A near-infrared VISTA of the Small Magellanic Cloud

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Abstract. VISTA observed the Small Magellanic Cloud (SMC), as part of the VISTA survey of the Magellanic Clouds system (VMC), for six years (2010–2016). The acquired multi-epoch YJK_s images have allowed us to probe the stellar populations to an exceptional level of detail across an unprecedented wide area in the near-infrared. This contribution highlights the most recent VMC results obtained on the SMC focusing, in particular, on the clustering of young stellar populations, on the proper motion of stars in the main body of the galaxy and on the spatial distribution of the star formation history.

Keywords. galaxies: Magellanic Clouds, surveys, techniques: photometric, astrometry

1. Introduction

The VISTA survey of the Magellanic Clouds system (VMC; Cioni *et al.* 2011) is a near-infrared deep and wide-field study of the history and structure of the Magellanic Clouds. Observations are performed with the VIRCAM instrument mounted at the VISTA telescope, they began in late 2009 and are about to be completed. The VMC survey covers a total sky area of $\sim 170\,\mathrm{deg}^2$ with a spatial resolution of $< 1''$ in the YJK_s filters reaching a sensitivity of about 21 mag (S/N = 10 in the Vega system). The VMC survey comprises of multi-epoch observations, at least 3 epochs in the Y and J filters and at least 12 epochs in the K_s filter. More than thirty refereed journal papers have been published by the VMC survey team to-date and in this contribution we highlight the results from the three most recent ones.

2. Hierarchical star formation in the SMC

The distribution of young (< 250 Myr old) upper main sequence stars across the SMC was studied using a cluster analysis technique in order to understand their formation mechanism (Sun *et al.* 2018). Stars were selected from the VMC colour-magnitude diagram, $J - K_s$ versus K_s, to lie within a box on the upper main sequence, while taking into account of possible shifts due to metallicity, extinction, and the SMC's line-of-sight

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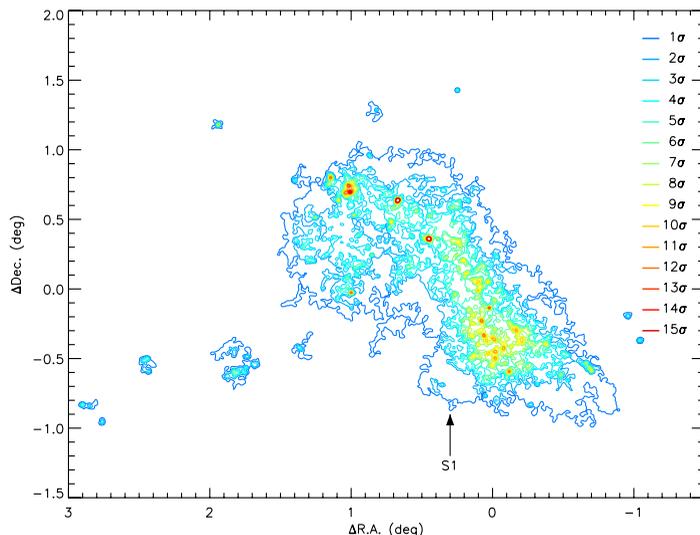
Figure 1. Boundaries of all identified young stellar structures, with the colours coded according to their significance levels, see Sun *et al.* (2018) for details. The map is centred at ($\alpha_{2000} = 00^{\text{h}}$:$50^{\text{m}}$:$20.8^{\text{s}}$, $\delta_{2000} = -72°$:$49'$:$43''$). Note that the gap in VMC observations (cf. Fig. 2) was filled using data from the Magellanic Clouds Photometric Survey (MCPS; Zaritsky *et al.* 2000).

depth. They were used to identify 556 separate over densities on 15 significance levels (Fig. 1). These structures appeared to follow a hierarchical distribution such that larger structures on lower significance levels contain smaller ones on higher levels. Their properties (size, number of stars, and surface density) as well as their irregular morphologies (characterised by a perimeter−area dimension of $D_{\text{p}} = 1.44 \pm 0.02$) are similar to those of the interstellar medium which is regulated by supersonic turbulence. This highlights the importance of turbulence in controlling star formation over a large scale range.

3. The proper motion of the SMC

The proper motions of the stellar populations in the centre of the SMC have been derived using multi-epoch VMC observations. Four VMC tiles were examined and the reflex motions of about 33, 000 background galaxies was measured with respect to about 700, 000 stars. The proper motions were measured from the pixel displacements in the x and y directions of the source centroids which were obtained from point-spread-function photometry on individual pawprint K_{s}-band detector images. On average, 12 independent epochs over a time baseline of ~ 24 months were available and each detector contained about 6, 000 stars and 150 background galaxies. A median systemic proper motion of the SMC, $(\mu_\alpha cos(\delta), \mu_\delta) = (1.087, -1.187)$ mas yr^{-1} with systematic uncertainties of 0.192 and 0.008 mas yr^{-1} for the two components and a random uncertainty of 0.003 mas yr^{-1}, was found. This is consistent with previous studies. Furthermore, from the median-subtracted proper motion distribution (Fig. 2) we identified regions of non-uniform velocity, in the densest area and in the southeast of the galaxy, probably associated to tidal stripping events. While the latter feature points towards the Wing and the Bridge, the former might be associated to the Counter-Bridge (Diaz & Bekki 2012).

4. The star formation history of the SMC

The star formation history across the central ~ 24 deg^2 region of the SMC (14 VMC tiles) has been derived from the reconstruction of the observed VMC colour-magnitude diagrams ($Y - K_{\text{s}}$ versus K_{s} and $J - K_{\text{s}}$ versus K_{s}) by Rubele *et al.* (2018). The analysis
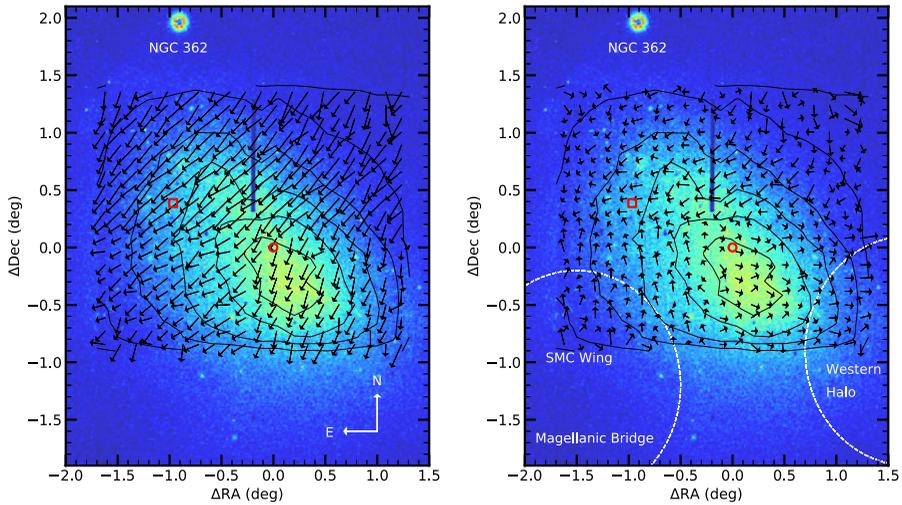
Figure 2. Proper-motion field (black arrows) of the central regions of the SMC from four tiles of VMC data superimposed to a star density map. Each panel is centred at the optical centre of the SMC (red circle; $\alpha_{2000} = 00^h{:}52^m{:}12.5^s$, $\delta_{2000} = -72°{:}49'{:}43''$), also shown as a red square is the kinematical H I centre. North of the main body of the SMC, the foreground Galactic globular cluster NGC 362 is visible. The contours are at 500, 1500, 3500, 5500, 7500 and 9500 stars per grid cell. The vertical dark stripe at RA$= -0.2°$ is due to a narrow gap in the observations. In the left-hand panel, the arrows indicate the observed absolute proper motion, whereas in the right-hand panel, the arrows show the residual proper motions after subtraction of the systemic velocity of the SMC, see Niederhofer *et al.* (2018) for details.

was performed within individual subregions of 0.143 deg^2 in size. Figure 3 shows that at young ages ($log(t) = 7.4$ or ~ 12 Myr) the star formation is concentrated in the Bar and Wing areas while the separation between these two substructures is less clear at older ages. A northwestern edge, possibly resulting from the dynamical interaction with the Large Magellanic Cloud ($log(t) = 8.3$ or ~ 200 Myr ago), becomes well delineated. The distribution traced by old ($log(t) = 9.7$ or ~ 5 Gyr old) stars is significantly rounder than that resulting from younger stars. We explored the age interval from 8 Myr to 10 Gyr and all maps are included in Rubele *et al.* (2018). In this study, we also derived the spatial distribution of the mean reddening and distance of the stellar populations as well as an estimate of the total stellar mass, $(5.31 \pm 0.05) \times 10^8$ M$_\odot$, that the galaxy produced over its lifetime.

5. Conclusions

The VMC observations across the SMC area were completed in 2016 and the data are currently being reprocessed with the latest version of the CASU pipeline (v1.5) to adjust the zero points and to apply a correction to the distortion of tile images, more details are given in Gonzalez-Fernandez *et al.* (2018). Several works have resulted from the previous reductions (i.e. v1.3) and analysis of the data, e.g.: a study of the three-dimensional structure of the SMC using Cepheids (Ripepi *et al.* 2017) and RR Lyrae stars (Muraveva *et al.* 2018), the discovery of a bi-modality in the red-clump distribution (Subramanian *et al.* 2017) and of new star clusters (Piatti *et al.* 2016), while in this contribution we focused on the three most recent publications. In future works, we will complement the star formation history and the proper motion analysis of the SMC with VMC tiles covering the external regions of the galaxy. We also plan to extend
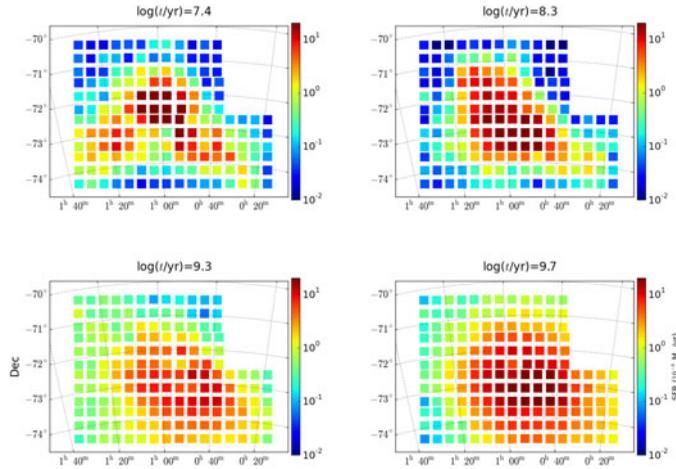
Figure 3. Star formation rate maps across the SMC as a function of age, for four out of fourteen age bins considered in Rubele *et al.* (2018). Each square corresponds to a subregion of 0.143 deg^2 in size, with colours indicating the star formation rate in units of $10^{-4}\mathrm{M}_\odot$ yr^{-1}.

these studies, the study of the clustering of young stellar structures and that of the three-dimensional structure to the Large Magellanic Cloud.

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