Low-Metallicity Star Formation:
From the First Stars to Dwarf Galaxies
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SMC in space and time: a project to study the evolution of the prototype interacting late-type dwarf galaxy

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Abstract. We introduce the *SMC in space and time*, a large coordinated space and ground-based program to study star formation processes and history, as well as variable stars, structure, kinematics and chemical evolution of the whole SMC. Here, we present the Colour-Magnitude Diagrams (CMDs) resulting from HST/ACS photometry, aimed at deriving the star formation history (SFH) in six fields of the SMC. The fields are located in the central regions, in the stellar halo, and in the wing toward the LMC. The CMDs are very deep, well beyond the oldest Main Sequence Turn-Off, and will allow us to derive the SFH over the entire Hubble time.

Keywords. (galaxies:) Magellanic Clouds, galaxies: dwarf, galaxies: evolution, galaxies: stellar content

1. Introduction

The Small Magellanic Cloud (SMC) is the closest late-type dwarf and has many properties similar to those of the vast majority of this common class of galaxies. Its current metallicity (Z$\simeq$0.004 in mass fraction, as derived from HII regions and young stars) is typical of dwarf irregular and Blue Compact Dwarf (BCD) galaxies, the least evolved systems, hence the most similar to primeval galaxies. Its mass (between 1 and $5 \times 10^9 M_\odot$, e.g. Kallivayalil *et al.* 2006 and references therein) is at the upper limit of the range of masses typical of late-type dwarfs. These characteristics, combined with its proximity, make the SMC the natural benchmark to study the evolution of late-type dwarf galaxies. Moreover, its membership to a triple system allows detailed studies of interaction-driven modulations of the star formation activity.

A wealth of data on the SMC are available in the literature, although not as much as for its bigger companion, the LMC. Yet, much more are needed for a better understanding of how the SMC has formed and evolved. We have thus embarked on a long-term project to study the evolution of the SMC in space and time. Our project plans to exploit the high performances in depth, resolving power or large field of view of current and forthcoming, space and ground based, telescopes, such as HST, VLT, Spitzer, SALT and VST.

2. The SMC in Space and Time

Primary goals of our long-term project are the derivation of the star formation history (SFH) in the whole SMC from deep and accurate photometry and of stellar chemical abundances from high and intermediate resolution spectra. These data will allow us to infer the age-metallicity relation (or lack thereof) of stars resolved in different regions of the galaxy and to better constrain numerical models for the chemical evolution of the various SMC regions as well as for the galaxy as a whole. Since the SFH and the age-metallicity relation are key parameters in chemical evolution modeling, these new models will be of unprecedented accuracy for an external galaxy, reaching the level of reliability currently attained only for the solar neighbourhood.

Part of the project is devoted to the study of the SMC variable stars of all types, to classify them and use the unique aspects of variability to get their physical properties. We will study the spatial distribution of the various types of variables and this will provide unique information on the space and time confinement of the formation of their parent stellar populations. Standard candles such as the RR Lyraes will also provide information on the 3D structure of the galaxy and on its reddening distribution.

The SFH will be derived from Colour-Magnitude diagrams (CMD) using the synthetic CMD technique. This kind of study has already been performed by other authors (e.g. Dolphin 2001, Harris & Zaritsky 2004, Chiosi *et al.* 2006, Noel *et al.* 2007). Our plan, however, is to have CMDs several magnitudes fainter than the oldest main-sequence (MS) turn-off (TO) for the entire galaxy, including its halo and the wing in the direction of the LMC, allowing us to infer for the first time the SFH of the whole SMC over the entire Hubble time.

Time has already been awarded to this project on HST (PIs A. Nota and J. Gallagher) and on VLT (PI E.K. Grebel) and is guaranteed on VST (PI V. Ripepi). HST/ACS photometry was acquired in Cycle 13 for 4 young star clusters, 7 older clusters and 6 fields. Fig. 1 shows the location of our HST/ACS targets (except for the two outermost old clusters). Results from these data have already been published on the young clusters NGC 346 (Nota *et al.* 2006 and Sabbi *et al.* 2007) and NGC 602 (Carlson *et al.* 2007) and on the seven old clusters (Glatt *et al.* 2008a for NGC 121, and Glatt *et al.* 2008b for NGC 339, NGC 416, NGC 419, Lindsay 1, Lindsay 38 and Kron 3). More details on the young clusters are presented by Sabbi *et al.* in this volume, while the derivation of the SFH in the region of NGC 602 is described by Cignoni *et al.* (2008).

3. The HST/ACS fields

The six SMC fields have been observed in Cycle 13 (GO 10396, PI J. Gallagher) with the Wide Field Channel of the HST/ACS in the F555W (V) and F814 (I) bands for a total of 12 orbits. The target fields (indicated by white circles in Fig. 1) have been chosen to maximize possible stellar population differences between different SMC regions. Three fields are in the central region: one (SF4) close to the barycenter of the young population, one (SF1) close to the barycenter of the old population, and one (SF5) in an intermediate zone. Two fields are located in the wing, the SMC extension towards the LMC: one (SF9) in the wing outer part, and one (SF10) in its inner part. The last field (SF8) is in the opposite side, in what can be considered the SMC halo.

The observations were performed with the ACS/WFC, following a standard dithering pattern to improve PSF sampling, allow for hot pixel and cosmic ray removal and fill the gap between the two WFC detectors. The photometric analysis has been performed independently with two packages suited for PSF fitting in crowded fields: Stetson's Daophot and Anderson's imgxy-WFC.01x10. Extensive artificial star tests have been performed on the images to assess photometric errors, incompleteness and blending factors.

The CMDs resulting from the application of Anderson's photometric package are shown in Fig.2, where a 7 Gyr isochrone with metallicity Z=0.001 (from Angeretti *et al.* 2007) is also plotted for reference. As in all resolved galaxies, there is a clear stellar density gradient from the SMC center to the periphery, the field containing the largest number of stars (25300) being SF5. All regions turn out to contain old stellar populations whose evolutionary phases are visible in the CMDs: main-sequence (MS), subgiant branch (SGB), red giant branch (RGB), clump and asymptotic giant branch (AGB). The age of these old populations appears to be of several Gyr, mostly around 7 Gyr.

All fields, but the halo one, also show the blue plume typical of late-type dwarf galaxies, populated by high and intermediate mass stars in the main-sequence phase or at the blue edge of the blue loops (corresponding to the central He-burning phase). It is interesting to notice the contrast between the outer wing, where in spite of a relatively low number

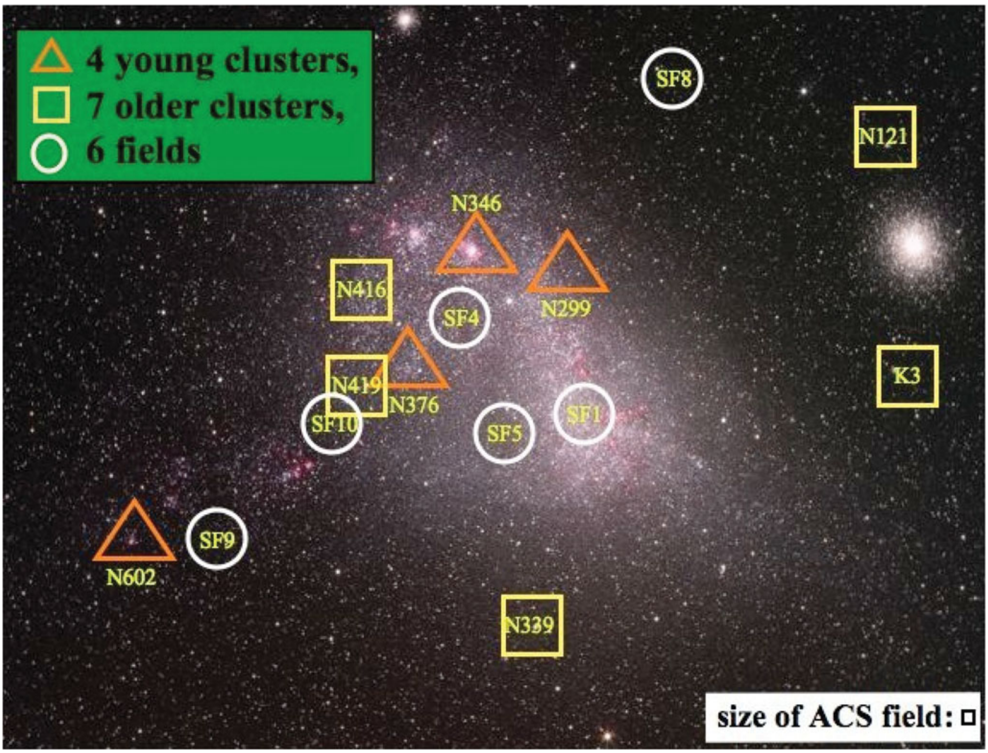

Figure 1. Location of our HST/ACS targets, overimposed on an SMC image (courtesy Stéphane Guisard). The young clusters are indicated by (orange) triangles, the older clusters by (yellow) squares, and the fields by the white circles. The name of the target is shown, with N standing for NGC and K for Kron. Lindsay 1 and Lindsay 38 fall out of the shown sky area. The actual size of the ACS field is shown in the bottom-right corner.

of measured stars the blue plume is well populated with young stars, and the much older halo in the SF8 field.

An interesting feature of the six CMDs is the apparent homogeneity of the old populations: in all panels of Fig.2 a) the old SGBs have roughly the same magnitude and the old MS TOs have roughly the same colour, and b) the clumps have roughly the same magnitude and colour. This circumstance suggests that no large differences in age and metallicity exist among the SMC old stars, irrespectively of their spatial location. By inspecting the CMDs in more detail (for instance with the aid of the 7 Gyr isochrone), we do see that the stars in the halo field (SF8) are bluer than the others, presumably because they are metal poorer and/or less reddened, whilst those at the barycenter of

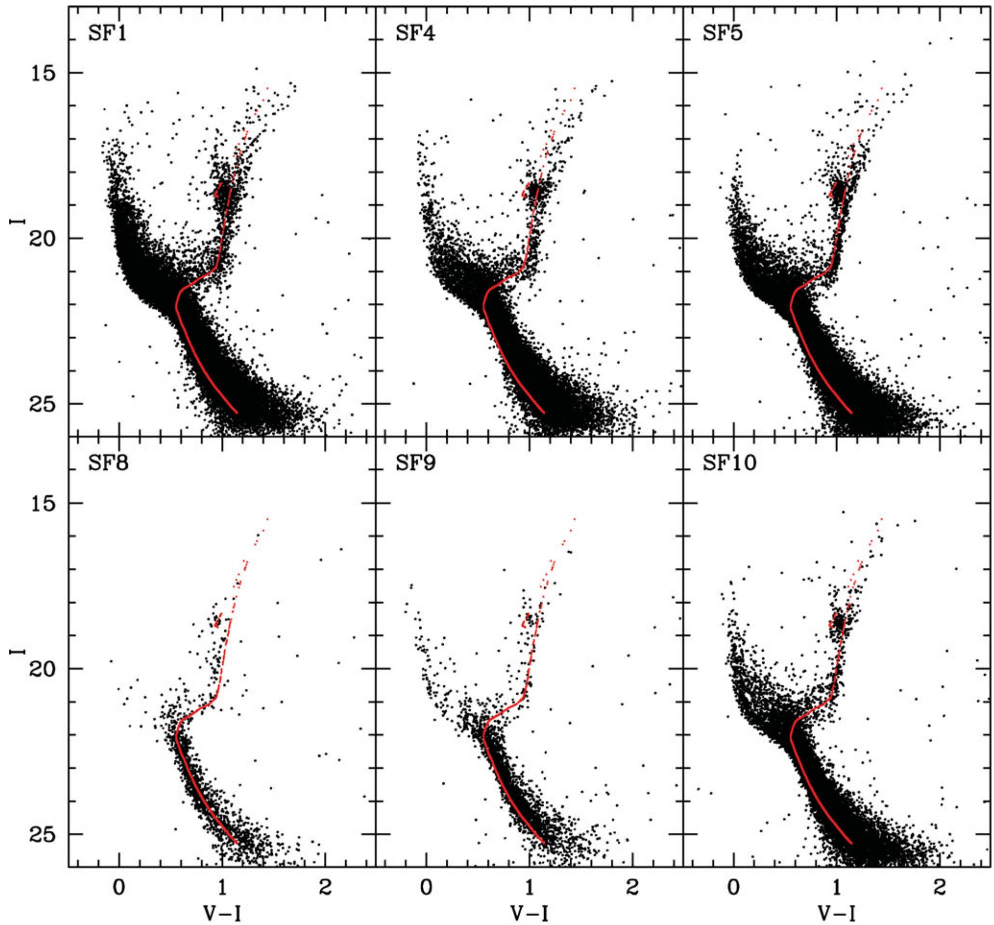

Figure 2. CMDs of the six SMC fields observed with HST/ACS. The three top panels refer to the central regions: SF1, with 28000 measured stars, SF4, with 16000 stars, and SF5, with 25300 stars. The bottom-left panel refer to the halo field, SF8, with 1550 stars. The central bottom panel shows the CMD of the outer wing field SF9, with 2440 stars, while the CMD of the inner wing field, SF10, with 13700 stars, is in the bottom-right panel. The 7 Gyr isochrone with Z = 0.001, interpolated by Angeretti *et al.* (2007) from the Padova stellar evolution models (Fagotto *et al.* 1994a and Fagotto *et al.* 1994b) is also shown in all panels for reference. The assumed intrinsic distance modulus and reddening are $(m\text{-}M)_0 = 18.9$ and E(B-V) = 0.08.

the SMC young population (SF4) are the reddest of all, probably because they are metal richer or more reddened. Also the widths of the various evolutionary phases appear somewhat different from one field to the other, which could be due either to actual age or metallicity spreads or to differences in the distribution of stars in distance within the SMC. At any rate, the CMDs are too similar to each other in the phases relative to old stars to allow for macroscopic differences in the early evolution of the six fields. The six regions seem to share a relatively late onset of the bulk of star formation activity, not much earlier than 7 Gyr ago. This result is in agreement with the findings by Dolphin *et al.* (2001) and Noel *et al.* (2007) for other SMC regions, and at variance with Harris & Zaritsky (2004) conclusions, based, however, on shallower photometry not reaching the old MS TO.

To infer the details of the SFH in the six regions, fully exploiting all the photometric information, we will apply the synthetic CMD method taking into account photometric errors, incompleteness and crowding effects as estimated with the artificial star tests. For a better assessment of the uncertainties involved in the SFH derivation, we will apply three different and independent approaches of the synthetic CMD method: Cignoni's (see e.g. Cignoni *et al.* 2006), Cole's (see e.g. Cole *et al.* 2007) and Tosi's (see e.g. Tosi *et al.* 1991 and Angeretti *et al.* 2005). The CMDs presented here already allow to forecast interesting results. When the VST will be operating and we will cover the whole SMC, wing included, with B, V, I photometry reaching several magnitudes below the oldest MS TO, we will be able to assess precisely how the star formation activity has evolved both in space and in time.

Acknowledgements

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