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The VMC survey: a deep YJK$_s$ view of the Magellanic Clouds

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Abstract. VISTA has observed the Magellanic Clouds as part of the VMC survey since 2009. This large scale project has produced a comprehensive set of Y, J and K_s band images that reach stars below the main sequence turn off of the oldest stellar population and that provide at least 12 independent epochs at K_s. This unique data allows us to derive accurate star formation histories, to characterise different stellar populations, such as variable stars that can be used to study the geometry of the system, and also to measure proper motions. The status of the survey is reviewed with emphasis on the quality of the data to address difference science topics, and in particular its relevance for the study of star clusters. Some large-scale properties of this interacting system that are perhaps linked to the formation and evolution of star clusters are also described.

Key words. Surveys: Magellanic Clouds - Infrared: stars.

1. Introduction

The Magellanic Clouds are the most luminous and largest dwarf satellite galaxies of the Milky Way. They are metal poor, nearby and represent a clearly interacting system with an associated Bridge and Stream. They contain gas and stars that span the entire age-range of the Universe and they have only recently approached the Milky Way, possibly with their own associated satellites. They represent an early stage of a minor merger event.

The Magellanic Stream (D'Onghia & Fox 2016) is the product of the interaction between the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC) as well as from ram pressure stripping by the Milky Way. Each of the LMC, SMC, Bridge and Stream contain about 10^8 $M_\odot$ of neutral hydrogen. The Stream contains material that originated in both the LMC and SMC, because of two chemically distinct filaments. The Stream is mostly gaseous, but stars have been found in the leading arm. The latter might be the result of gas stripped from Magellanic Clouds satellites (Hammer et al. 2015).

The number of known Local Group satellite galaxies has doubled in the last two years thanks to surveys of the sky that reach faint stars in regions previously unexplored to these sensitivities, e.g. (Bechtol et al. 2015). Several of the newly discovered satellites were found in the proximity of the Magellanic Clouds outlining a clearly asymmetric distribution with respect to that of the overall Local Group satellites. Hence, some of these satellites might be satellites of the Magellanic Clouds themselves.

Recent results from the OGLE IV survey have shown that we are able to characterise the three dimensional (3D) geometry of the Magellanic Clouds much better than before. The Magellanic Clouds are inclined towards each other. The line-of-sight depth of the LMC is comparable to the distance that separates it from the SMC while the depth of the SMC is three times larger. This extended structure is supported by both the distribution of young (a few Myr old) Cepheids and the distribution of old (> 10 Gyr old) RR Lyrae stars, e.g. Jacyszyn-Dobrzeniecka, et al. (2016).

The outer regions of the Magellanic Clouds present a high level of substructure. Results from the first Gaia data release indicate the presence of a secondary Bridge traced by RR Lyrae star candidates contrary to the primary Bridge traced by young stars (Belokurov et al. 2017). Furthermore, intermediate-age asymptotic giant branch (AGB) stars show several protuberances and tails (Deason et al. 2017). Stellar streams in the outer regions of the Magellanic Clouds have been discovered from the analysis of the distribution of blue horizontal branch stars at different distances from the Magellanic Clouds (Belokurov, & Koposov 2015). These streams may or may not be associated with some of the candidate Magellanic Clouds satellites.

Recent models of the orbit of the LMC around the Milky Way suggest either a first passage scenario or a long period (5 Gyr) orbital motion (Patel et al. 2017). A comparison with analogous systems in the Illustris simulations support a first infall scenario. It is interesting that in both scenarios the LMC entered the Milky Way potential a few Gyr ago which corresponds to the mean age of AGB stars. A first approach implies a Milky Way mass $< 1.5\times10^{12}$ M$_\odot$ and that the LMC has retained most of its cosmological mass. A large LMC mass perturbs also the Milky Way potential (Peñarrubia, et al. 2016). Knowledge about the mass of the LMC is limited to the poor sampling of its radial velocity curve (van der Marel et al. 2014). Tangential velocity measurements are currently limited to 5 kpc while line-of-sight velocity measurements reach 8.7 kpc. This implies a circular velocity of $\sim$ 92 km/s and a total mass of $\sim 1.7\times10^{10}$ M$_\odot$ which represents a lower limit. The inclination of the LMC plays a major role in the uncertainty in the radial velocity curve.

The study of stellar clusters and their use to understand properties of the Magellanic Clouds needs to take into account of the complex structure of the system as outlined above. Have star clusters formed in situ or have they been accreted from SMC to LMC or viceversa and/or from a satellite galaxy?

2. The VMC survey

The near-infrared YJK_s VISTA ESO public survey of the Magellanic Clouds system aims to uncover the detailed spatially resolved star formation history and the 3D geometry of the system from different age indicators (Cioni et al. 2011). This is an imaging program in three filters sampling an area of ~ 170 deg^2 and stars as faint as ~ 22 mag (5σ Vega) in each waveband. It also includes a monitoring component with at least 3 epochs in the Y and J filters and 12 epochs in the K_s filter. VMC observations started in 2009 and will be completed in 2018. This is the most sensitive survey in the near-infrared to date.

The depth of VMC is driven by the necessity to reach stars of the oldest main sequence turn off that allow us to describe the overall star formation history of galaxies. The latter is obtained from the interpretation of colour-magnitude diagrams with theoretical models. The VMC monitoring component is driven by the necessity to sample the light-curve of variable stars (i.e. of Cepheids and RR Lyrae stars) that are used to measure distances. Distances are also derived from the red clump giant stars and from the tip of the red giant branch method, as well as from other indicators. The VMC data have been used for legacy application such as the study of foreground Milky Way stars (e.g. brown dwarfs), the investigation of regions of star formation, the discovery and characterisation of stellar clusters, and the identification of quasar candidates.

The field of view of VISTA is 1.65 deg^2 and is sampled by 16 detectors with large gaps (a pawprint). A mosaic of 6 pointings is used to filled the gaps and obtained the observation of a contiguous area of sky (a tile). The VMC survey comprises of 110 overlapping tiles. The observing strategy acquires Y and J band observations at any time and K_s band observations with a cadence that imposes a minimum spacing of $0 - 1 - 3 - 5 - 7$ and 17 days for each subsequent epoch. The observation of a given tile at a given filter takes about 1 hour. The whole VMC survey takes $\sim$ 2000 hours or $\sim$ 250 nights. Observations are carried out by ESO staff in service mode which guarantees a high level of homogeneity in terms of sky quality (transparency, airmass, and seeing).

The VMC data after being acquired at the VISTA telescope are first reduced at the Cambridge Astronomy Survey Unit (CASU) using the VISTA Data Flow System Pipeline (VDFS). Pawprint images, tile images and their associated catalogues and confidence maps are created from the combination of individual observations and calibrations. The data are further processed at the Wide Field Astronomy Unit (WFAU) where deep stacked images and their associated catalogues are created as well as links among the multiple epochs. At WFAU the data are ingested into the VISTA Science Archive which represents an entry point for the community to access the VMC data. The VMC data are also publicly available from the ESO archive. The VMC team checks the data at various stages of the processing path and produces additional data products like point-spread function (PSF) photometry and the parameters of variable stars (amplitudes and mean magnitudes obtained in combination with periods derived from other surveys). At the following web page, `http://star.herts.ac.uk/~mcioni/vmc`, it is possible to browse the VMC tile images and appreciate the details of the detected structures (dense stellar fields, stellar clusters, background galaxies and galaxy clusters).

The VMC survey is at present 92% observed. The 2017 data release comprises of 19 completed tiles: 10 in the LMC, 5 in the SMC, 2 in Bridge and 2 in the Stream. Individual tile and pawprint images along with deep tile images are made available together with their associated catalogues including additional data product (i.e. PSF photometry and parameters for some variable stars).

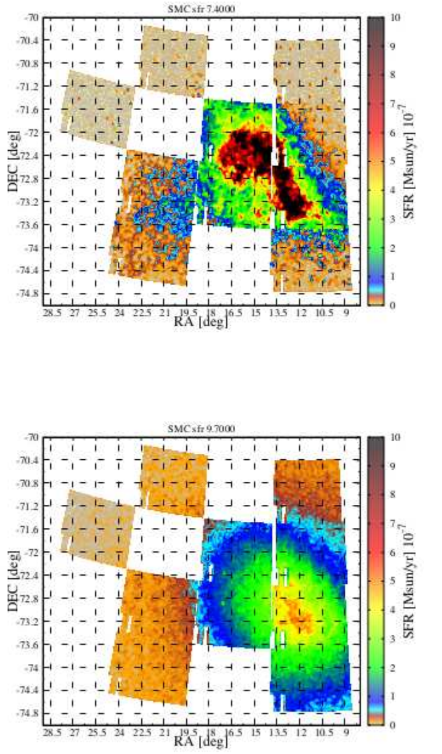

Fig. 1. Star formation rate across the SMC 25 Myr ago (top) and 5 Gyr ago (bottom). More details are given in Rubele et al. (2015).

2.1. Science highlights

2.1.1. Star formation history

One of the main goals of the VMC survey is to obtain a detailed spatially resolved star formation history across the Magellanic system. First results on the LMC were published in Rubele et al. (2012). In that paper the methodology to extract the star formation history parameters (age and metallicity) from the best combination of partial models was outlined. Distance moduli and average extinctions towards each tile subregion (a 12th of a tile) are also obtained. A subsequent study analysing 10 tiles across the SMC was published in Rubele et al. (2015). It showed the most detailed star formation history maps to date with a spatial resolution of 20×20 arcmin^2 (Fig. 1). They indicate that the SMC has acquired most of its mass at about 5 Gyr ago. The star formation was modest (0.15 $M_\odot$ yr^{-1}) at earlier ages. A peak of star formation at 1.5 Gyr ago agrees with a similar peak in the LMC and they may be both related to a dynamical interaction. Star formation propagated from the south-west to the north-east. At present, we are revising the star formation history analysis including all tiles observed in the SMC and taking into account of the spatial orientation of the galaxy in the sky. As seen in Rubele et al. (2015) a correction for the distance of stars that belong to an inclined disc significantly reduces the systematic uncertainties in the best fit ages and metallicities.

2.1.2. Double red clump

The analysis of SMC tiles revealed the presence of a double red clump feature (Subramanian et al. 2017; Fig. 2). Red clump stars are $2 - 9$ Gyr old giant stars with initial masses of $1 - 3$ $M_\odot$. The best interpretation of this feature is that it is due to two distance components separated by about 10 kpc. The double red clump originates in the inner 2-2.5 kpc of the SMC and it is prominent towards the Bridge; it is likely due to tidally stripped material. This analysis is currently being extended to all SMC tiles to provide a comprehensive characterisation of the strength and extent of the stripped population.

2.1.3. 3D structure from Cepheids

Classical Cepheids are young (a few Myr old) giant stars with a mass of $4 - 20$ $M_\odot$ burning Helium in their core. They obey tight period-magnitude-colour relations that allow us to measure accurate distances. Cepheids are easily recognized from the typical light-curve variation which is more sinusoidal at longer wavelengths. In Ripepi et al. (2016) we constructed light-curve templates in the VMC wavebands for classical Cepheids in the SMC spanning a range of periods. We used these templates to derive the mean magnitude of all SMC classical Cepheids identified by the OGLE survey and with a counterpart in the VMC data. We built period-luminosity-colour relations for fundamental and overtone pulsators which resulted in an rms of ~ 0.15 mag suggestive of the intrinsic depth of the galaxy.

A detailed study of the 3D structure traced by SMC Cepheids towards the SMC is presented in Ripepi et al. (2017). An highly elongated (25-30 kpc) and asymmetric structure of the SMC, as indicated by previous authors, was confirmed (Fig. 3). Furthermore, old ($\sim$ 200 Myr old) Cepheids dominate the central region of the galaxy and follow elongated structures in the outskirts indicative of having been subjected to tidal stripping resulting, for example, from the interaction between the LMC and the SMC at the time of the formation of the Bridge. On the contrary, young ($\sim$ 100 Myr old) Cepheids, albeit being distributed overall the main galaxy, dominate an off-centre region to the north-east. It is possible that these Cepheids formed after the gas was stripped from the SMC at the moment of its interaction with the LMC.

2.1.4. Proper motion

The VISTA data on a given tile span a time range of about 2 years. Combined with their spatial accuracy and sensitivity that allow us to detect both a large number of stars and a large number of background galaxies they are well suited to calculate the proper motion of the Magellanic Clouds and of the stellar populations they contain. A pilot study comparing the ability to obtain proper motions using VMC data combined with 2MASS data and VMC tile data alone was published by Cioni et al. (2014). An improved calculation of the proper motion, based on individual pawprint detectors, was given in Cioni et al. (2016) where the proper motion of the SMC and of the Milky Way star cluster 47 Tucanae (47 Tuc) were presented. The VMC tile containing the 47

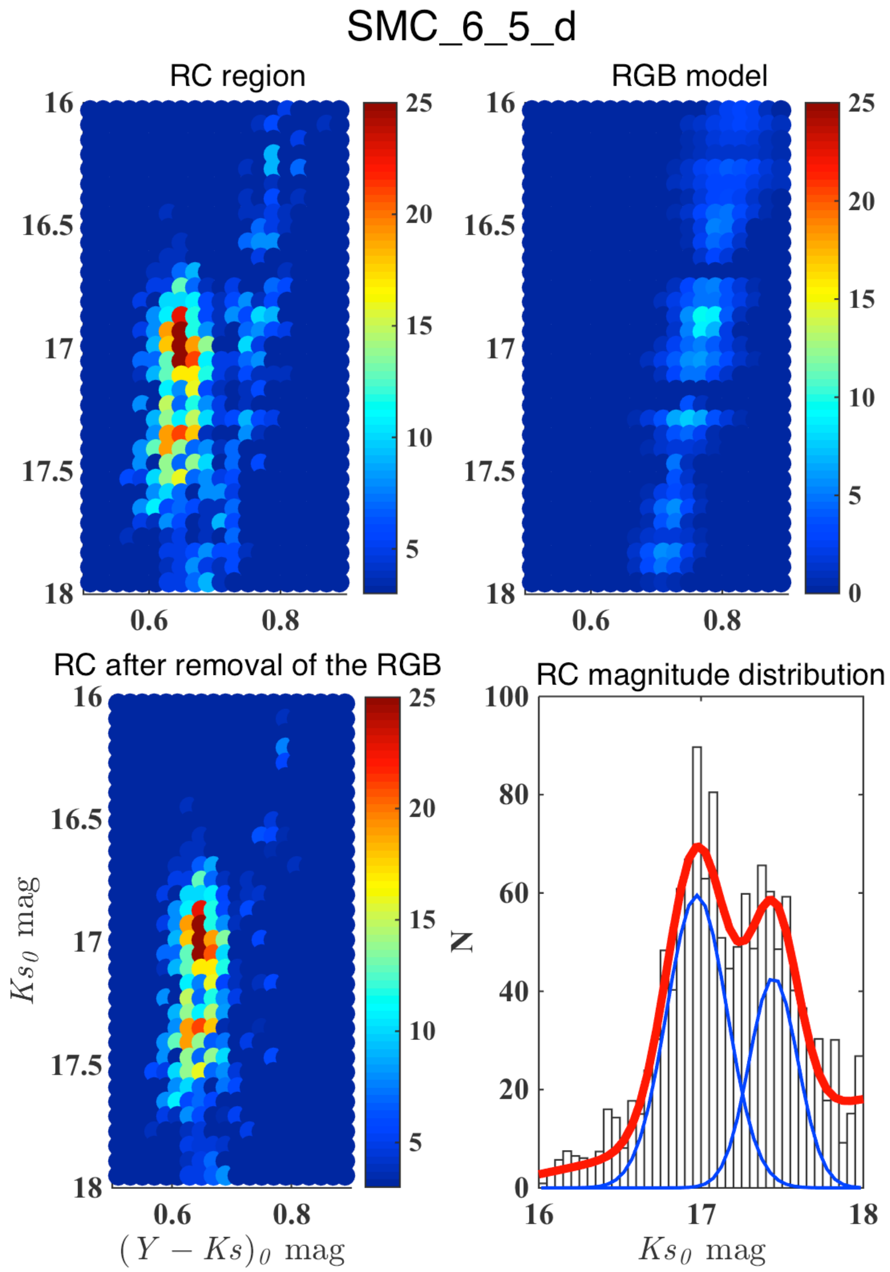

Fig. 2. Top-left: Reddening corrected and foreground subtracted colour-magnitude diagram. Top-right: red giant branch model. Bottom-left: red giant branch subtracted diagram. Bottom-right: red clump magnitude distribution. See Subramanian et al. (2017) for more details.

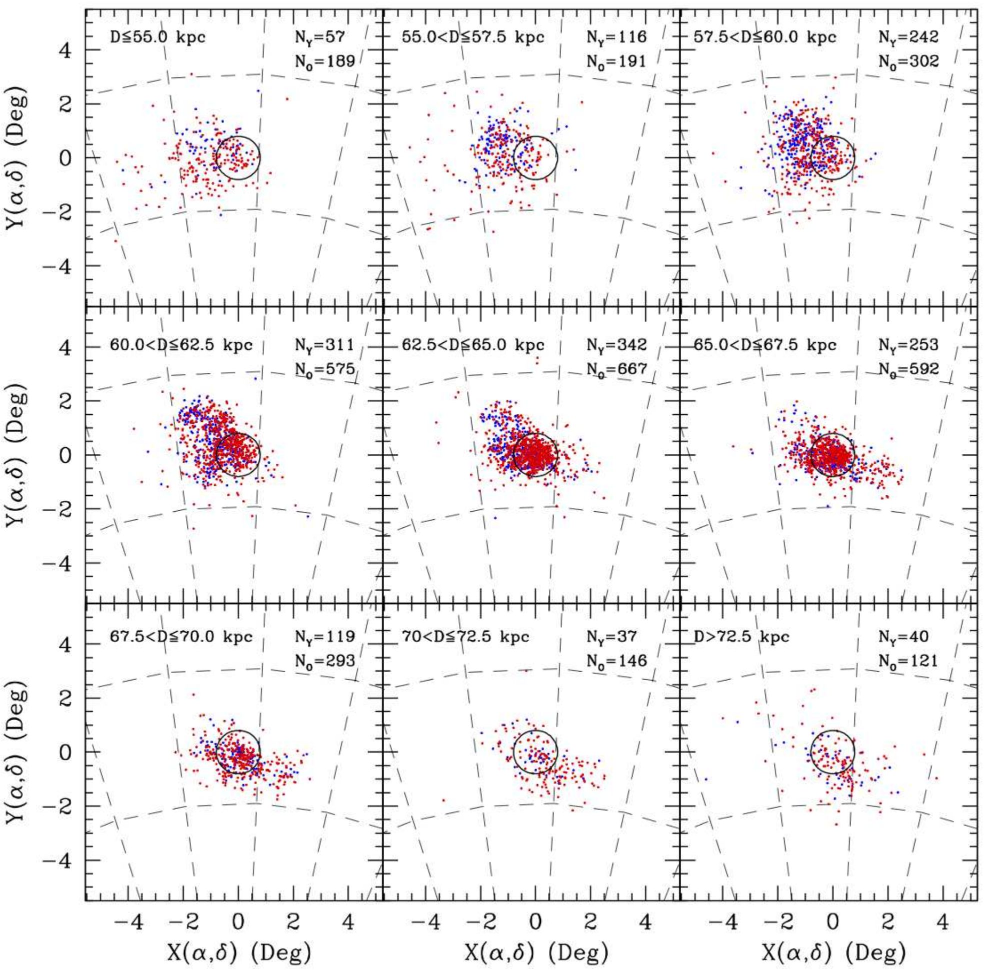

Fig. 3. Spatial distribution of classical Cepheids: young (~ 100 Myr old; blue) and old (~ 200 Myr old; red). From top to bottom and from left to right different line-of-sight distances are indicated. The top-left corner corresponds to $\leq$ 55 kpc and the bottom right to $>$ 72.5 kpc. The central panel is for $62.5 < D \leq 65$ kpc. Numbers in the legend of each panel indicate the numbers of young and old populations, respectively. The reference circle has a size of 0.8 kpc. See Ripepi et al. (2017) for more details.

Tuc cluster shows a high level of superposition of different stellar populations. In regions that are not strongly influenced by the foreground stars, the proper motion of the SMC as traced by giant stars is in excellent agreement with that obtained from the Hubble Space Telescope (HST), e.g. Kallivayalil, et al. (2013). More recently we have revisited the proper motion of 47 Tuc using PSF photometry that allows for a better detection of sources in crowded regions. This provides a proper motion that is also well in line with previously obtained HST measurements (Niederhofer et al. sub.). These proper motion studies have allowed us to understand the astrometric properties of the VMC data and set the stage for their applications to the entire data set. The main goal of this investigation is to reconstruct the internal kinematics and orbital history of the Magellanic system.

3. Conclusions

Studies of the Magellanic Clouds have gained momentum thanks to the availability of deep photometric observations in the optical (e.g. the SMASH survey; Niedever et al. 2017) and near-infrared domain. The VMC survey is the most sensitive near-infrared survey to date. It is almost completely observed and it resulted already in 27 journal papers addressing a wide range of science topics that reach well beyond the original goals of the survey, from the Milky Way (e.g. the study of the proper motion of the 47 Tuc star cluster) to the distant Universe (e.g. the identification of quasar candidates), and including the discovery of new star clusters, e.g. Piatti et al. (2016). First results on the star formation history and 3D structure of the Magellanic Clouds surpass expectations while the proper motion opens up a promising window to further characterise the stellar content of the system, its mass and origin. The near future will be dominated by follow-up spectroscopic studies to derive line-of-sight velocities and chemical composition of many stars. Future project, e.g. LSST, will allow us to characterise faint stellar populations and to study also Magellanic analogs.

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References

Bechtol, K., et al. 2015, ApJ, 807, 50
Belokurov, V., & Koposov, S. E. 2015, MNRAS, 456, 602
Belokurov, V., et al. 2017, MNRAS, 466, 4711
Cioni, M. -R. L., et al. 2011, A&A, 527, A116
Cioni, M. R. L., et al. 2014, A&A, 562, A32
Cioni, M. -R. L., et al. 2016, A&A, 586, A77
Deason, A. J., et al. 2017, MNRAS, 467, 1259
D'Onghia, E., & Fox, A. 2016, ARA&A, 54, 363
Hammer, F., Yang, Y. B., Flores, H., Puech, M., & Fouquet, S. 2015, ApJ, 813, 110
Jacyszyn-Dobrzeniecka, A.M., et al. 2016, Acta Astron., 66, 149
Kallivayalil, N., et al. 2013, ApJ, 764, 161
Patel, E., et al. 2017, MNRAS, 464, 3825
Peñarrubia, J., et al. 2016, MNRAS, 456, L54
Piatti, A.E., et al. 2016, MNRAS, 460, 383
Ripepi, V., et al. 2016, ApJS, 224, 21
Ripepi, V., et al. 2017, MNRAS, 472, 808
Rubele, S., et al. 2012, A&A, 537, A106
Rubele, S., et al. 2015, MNRAS 449, 639
Subramanian, A., et al. 2017, MNRAS, 467, 2980
van der Marel, R. P., & Kallivayalil, N. 2014, ApJ, 781, 121