STEP: The VST Survey of the SMC and the Magellanic Bridge

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STEP (Small Magellanic Cloud in Time: Evolution of a Prototype interacting late-type dwarf galaxy) is a Guaranteed Time Observation survey being carried out at the VLT Survey Telescope. STEP will obtain homogeneous photometry in the *g*-, *r*-, *i*- and Hα-bands over an area of 74 square degrees covering the main body of the Small Magellanic Cloud (42 square degrees), the Bridge that connects it to the Large Magellanic Cloud (30 square degrees) and a small part of the Magellanic Stream (2 square degrees). Our photometry will allow us to detect and measure the magnitudes of individual stars well below the main sequence turnoff of the oldest populations. Here we describe the observing strategy, the photometric techniques, and the upcoming data products of the STEP survey. Preliminary results for the first two fields for which data acquisition is complete are also presented.

Introduction

The Local Group dwarf galaxies provide an ideal laboratory for studying and testing galaxy formation theories and cosmology. Their close proximity allows individual stars to be resolved, with accurate photometry and spectroscopy. (see e.g., Tolstoy et al., 2009). Their stellar populations can be characterised in detail and their star formation histories (SFHs) derived. The Small Magellanic Cloud (SMC) is the closest dwarf galaxy of late morphological type; hence the best location for detailed studies of the properties of this the most common class of galaxies. Its low chemical abundance (Z = 0.004) makes the SMC the best local counterpart to the large majority of dwarf irregulars and blue compact galaxies, whose metallicity distribution is peaked at this mean value. The SMC is also a member of the nearest group of interacting galaxies. In fact, it is tidally interacting with its neighbours, the Large Magellanic Cloud (LMC) and the Milky Way. Investigating the signatures of these interactions (the Bridge towards the LMC and the Magellanic Stream) will allow us to constrain models of galaxy interaction. Hence the SMC is an ideal benchmark in the study of the effects of tidal interactions on galaxy evolution.

We are carrying out the first deep and homogeneous photometric survey of the entire SMC body and of the Bridge by exploiting the large field of view (FoV) and the high resolution of the OmegaCAM instrument on the VLT Survey Telescope (VST); see Ripepi et al. (2014) for a detailed presentation of the survey. The STEP survey is the optical complement to the VISTA Magellanic Cloud (VMC[1]) ESO Public Survey (Principal Investigator [PI] M.-R. Cioni), which is collecting *Y*, *J* and *Ks* near-infrared photometry over an area of about 184 square degrees covering the LMC, SMC and Bridge. STEP is part of a large international effort aimed at studying in detail stellar populations, structure and evolution of the SMC, and based on photometric and spectroscopic data acquired at the major international facilities (e.g., Hubble Space Telescope [HST] and Very Large Telescope [VLT]).

The colour–magnitude diagram (CMD), containing stars born over the whole lifetime of the galaxy, is a fossil record of its SFH. Since the lookback time that can be safely be investigated is of the order of the evolutionary time of the least massive main sequence (MS) star that can be resolved, deep CMDs are crucial to detect Solar-like MS stars (corresponding to the oldest MS turn-off with evolutionary times comparable with an entire Hubble time). Although this is usually the realm of HST (see e.g., Cignoni et al., 2012; 2013), HST's small FoV does not allow a systematic study of the whole SMC.

With STEP we aim to investigate the stellar populations of the SMC with CMDs up to 1–2 magnitudes fainter than the turn-off (TO) of the oldest population (with sufficient photometric quality to reach a 2 Gyr resolution for stars born 10 Gyr ago), for a huge area including the entire SMC and the Bridge as well. We also intend to use classical variable stars (e.g., RR Lyrae and Cepheid stars), as population tracers in the relatively unexplored region of the Bridge, and a spatially complete census (up to ~ 1 $M_{\odot}$) of pre-main sequence (PMS) objects to investigate the first stages of star formation.

With these broad capabilities, the STEP survey will allow us to answer the following open questions: 1) What is the global SFH and age–metallicity relation (AMR) of the SMC?; 2) Do field and star cluster components share the same

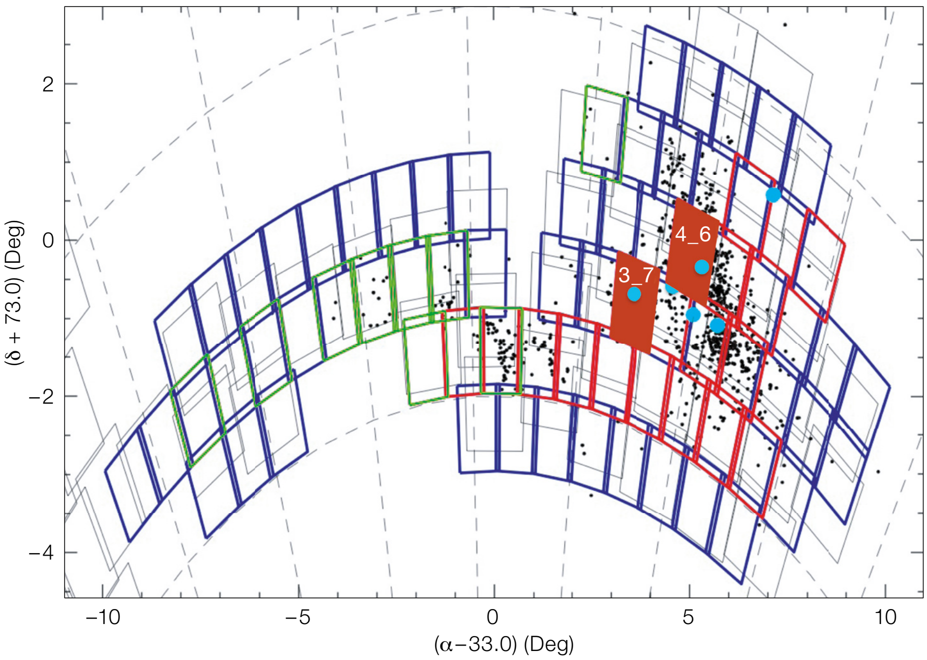

Figure 1. Map of STEP tiles (the two tiles centred in the direction of the Magellanic Stream are outside of the figure). To highlight the location of the SMC body and of part of the Bridge, black dots indicate the position of known star clusters and associations (according to Bica et al. [2008]). The thick boxes correspond to the 1 square degree FoV of the VST tiles. Red boxes represent tiles whose observations are completed, green boxes those with completed time series photometry and blue boxes the remaining ones. For comparison, thin grey boxes show the VMC tiles, whereas the HST fields are the small cyan-filled circles (note that the true size of HST fields is significantly smaller). The two tiles analysed in this work (tiles 3_7 and 4_6) are highlighted with filled red boxes.

SFH and AMR?; 3) Are there trends in SFH connected with the interaction history of the SMC?; 4) How did the stellar component of the Bridge form and what is its SFH?; 5) What is the impact of metallicity on PMS accretion and on the global properties of star formation?

STEP observing strategy

In order to address the questions listed above, we proposed, and have obtained, part of the VST Guaranteed Time Observation (GTO) allocation by ESO to the Italian Istituto Nazionale di Astrofisica (INAF) in return for the procurement of the telescope. With STEP we aim at acquiring *g*, *r*, *i* and Hα photometry for 72 square degrees covering the whole SMC body, the Bridge and 2 square degrees of the Magellanic Stream down to a limiting magnitude (on the AB system) of *g* ~ 24 mag with signal-to-noise (S/N) of 10 and Hα photometry to ~ 22.5 mag with S/N of 5.

The survey is organised into tiles of one square degree each, partially overlapping with each other to allow a homogeneous calibration (see Figure 1). In addition, we acquired 24-epoch time series photometry of 8 square degrees on the Bridge down to *g* ~ 19.5 mag (i.e., reaching fainter than the mean magnitude of the RR Lyrae stars), with S/N of 100. When summed, these images will allow us to reach *g* ~ 24 mag with S/N of 10. Originally, we planned to image the whole Bridge with time series. However, the overheads proved to be too high and we decided to cover the remaining Bridge fields without time series. STEP tiles are placed so as to maximise the overlap with the VMC survey (Cioni et al., 2011).

The STEP observing strategy is reported in Table 1, whereas Table 2 shows the constraints for our observations. For each tile and for each filter in the SMC body we obtain a couple of mosaics created by merging five dithered sub-images. We acquire a mosaic of short- and long-exposure times in order to reach faint magnitudes, avoiding saturation for any star. The time series images, on the contrary, consist of just one shot for each filter. For each tile we also obtain pairs of *g*, *i* (*r*, Hα) images during a photometric night, in order to build up lists of secondary standards for the final photometric calibration (usually the scientific images are taken in non-photometric conditions, to increase the probability of execution — see Table 2).

Table 1. Observing strategy of the STEP survey (e.g., 5 × 25 s means five dithered exposures of 25 s each).

Period	$T_{exp}(g)$	$T_{exp}(i)$
88–90	5 × 25 s; 5 × 520 s	5 × 25 s; 5 × 520 s
91–93	5 × 25 s; 10 × 300 s	5 × 25 s; 10 × 300 s
	Photometric calibration	
88–93	1 × 45 s	1 × 45 s
	Time series	
88–91	1 × 25 s; 1 × 120s	1x25 s; 1 × 180 s

Field	Seeing (arcseconds)	Moon	Airmass	Weather
SMC	1.0–1.1	0.5	1.8	Clear
Bridge	1.1	0.5	1.8	Clear
Bridge (TS)	1.4	0.8	1.8	Thin cirrus
Phot. Cal.	1.5	0.8	1.8	Photometric

Table 2. Observing constraints. Seeing is to be interpreted as the full width at half maximum measured on the image. TS stands for time series while Phot. Cal. means photometric calibration.

Observations and data reduction

The VST (built by the INAF–Osservatorio Astronomico di Capodimonte, Naples, Italy) is a 2.6-metre-wide field optical survey telescope (Capaccioli & Schipani, 2011) sited on Paranal. The telescope is equipped with OmegaCAM, a 1-square-degree camera built by a consortium of European institutes (Kuijken, 2011). The camera is a 32 CCD, 16 k × 16 k detector mosaic with 0.214 arcseconds per pixel scale.

STEP observations started in late 2011 during ESO Period 88 and are currently continuing. Usually, the observations are carried out in service mode. The different colours of the tiles shown in

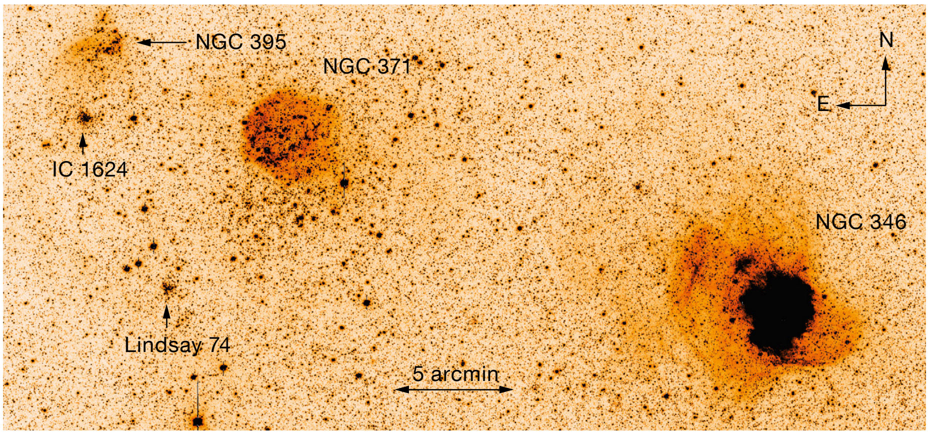

Figure 2. *g*-band VST plate showing the northern part of tile 4_6, including the well-known star-forming region NGC 346 and several other interesting clusters and associations, which are labelled.

Figure 1 illustrate the execution status as of Period 92. The total number of hours of observation allocated up to now to STEP during Periods 88–92 is 182 h; the hours of actual observations in the same period were about 98.7, with an efficiency (hours observed/allocated) of about 50 %. As a consequence of this rather low observing efficiency, the current percentage of completion of the entire survey is about 30 %.

In the following we describe the first two tiles that have been completely reduced and analysed, namely tiles 3_7 and 4_6 (see Figure 1). These tiles are representative of different environmental conditions in the SMC: tile 3_7 is located in the Shapley wing, a substructure whose origin is likely connected to the interaction with the LMC, whereas tile 4_6 is placed in the relatively unperturbed, but mostly active, northern part of the body of the SMC.

The data reduction was carried out by means of the VSTTube package (Grado et al., 2012), which has been specifically developed to handle OmegaCAM data. The pipeline includes the following steps: 1) accurate gain homogenisation (flat-fielding); 2) image concentration correction; 3) preliminary absolute photometric calibration; 4) relative photometry, relative and absolute astrometry by means of SCAMP[2]; and 5) image resampling and co-addition through the SWARP[3] package. A portion of the final mosaic for tile 4_6 is shown in Figure 2, where several star clusters and associations are clearly visible.

The PSF photometry on the final mosaics was carried out with Peter Stetson's DAOPHOT/ALLSTAR package. The catalogues were matched by means of a custom procedure. The final precision of the photometry can be appreciated in Figure 3 (upper panels). It can be seen that our sensitivity requirement is met even in the crowded regions of the SMC body. A detailed estimate of the completeness of our photometry is a fundamental stage in an accurate reconstruction of the SFH. To this aim, we have devised a custom procedure to add several thousands of artificial stars to our images without generating self-crowding. The result of the completeness experiments for both tiles is shown in Figure 3 (lower panels). It can be seen that 50 % completeness is achieved for $g \sim 23.5$ mag in tile 4_6, which is much more crowded than tile 3_7; we reach the same completeness level at $g \sim 24$–24.5 mag in tile 3_7.

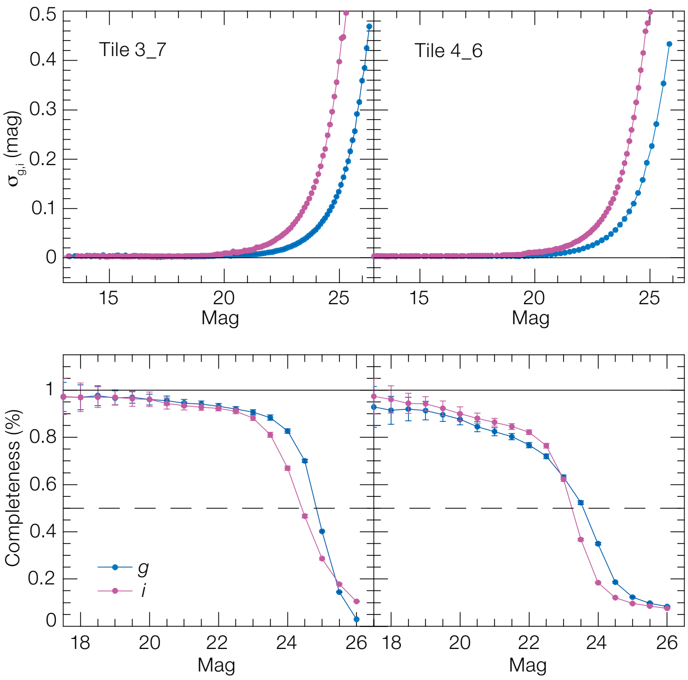

Figure 3. Upper panels: The photometric errors (averaged per bins of magnitude) in *g* (blue) and *i* (magenta) are shown for a sub-frame 20 × 21 arcminutes in size, placed in the middle of tiles 3_7 and 4_6. Lower panels: the completeness in the same regions are shown. The 100 and 50 % levels of completeness are shown with black solid and dashed lines, respectively.

The colour–magnitude diagram

Figure 4 shows the CMDs of the stars measured in tile 3_7 (left panel) and 4_6 (right panel). Since tile 4_6 is located in a populous part of the SMC, the corresponding CMD hosts over four times more stars than tile 3_7, which is placed in the relatively low density and peripheral wing. As a consequence crowding is more severe in tile 4_6 and the corresponding CMD much shallower (but still 1 mag deeper than the oldest MS TO) and sparser. To guide the eye, isochrones of different ages and metallicities (Marigo et al., 2008) are overlaid on the CMDs. The metallicity of the youngest isochrones is assumed to be $Z = 0.004$, which is consistent with spectroscopic derivations from H II regions in the SMC and from stellar abundances in very young stars, while the metallicity of the older isochrones is chosen to best fit the red giant

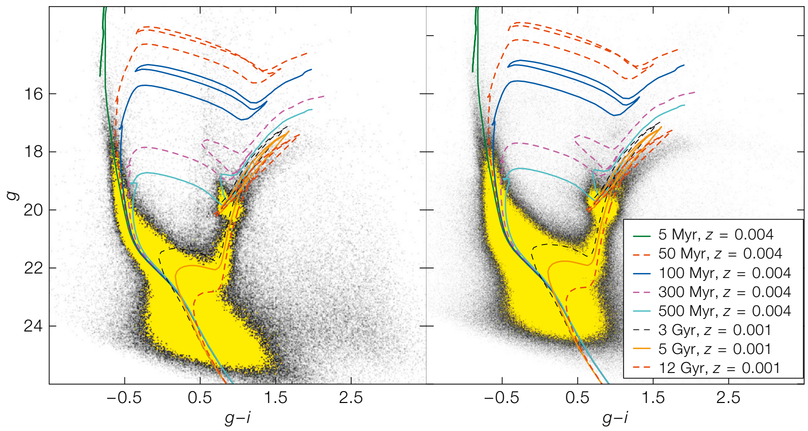

Figure 4. CMD of tile 3_7 (left panel) and 4_6 (right panel) with overlaid stellar isochrones from Marigo et al. (2008): for metal abundance $Z = 0.004$, ages 5 Myr (green continuous line), 50 Myr (red dashed line), 100 Myr (blue continuous line), 300 Myr (pink dashed line) and 500 Myr (cyan continuous line); for $Z = 0.001$, ages 3 Gyr (black dashed line), 5 Gyr (orange continuous line) and 12 Gyr (dashed red line). The assumed distance modulus and reddening E(B - V) are 18.9 and 0.08 mag for tile 3_7 (left panel), 18.9 and 0.04 mag for tile 4_6 (right panel) respectively.

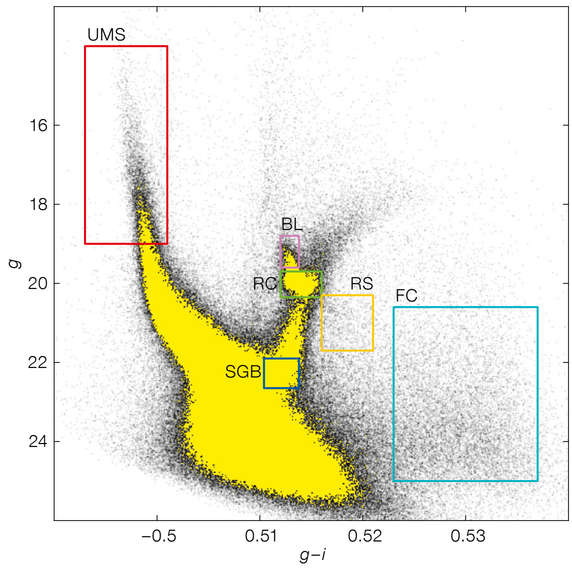

Figure 5. For tile 3_7, the CMD regions used to identify Upper Main Sequence (UMS), Blue Loop (BL), Red Clump (RC), Sub Giant Branch (SGB), reddened RC stars (RS) and Field Contamination (FC) sources are illustrated.

branch (RGB). The assumed distance modulus is $(m - M)_0 = 18.90$ mag, while the assumed reddening values, E(B - V) = 0.08 and 0.04 mag for tiles 3_7 and 4_6, respectively, are chosen to provide the best fit.

In terms of stellar populations, the mere presence in both fields of an extended MS, a well-populated blue loop (BL) and red clump (RC) phase, as well as a wide RGB, is a clear indication of common prolonged activity in the SMC. Indeed, RGB and RC stars are stellar evidence of activity prior to 1 Gyr ago, while BL and bright MS stars are tracers of activity a few hundreds of Myr and a few Myr ago, respectively. However, both CMDs show an apparent lack of horizontal branch (HB) stars, suggesting that both the regions, and presumably the entire SMC, formed a minor fraction of their stars at epochs older than 10 Gyr ago.

There are interesting differences between the CMDs for tiles 3_7 and 4_6. First of all, the morphology of the RC is rather elliptical in tile 4_6 CMD, while it shows a clear protrusion towards brighter magnitudes in tile 3_7. Considering that the RC protrusion is likely populated by objects at the transition between the RC and BL phases, hence stars with ages between 500 Myr and 1 Gyr, our conclusion is that the region of tile 3_7 has been relatively more active than for tile 4_6 at these epochs. If we take into account the fact that tile 3_7 is in the low-density wing, at the frontier of the Bridge connecting the SMC to the LMC, it is tempting to relate the higher activity in tile 3_7 with an SMC/LMC interaction. Moreover, the CMD of tile 4_6 shows a prominent RGB bump (physically caused by the H-burning shell crossing the chemical discontinuity left over by the convective envelope), just above the RC, a feature absent in tile 3_7.

From a theoretical point of view, the evidence of an RGB bump brighter than the RC is a clear indication that intermediate and old star formation took place at relatively low metallicity ($Z = 0.001$ or less) in tile 4_6. However its apparent lack in tile 3_7 CMD could be just due to the lower number of stars and requires further exploration with a synthetic CMD approach in order to be corroborated. On the other hand, the populous RC protrusion in the CMD of tile 3_7 represents a significant difference from tile 4_6, since the latter is globally much more populated. All these differences have to be investigated taking into proper account the larger crowding of tile 4_6, and the corresponding larger photometric errors and blending effects.

The spatial distribution

The spatial distribution of stars in different evolutionary stages yields important information on the star formation processes over the region. We have counted stars in different age regions of the CMD (see Figure 5), sampling the upper main sequence (UMS; red box), blue loop (BL; pink box), red clump (RC; green box), and sub-giant branch (SGB; blue box). Field contamination (FC; consisting of interlopers from the Milky Way and background galaxies) and highly reddened RC stars (RS) are sampled within the cyan and yellow boxes, respectively. In order to illustrate the power of this approach, Figure 6 shows the spatial distributions of these different groups of stars for tile 4_6.

It is clear that tile 4_6 harbours many clusters and associations, probably because of the generally high activity of this region. The stellar density of older populations (RC and SGB, middle left and bottom left panels, respectively) increases smoothly towards the SMC centre (in this case, the lower-right corner of tile 4_6), while the density of younger populations (UMS and BL, top left and top right panels, respectively) is very irregular and dominated by inhomoge-

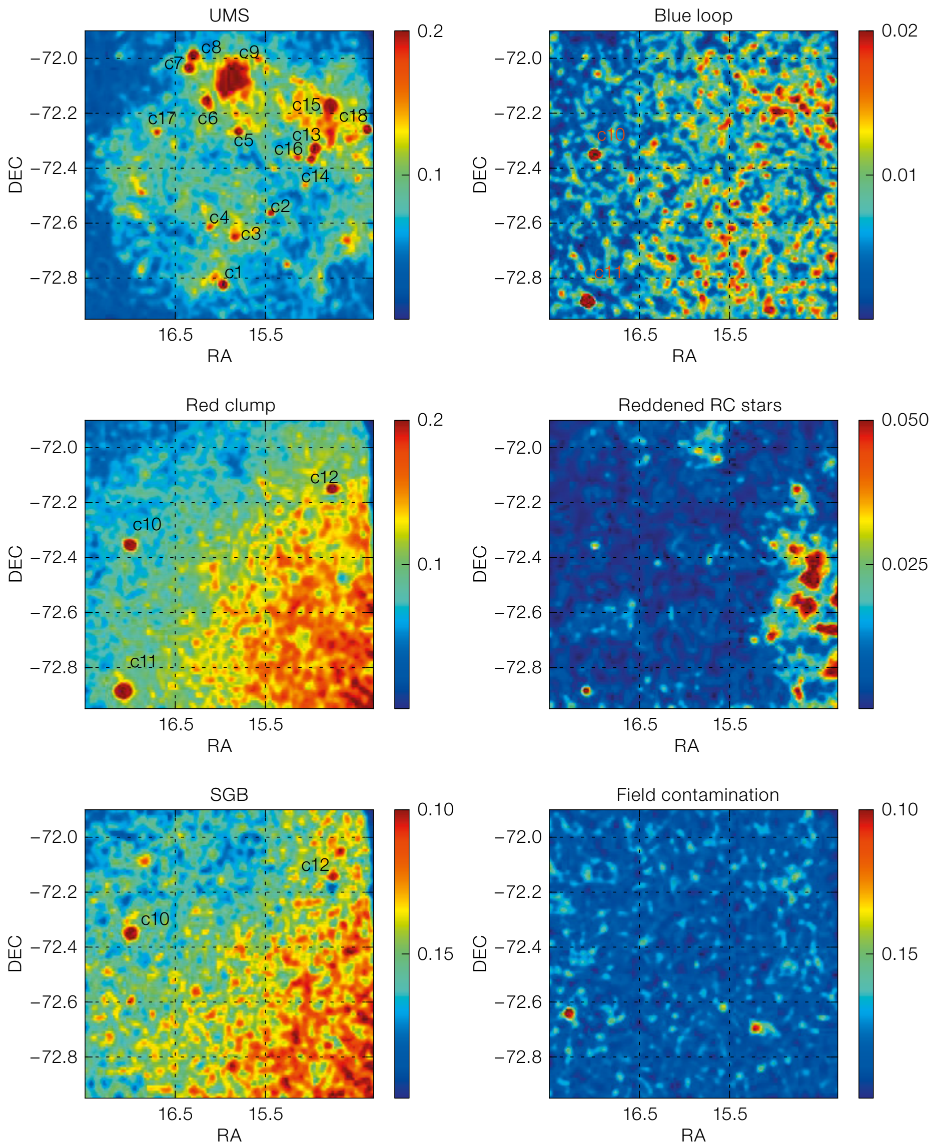

Figure 6. The spatial distributions of the stellar populations selected from the CMD of Figure 5 are shown. The maps are produced by calculating a 2D histogram of stellar positions and then smoothing the result with a Gaussian kernel. Labels c1 to c18 indicate clusters identified by eye.

neities. Indeed, most UMS stars are found aggregated in clusters/associations (identified clusters are indicated with labels c1 to c18 in the maps in Figure 6), with the most prominent ones corresponding to NGC 346 (c15 in the map) and NGC 371 (c9).

We point out that the distribution of RC stars shows clusters as well (c10, c11, c12), but that none of them turns out to have a counterpart in the UMS map (Figure 6). A simple explanation is that all agglomerates found in the latter are younger than 100 Myr, and hence, too young to host RC stars, while clusters detected only in the RC maps are necessarily too old to still have UMS stars in existence. It is also worth noting that among the clusters visible using RC stars, namely c10, c11 and c12, only c10 and c12 are seen also in the SGB map. Indeed, the c11 cluster, the well-known NGC 419, is about 1 Gyr old, and hence, the transition between the MS and the RGB phase, i.e. the SGB phase, is poorly populated (the Hertzsprung Gap). There is an excellent correspondence between the literature ages and the evolutionary phase adopted to detect the different c1–c18 structures, testifying to the reliability of this approach. Finally, the map of reddened RC stars (middle right panel in Figure 6) suggests a very patchy reddening distribution.

Star clusters

Stellar clusters and associations are among the main targets of the STEP survey. The known objects will be characterised in detail, and new clusters and associations, possibly missed by previous studies, will be searched for. In the previous section we have shown how several clusters can be detected in tile 4_6 through the analysis of the spatial distribution. However these objects are only a small part of the clusters/associations content of tile 4_6, and the compilation by Bica et al. (2008) lists 114 clusters and associations in tile 4_6 alone.

In order to get an idea of STEP's capabilities for cluster studies, we have analysed in more detail two systems located in tile 4_6: NGC 419 and IC 1624. NGC 419 is a well-known intermediate-age (~ 1 Gyr) cluster, carefully studied on the basis of HST data and showing a dispersion in age of about 0.15 dex (e.g., Glatt et al. 2009). It is extremely crowded and the central regions are almost inaccessible with the VST. IC 1624 is a younger and looser cluster with respect to NGC 419. We characterised the two clusters by measuring the structural parameters through the analysis of their surface brightness profiles and estimating their ages.

The number densities and surface brightness profiles (SBPs) are useful tools to study the properties of star clusters in different galactic environments. These profiles contain information about the cluster's formation and evolution due to internal dynamical processes and the interaction with the galactic environment. The analytical function most suitable to describe the SBPs of young Magellanic Cloud star clusters is that suggested by Elson, Fall & Freeman (1987, EFF). We used these models in our analysis.

The SBPs of NGC 419 and IC 1624 are shown in the upper panels of Figure 7;

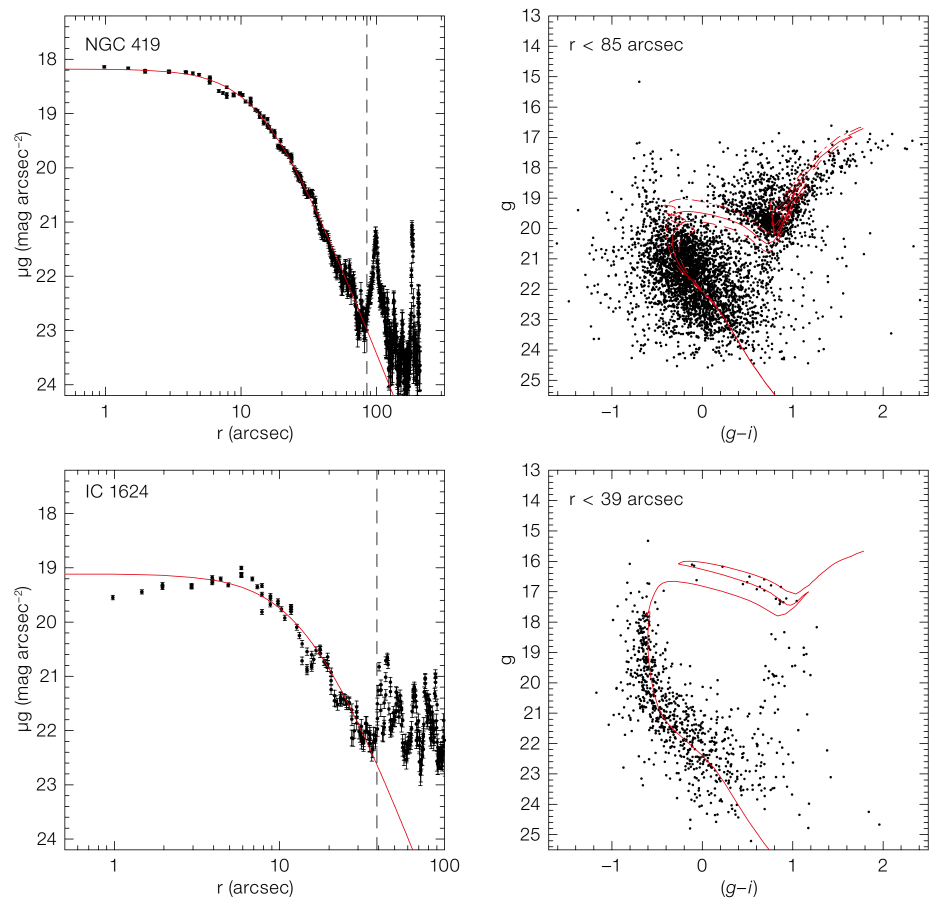

Figure 7. Left panels: Black dots show the observed radial stellar surface brightness profile around the centres of the clusters NGC 419 and IC 1624. The solid red line shows the profile fitting from the EFF law, while the dashed line represents the fitting radius. Right panels: The CMDs of the same clusters within the fitting radius (dots); the red solid and dashed lines in the upper-right panel (NGC 419) show the isochrones for 900, 1000 and 1100 Myr, respectively. The red solid line in the lower-right panel (IC 1624) shows the isochrone for 170 Myr.

in each panel the vertical dashed line indicates the "fitting radius", i.e., the limit within which the fitting procedure is carried out. The profiles in Figure 7 were obtained by: 1) estimating the cluster centre; 2) dividing the profile in annuli of different sizes; 3) averaging the counts in each annulus. Each panel shows the EFF law that best fits the data. We verified that the results for both clusters are in agreement with similar analyses, confirming the reliability of our approach.

To estimate the ages of the two clusters, we first plotted their CMDs within the fitting radius defined above (Figure 7 lower panels). The CMD of NGC 419 is rather scattered, due to the high crowding, which boosts dramatically photometric errors and incompleteness towards the cluster centre. However, the CMD of IC 1624 is rather loose because of the global paucity of stars in this cluster. In terms of age, there is a clear difference between the two clusters, with IC 1624 being much younger than NGC 419.

To be more quantitative, we adopted the isochrones from Marigo et al. (2008) with proper assumptions about reddening and distance modulus to fit the observed CMDs (red solid lines in Figure 7). As a result, for NGC 419, the magnitude difference between RC and bulk of the MS-TO suggests an age between 900 and 1100 Myr, but the large photometric errors prevent any definitive conclusion about a genuine age spread. The situation is completely different in IC 1624. The 170 Myr old isochrone fits all the main evolutionary phases very well, including the MS-TO, the red envelope of the BL and the average luminosity of the loop. The results for the ages of both clusters are, again, in very good agreement with literature results. Similar work will be carried out for all the clusters detected in the context of the STEP survey.

We are looking forward to a timely completion of all the data acquisition in order to exploit STEP at its best and provide the ESO community with the deepest homogeneous survey of the whole SMC ever performed.

References

Bica, E. et al. 2008, MNRAS, 389, 678
Capaccioli, M. & Schipani, P. 2011, The Messenger, 146, 2
Cignoni, M. et al. 2013, ApJ, 775, 83
Cignoni, M. et al. 2012, ApJ, 754, 130
Cioni, M. R. L. et al. 2011, The Messenger, 144, 25
Elson, R. A. W., Fall, S. M. & Freeman, K. C. 1987, ApJ, 323, 54
Glatt, K. et al. 2009, AJ, 138, 1403
Grado, A. et al. 2012, MemSAIT, 19, 362
Marigo, P. et al. 2008, A&A, 482, 883
Kuijken, K. 2011, The Messenger, 146, 8
Ripepi, V. et al. 2014, MNRAS, 442, 1897
Tolstoy, L., Hill, V. & Tosi, M. 2009, ARAA, 47, 371

Links

[1] VMC Survey: http://star.herts.ac.uk/~mcioni/vmc/
[2] SCAMP package: http://www.astromatic.net/software/scamp
[3] SWARP package: http://www.astromatic.net/software/swarp