that is the formal error from IAC-pop, calculated as the dispersion of 20 solutions with $\chi^2_\nu = \chi^2_{\nu,min} + 1$. Horizontal tracks are not error bars, but show the age interval associated to each point. The solid line shows the results of a cubic spline fit to the results. We do not have a constraint on the $\psi(t)$ at 13 Gyr old and the end point of our spline fit was chosen to be zero arbitrarily (dashed lines between 12 and 13 Gyr ago in the spline fit).

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4. Discussion

As discussed in the introduction, the knowledge of detailed SFHs in representative portions of both the LMC and the SMC will provide important insight into general questions related to the galaxy formation and evolution process. We will discuss here some of the evidence provided by the MC SFHs reviewed in this paper on the questions posed in the introduction.

Both the LMC and the SMC seem to have begun forming stars as early as the Milky Way and basically all its satellites. This statement is particularly secure in the case of the LMC, which hosts a number of old clusters with relative ages measured with respect to *bona fide* old Milky Way globulars. Also the field star formation in both galaxies seems to have started very early on, even though a precise dating (to within $\simeq$ 1-2 Gyr) is difficult. If the recent claims about a late accretion of the MCs into the Milky Way system are confirmed (e.g. Besla *et al.* 2007; Costa *et al.* 2008, in preparation), the MCs would be added to the list of *external* galaxies with a very old stellar population, thus adding further evidence for an independence on the time of onset of star formation with respect to host galaxy type, mass or environment.

It is interesting, however, that the main SFH features differ substantially between the LMC and the SMC: the most ubiquitous SMC episode of enhanced star formation occurs at the time of lowest activity in the LMC ($\simeq$ 4-7 Gyr ago). It will be important to relate these SFHs with more secure orbits of both galaxies, which will provide information about to what extent, and in which conditions, a galaxy's SFH is affected by galaxy interactions.

In relation to the question of whether the cluster formation history can be considered representative of the field SFH, we note that the features in the LMC SFH are somewhat reminiscent of the age distribution of star clusters in this galaxy, particularly regarding the existence of the age gap which could be related to the epoch of decreased field star formation at intermediate age. The old field star formation event, however, seems to span a quite wide age range, in contrast with the narrow age range of the old LMC clusters. The SMC, on the other hand, has a continuous cluster age distribution which is consistent with the fact that no important epochs of quiescence are observed in its SFH.

Finally, stellar population gradients are observed both in the LMC and in the SMC, in the sense that the strength of the intermediate-age and young star formation in relation to that of the old population decreases toward the outer part of both galaxies, i.e. the average age of the stellar population becomes older as galactocentric radius increases. Even though the reasons for this behavior (e.g. changes in the star formation activity as a function of radius and time, or migration of the stars from the central part of the galaxy where star formation preferentially takes place) will still need a fair amount of research, this information provides some insight into the nature of stellar population gradients observed in more distant late type galaxies.

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Discussion

A. Sarajedini: Do the star formation bursts seem in the field stars correlate with those of the clusters? Do they correlate with close encounters of the LMC/SMC/MW system?

C. Gallart: The relation between cluster formation epochs and enhancements of star formation in field stars is not tight, but I think a loose correlation is observed in both the LMC and the SMC: the two main events of field star formation in the LMC are separated by a decrease in the star formation activity around ~ 7 Gyr ago, and this might be related to the LMC cluster age gap. In contrast, in the SMC the SFH appears more continuous in the field (the difference between the amount of star formation in the peaks and the valleys seems to be smaller), and so is the cluster formation history. In any case, I think that much more work is needed both in increasing the area for which the field SFH is determined and the number of cluster for which accurate ages are known. About the correlation with close encounters of the LMC/SMC/MW system, we have identified some correlation between SMC/MW pericenter passages as predicted by the new orbit proposed by Kallivayalil *et al.* (2006, ApJ, 638, 772). However, I think that more precise orbits are necessary, and we will certainly have these in the next few years, thus opening a very interesting prospect of studying in detail the relationship between interactions and star formation history.

G. DeMarchi: Your data show a nice radial trend between age and distance from the LMC. Could it be that you see very few young stars moving away from the LMC because massive stars do not form there? Could it be that low-mass stars of younger ages are still there, hidden in the photometry?

C. Gallart: Under the reasonable, I think, assumption, of an IMF constant with time, the scenario you propose can be excluded.

V. Hill: I presume in the case of the SMC the line-of-sight effect is non-negligible. How does this affect the ages and star formation histories derived from the various fields?

C. Gallart: It would tend to smooth the SFH features, for example, widening the time-span of episodes of increased star formation. The depth effect can be modeled in the synthetic CMDs used to obtain the SFH to constrain the possible effect on the derived SFH.

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