The Magellanic Clouds as a template for the study of stellar populations and galaxy interactions

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The Magellanic System represents one of the best places to study the formation and evolution of galaxies. Photometric surveys of various depths, areas and wavelengths have had a significant impact on our understanding of the system; however, a complete picture is still lacking. VMC (the VISTA near-infrared YJK_s survey of the Magellanic System) will provide new data to derive the spatially resolved star formation history and to construct a three-dimensional map of the system. These data combined with those from other ongoing and planned surveys will give us an absolutely unique view of the system opening up the doors to truly new science!

Keywords: Magellanic Clouds — surveys

1 Introduction

The Magellanic Clouds (MCs) are interacting SBm galaxies similar to many that exist in Universe. They are the largest neighbouring satellites of the Milky Way, reflecting a typical environment of a large galaxy surrounded by satellites. They contain stars which are as old as the Universe as well as newly forming and this extended range of star formation is a highly valuable source to understand the process of formation and evolution of galaxies in general.

The MCs are overall more metal poor than the Galaxy and therefore may hold information about the Universe at its early stages. They are located at a fairly well known distance, which makes it easier to measure details of their stellar component and structure. They are also fortunately located in a region of sky only lightly affected by Galactic reddening, which translates into the capability of detecting their faint stellar populations.

The MCs belong to a complex system, the Magellanic System, which has in total four distinct components: the Large Magellanic Cloud (LMC), the Small Magellanic Cloud (SMC), the Bridge connecting the two Clouds and the Stream attached to the SMC. The latter two are predominantly formed of gas and are of tidal origin.

2 A near-infrared view of the Magellanic Clouds

The evolved stellar population of the Magellanic Clouds is best studied in the near-infrared window. At these wavelengths luminous giant stars: asymptotic giant branch (AGB) stars and upper red giant branch (RGB) stars have been detected in large numbers across the galaxies by wide-field surveys like DENIS and 2MASS.

These surveys have shown that the number density distribution of these stars traces the morphology and structure of the galaxies. The ratio between C-rich (or C-type) and O-rich (or M-type) AGB stars, (the C/M ratio) is an indicator of the iron abundance ([Fe/H]); the relation between these two quantities has been calibrated using homogeneous observations of AGB stars in various galaxies of the Local Group (Battinelli & Demers 2005). The distinction between the two AGB types depends on the stellar surface chemistry that can be dominated either by carbonaceous or silicate molecules. These molecules are responsible for the opacity directly affecting broad-band colours; C-rich AGB stars populate a large range of $J - K_s$ colours a narrow range of K_s magnitudes contrary to O-rich AGB stars. The K_s magnitude distribution of AGB stars, interpreted using appropriate theoretical models, is a simple indicator of the mean age and metallicity of the underlying stellar population showing considerable inhomogeneities across both galaxies. These results are described in more detail below.

2.1 The structure of the LMC

The distribution of AGB stars (Fig. 1), regardless of their spectral type, shows a smooth outer elliptical structure embedding a thick bar and protuberances emerging from it, hinting at the existence of spiral arms (Cioni, Habing, & Israel 2000).

By selecting AGB stars in a narrow range of colours, their mean luminosity will trace distances across the structure of the galaxy. In fact, this method allowed us to derive the orientation of the LMC in the sky, providing accurate measurements of the inclination and the position angle (van der Marel & Cioni 2001).

2.2 The C/M across the LMC

The distribution of the C/M ratio across the LMC (Fig. 2) shows clearly the existence of the classical metallicity gradient which is present in many galaxies: the iron abundance is higher in the centre and decreases more or less radially outwards (Cioni & Habing 2003). This trend has subsequently been confirmed using RGB stars (Alves 2004).

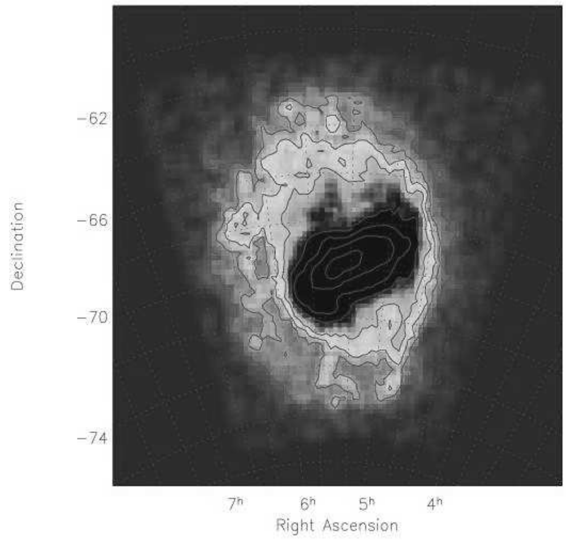

Figure 1: Distribution of AGB star counts across the LMC. Contours are at 3, 5, 10, 20, 30, 50, 100, 150 per 0.04 deg^2 (Cioni, Habing, & Israel 2000).

2.3 The K_s method

The K_s magnitude distribution of AGB stars holds important information on the metallicity and age of the overall stellar population. In particular, the observed magnitude distribution of C-rich and O-rich AGB stars can be interpreted using theoretical distributions constructed using stellar evolutionary models spanning a range of metallicity and age parameters. First, it is necessary to isolate the AGB component from other stellar components such as foreground stars or stars at other stages of evolution. This is done using the near-infrared colour-magnitude diagram ($J - K_s$, K_s). The same selection criteria are applied to synthetic diagrams obtained from stellar evolutionary models. Then, the resulting observed and theoretical samples are compared to identify the one that best represents the stellar population in the selected area (Fig. 3).

The study of the MCs using this technique with theoretical models from the Padova group (Girardi et al. 2000; Bertelli et al. 1994; Marigo, Giradi, & Bressan 1999) is presented in Cioni et al. (2006a,b). The authors showed that the star formation rate derived from localised regions within the galaxies does not apply to the galaxies as a whole but inhomogeneities in both metallicity and mean age are clearly present. This result is free from systematic differences that may occur because of the specific stellar models adopted.

2.3.1 The LMC mean age and metallicity

The stellar population across the LMC appears younger in the East than in the West. The bar has a composite stellar population and does not show up in the maps of mean age and metallicity. These maps have been corrected for the orientation of the LMC in the sky and for foreground, but not differential, reddening.

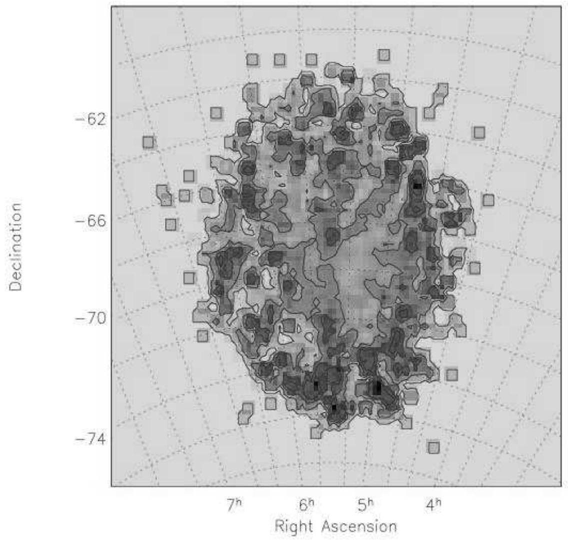

Figure 2: C/M ratio distribution across the LMC. Contours are at: 0.1, 0.25, 0.4, 0.55 per 0.04 deg^2 (Cioni & Habing 2003).

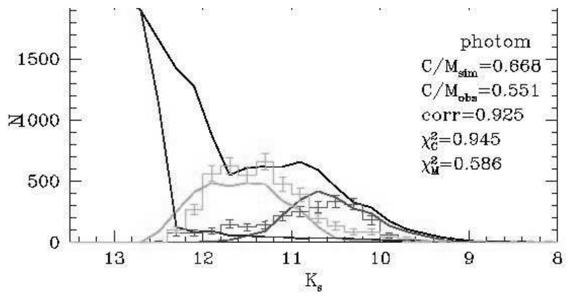

Figure 3: Observed magnitude distribution of C and M stars (histograms) compared with theoretical distributions (continuous lines) in a given region of the LMC (Cioni et al. 2006a).

The C/M ratio traces well the distribution of metallicity obtained from the K_s method confirming the validity of the C/M ratio as an indicator of [Fe/H]. There is a region North-East of the centre where the metallicity is high, as well as in an outer ring-like structure extending from the South to the West. While the first region probably corresponds to a place with active star formation, the latter might be affected by a low number statistics or by the size of the bins adopted to construct K_s histograms. In fact, the distribution of the C/M ratio derived in smaller bins (Fig. 2) shows clearly a metal poor ring around the LMC which surrounds a region where the metal content is higher. This substructure is washed out by larger bins necessary to obtain a statistically significant K_s magnitude distribution for both C-rich and O-rich AGB stars (Cioni et al. 2006a).

2.3.2 The SMC mean age and metallicity

The distribution of metallicity across the SMC as a function of age shows a very interesting pattern, perhaps associated with the propagation of star formation throughout time. A region of high metallicity is located South-East of the galaxy centre and corresponds to a mean age of 2 Gyr. Going back in time this region moves clockwise to the West, leaving the centre of the galaxy metal poor and with very little variation (Cioni et al. 2006b), Fig. 4.

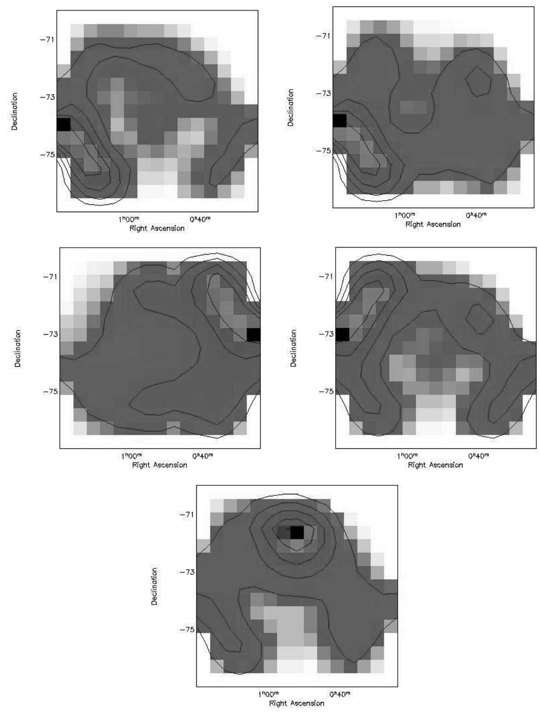

Figure 4: Clockwise from the top left: distribution of the metallicity that corresponds to the maximum probability for a star formation rate equivalent to a mean age of: 2.0, 3.9, 6.3, 8.7 and 10.6 Gyr for C stars across the SMC. Contours are at: 0.7, 0.8, 0.9, 0.94 and 0.98 expressed in terms of Z (Cioni et al. 2006b).

A similar ring-like feature traced by high metals was also detected by Harris & Zaritsky (2004) in their analysis of the MCs Photometric Survey database. They found that this substructure corresponds to a stellar population of about 2.5 Gyr old either originating from a gas rich merger or awaiting the subsequent inward propagation of star formation.

2.4 Origin of inhomogeneities

Inhomogeneities of metallicity and age are, according to Bekki & Cioni (2007), fossil records of clumpy pasts of galaxies. This means that stars form in clumps and each clump has an age and a metallicity. If clumps are smaller than 10^7 $M_\odot$ then they dissolve to form the field stellar population. On the contrary, if clumps are larger then they keep their identity and will form stable structures like galaxy cores and bars. From what the K_s method has shown us, it is possible to isolate regions in a galaxy that can be associated with a dominant mean age and metallicity suggesting that most of the population there originates from a given clump or from a combination of clumps which differs from the combination that was present in another spatially different region.

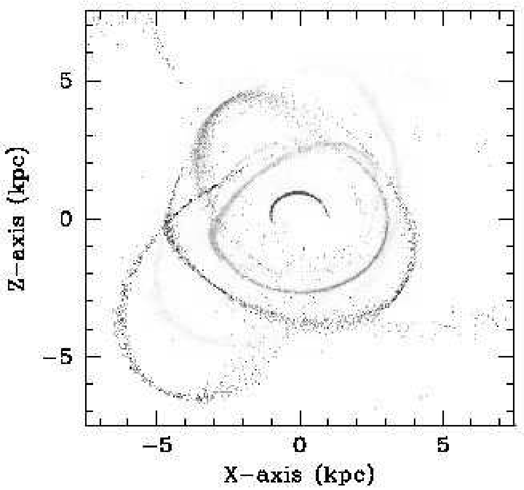

Figure 5: Distributions of stars originating from different stellar clumps projected onto the $x - z$ plane for different tidal interaction models tracing each a different arc; for a colour figure see (Bekki & Cioni 2007).

2.5 What is missing?

A complete picture of a galaxy is given by the age, metallicity and motion of all constituents at a given place. To obtain these we need to observe all objects (stars, dust and gas) and we need sophisticated theoretical models that convert observables into physical properties (e.g. age, metallicity).

The K_s method, however, provides only average values of the age and metallicity. The latter is also measured somewhat more accurately by the C/M ratio. What is needed are absolute values and to obtain those we need either new observations or, if applicable, more sophisticated analysis techniques and a large effort to develop new theoretical models that include and are able to reproduce all observational details.

The kinematics is certainly a fundamental aspect which will not be discussed in more detail in this paper. A knowledge of the full chemistry is also fundamental, this is not limited to the iron abundance discussed here but also to the abundance of other elements such as α elements which play a major role in the evolution of stars and galaxies.

A knowledge of the structural parameters of galaxies plays an important role in understanding the distribution of its stellar content. It is not always easy to disentangle the effect due to distance and that due to stellar populations from an observed magnitude shift, especially in galaxies of a moderate size.

3 The VISTA Public Survey of the Magellanic System

The VISTA public survey of the Magellanic System (VMC), lead by Cioni, is the result of an international collaboration of astronomers working in 9 different countries, but most of them are in the United Kingdom and Italy. We have prepared a Public Survey proposal to use the newly developed VISTA telescope with its infrared camera (Emerson, McPherson, & Sutherland 2006) to obtain unique observations of the Magellanic System that will considerably improve our understanding of its formation and evolution and could be used as a template for the study of galaxy evolution in general.

VMC is one of 6 public surveys approved by the European Southern Observatory; one of two targeting resolved stellar populations. For details about VISTA public surveys check the recent publication by Arnaboldi et al. (2007).

3.1 VISTA

The VISTA telescope is the premier infrared survey instrument for the foreseeable future. The 4-m telescope is located at the excellent Chilean site of Paranal. The 16 2048×2048 pixel detectors in the camera cover from 0.82 to 2.3 micron in wavelength via (seven) broad and narrow band filter sets. The pixel size is $0.339''$ with an instrument point spread function of $0.51''$.

In order to cover homogeneously an area of sky observations will be offset to fill in the gaps among the detectors. These amount to 95% in the x direction and 47.5% in the y direction. In particular, a minimum number of six offsets will cover 1.65 deg^2 where each pixel will be observed at least twice.

More details about telescope and camera can be found at http://www.vista.ac.uk/.

3.2 VMC observing strategy

VISTA observations of the Magellanic System will be obtained in three filters: Y, J and K_s. A total area of 184 deg^2 will be covered during five years; the survey is expected to begin in the fall of 2008. In detail, 116 deg^2 will cover the LMC, 45 deg^2 the SMC, 20 deg^2 the Bridge and 3 deg^2 the Stream (Fig. 6). Observations will be obtained in service mode when the observing conditions necessary to meet the survey goals are met. In practice, the most crowded regions like the bars of each galaxy will be observed when the seeing is $\sim 0.6''$ while less populous and outer regions will be observed with a seeing of $0.8 - 1.0''$.

The sensitivity that the VMC survey will reach is going to match existing observations at optical wavelengths and will also constitute their unique near-infrared counterpart. These limits, for S/N= 10, are: $Y = 21.9$, $J = 21.4$ and $K_s = 20.3$ mag. The expected

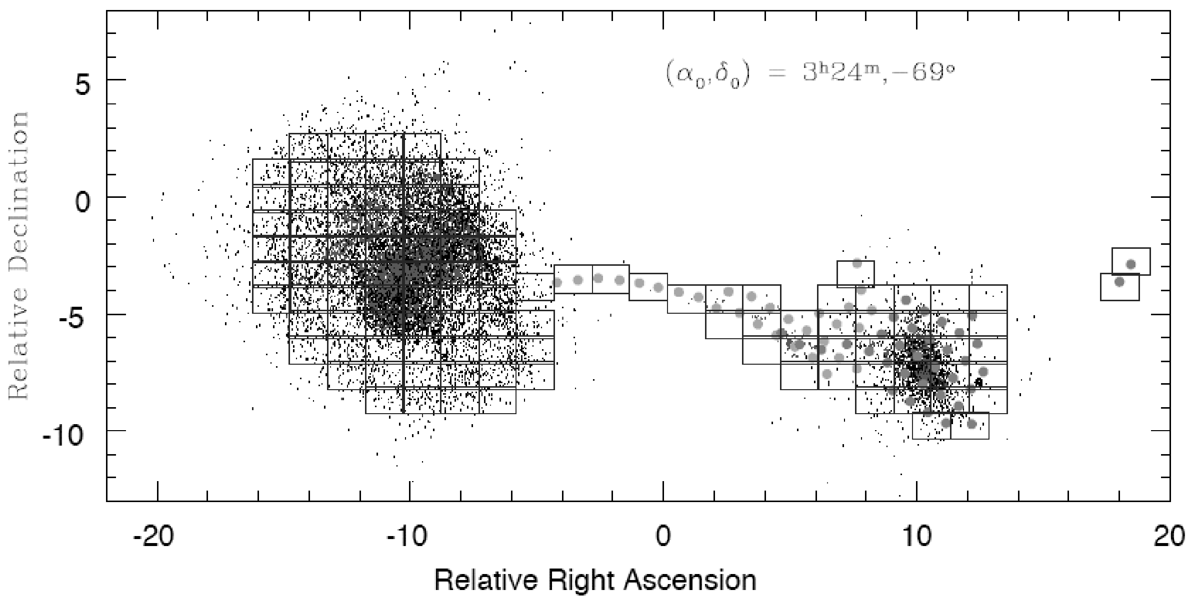

Figure 6: Distribution of VISTA tiles across the Magellanic System. Underlying small dots indicate the distribution of C stars, clusters and associations while thick dots show the location of observations to be performed with the VLT Survey Telescope in the optical domain.

efficiency of VMC observations is $\sim 80\%$, but this may change after telescope first light. To accumulate sufficient integration time to reach the aforementioned sensitivity the plan is to acquire one epoch at each filter during a given night and to accumulate two subsequent epochs in Y and J as well as 11 epochs in K_s during the same semester for a given field (a tile).

3.3 VMC science goals

The main VMC science goals are the determination of the spatially resolved star formation history and metallicity evolution across the Magellanic System, the three-dimensional geometry of the system and the age dependency (empirical and theoretical) as well as the search for substructures like new clusters and streams.

The sensitivity of VMC will allow us to employ different indicators to meet the major science goals. In particular, the survey will reach sources 6 mag fainter compared to the 2MASS and DENIS surveys, currently broadly used to study the stellar content of the Magellanic Clouds as a whole. These surveys despite covering both galaxies homogeneously do reach only upper red giant branch stars. VMC will include the entire red giant branch population, short period variables and in particular old RR Lyrae stars, down to the oldest turn-off stars. Simulations show that this is the required sensitivity to determine the age of the stellar populations with a resolution of 0.2 dex with 20% errors.

The geometry of the system will be measured using the luminosity of red clump stars, the period-luminosity (PL) relation of RR Lyrae stars and Cepheids and using standard candles in clusters. All these indicators are not free from *problems* but we expect to produce a convincing measurement by combining their results.

3.3.1 Star formation history

Information about the star formation history (SFH) of the LMC has been derived from the study of many relatively small regions located in the outer and inner disk as well as along the bar. In the SMC, apart from the comprehensive study by Harris & Zaritsky (2004), which does not probe the outer structure, there have been considerably fewer (and less detailed) observations of the field and cluster stellar populations than in the LMC. Using VMC data the distribution of field stars in different phases of evolution will be traced out to distances never yet explored. In particular we aim to sample the population of RGB stars because their behaviour is better understood and, because they are likely more metal poor and, they trace the tidally stripped parts of the galaxies and the extended halo component. Densities of different stellar objects are strongly correlated with the SFH.

The most powerful tool for quantitatively measuring the SFH in nearby galaxies is the analysis of colour-magnitude diagrams via objectives algorithms that search for the composite model that best fits the observations. A primary target of the VMC survey is to allow the SFH measurement in the Magellanic System with unprecedented accuracy and detail, via this kind of analysis. Figure 7 shows a typical simulation for the LMC assuming the VMC targeted depth and

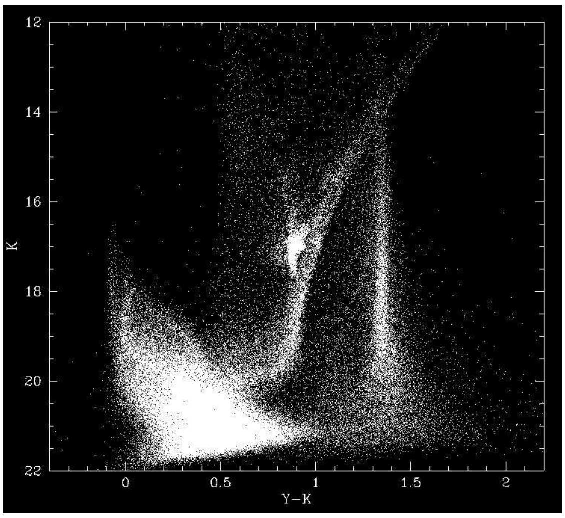

Figure 7: Simulated colour-magnitude diagram for a 0.6 deg^2 LMC area with a known star formation history. The main sequence, the complete RGB, early-AGB and red clump stars are clearly visible; the Galactic foreground stars are mostly comprised in an almost vertical sequence red-wards of the majority of LMC stars.

an input SFH constant over the $0.1 - 12$ Gyr range.

VMC data represent a unique, currently missing, counterpart for optical sources of similar depth, this will provide us with the ultimate understanding of the SFH across the system.

3.3.2 Short-period variables

RR Lyrae stars trace the old ($t > 10$ Gyr) stellar component and follow a PL relation only in the K band (Longmore, Fernley, & Jameson 1986). Although it is weakly affected by evolutionary effects, spreads in stellar mass inside the instability strip, and uncertainties in the reddening correction, it does depend on metallicity; Dall'Ora et al. (2004) show the application of this relation to refine the distance to the Reticulum cluster in the LMC. The theoretical calibration of this relation relies strongly on the $(V - K)$ colour. RR Lyrae stars in the MCs have $K_s \approx 18.0 - 19.0$ mag and optical data of comparable sensitivity covering most of the LMC and the SMC from which to derive the period of the variation, are or will be available from microlensing surveys while similar data covering the Bridge will be obtained from STEP (Sec. 3.3.5). Thus, it is of prime importance to measure the mean K_s-band magnitude of RR Lyrae stars with the VMC survey.

Cepheids are young or intermediate-age stars (100 Myr) which follow a much narrower PL relation in the K_s band than the corresponding optical relations and less affected by systematic uncertainties related to our knowledge of the reddening and metal content (Caputo, Marconi, & Musella 2000); the intrinsic accuracy of the PL-metallicity relation is ≈ 0.05 mag (Dall'Ora et al. 2004). The observed properties of RR Lyrae and Cepheid stars will be compared with updated theoretical work based on nonlinear convective models of pulsating stars (Marconi et al. 2003). For Cepheids, the application of theoretical PL and PL-colour relations to both near-infrared and optical data will allow us to evaluate self consistently distances, reddenings and metal abundances (Caputo, Marconi, & Ripepi 1999; Caputo et al. 2001). Moreover, information on the SFH could be inferred from the application of theoretical period-age and period-age-colour relations (Marconi et al. 2006).

3.3.3 Stellar clusters

Despite a wealth of detailed studies, e.g. Holtzman et al. (1999); Harris & Zaritsky (2004), it has not yet been firmly established whether the field star population has experienced the same, or a similar, SFH as the star cluster systems, e.g. Hunter et al. (2003); de Grijs & Anders (2006); Chandar, Fall, & Whitemore (2006); Gieles, Lamers, & Prte (2007); de Grijs & Godwin (2007) in either of the Clouds. By combining their integrated photometry with resolved stellar population studies, the MC cluster system offers a unique chance to independently check the accuracy of age (and corresponding mass) determinations based on broad-band spectral energy distributions (BB-SEDs).

Anders et al. (2004) and de Grijs & Anders (2006) developed a method that employs multiple passband observations to obtain simultaneously cluster ages, masses, metallicities and extinction values. Based on a minimum of well-chosen passbands, absolute ages were derived with a precision of 35% and relative ages to an order of magnitude better (de Grijs et al. 2005). Moreover, Anders et al. (2004) concluded that to both constrain the cluster ages *and* their metallicities independently using BB-SEDs, one would require high-quality photometry at *both* blue *and* red wavelengths. The requisite data quality at the reddest (near-infrared) wavelengths is lacking at present, yet its inclusion would allow us to (i) reach higher accuracy in the cluster age determinations (better than $\sim 20\%$, which would therefore lead to much firmer statistical and comparative conclusions regarding the cluster-field star connection, for instance) and (ii) as a consequence, minimise the occurrence of artefacts in our cluster age-dating techniques (sometimes referred to as 'chimneys'; see e.g. fig. 7 in de Grijs & Anders (2006). In addition, by including near-infrared passbands we can constrain any metallicity and extinction variations much more precisely than by using optical data alone (Ivanov & Borissova 2002; Valenti, Ferraro, & Origlia 2004).

Wide-field VMC data will produce a complete census of the cluster population (both the optically visible and the embedded clusters and associations) that will allow us to draw statistically robust conclusions; we will properly compare spatial differences within the Clouds and possibly – for the first time – strongly constrain the shape of the low-mass cluster mass function, see, e.g., de Grijs & Godwin (2007). This will provide the possibly best constraints on the evolution of the entire cluster mass function, and hence provide us with a handle on the clusters' potential for longevity.

3.3.4 Planetary Nebulae

The census of Planetary Nebulae (PNe) in the MCs is incomplete and biased. These objects trace the low- and intermediate-mass stellar evolution, are important extragalactic distance indicators and contribute to the replenishment of the interstellar medium with new elements out of which a new generation of stars may form. Deep wide-field VMC observations will allow us to uncover the missing number of PNe contributing to the study of their properties and of the properties of the host galaxy. A bi-product of this research will be the compilation of the Magellanic Extended Source Selection (MESS) catalogue.

PNe are recognized as emission line objects in particular of Hα and [OIII] but also of other elements. Bright central stars and nebulae in uncrowded regions of the MCs were imaged by the Hubble Space Telescope down to $V \sim 25$ and by Spitzer in the mid-infrared. In the near-infrared VMC will reach a comparable sensitivity. PN will be bright in K_s because of Brγ emission and much fainter, if detected, in Y and J (continuum) compared to other emission line objects; Brγ is less sensitive to reddening. The combination with deep optical imaging and spectroscopy will not only contribute to the selection and identification of new PNe but will resolve the ambiguity with HII regions, young stellar objects, SN remnants and background galaxies.

Recent observations have shown that the surface brightness of PNe is well correlated with size, the fainter PNe tend to be larger and current samples are highly incomplete at this level. Just the central 25 deg^2 of the LMC have been surveyed by deep Hα observations and that has already tripled the number of previously known PNe. Observations of the SMC cover a larger area of the galaxy but are on average shallower. In addition, older objects are considerably undersampled, these are usually found out to large distances from the centre. The present data show a spatially and evolutionary biased sample of PNe which limits a complete understanding of this late evolutionary phase and a broad use of these objects (i.e. luminosity function, progenitors). Considering that the AGB population of the LMC and SMC define smooth elliptical structures covering areas of about 116 deg^2 and 45 deg^2, respectively, there is plenty of room for new discoveries!

3.3.5 Ancillary goals

There are other science topics that VMC will considerably contribute to. Those in which the team is directly involved are: the determination of the distance to the LMC (a reference for the distance scale in the Universe) with an unprecedented quality that will reduce by a factor of two current uncertainties; finding obscured massive stars and unreddened 1.5 $M_\odot$ pre-main sequence stars; determine the proper motion of the Magellanic Clouds by using VMC data alone over the five years of the survey, resulting in an accuracy of ~ 0.05 mas/yr, or by combining VMC data with 2MASS data spanning a total time of about 15 years, reducing further the uncertainty in the measures. Finally, one of the most important aspects of VMC will be to provide targets for new follow-up observations using telescopes with a larger collecting areas like the Very Large Telescope (VLT).

3.4 VMC complementary surveys

The VMC data alone will be a valuable resource which aims to explain the Magellanic System but also to provide a highly valuable counterpart for stars detected by other means, building on the scientific value of the research each survey set out to produce. Among these complementary surveys are:

- EROS, OGLE and MACHO microlensing surveys that observed and/or are still observing extended areas centred on each MC periodically for/since several years allowing the characterisation and discovery of many short period variables such as RR Lyrae and Cepheids, these data will be used to measure the period of these variables while their mean K_s magnitude will be obtained by VMC, these period-magnitude relations will be used to trace the three-dimensional geometry of the MCs;
- SIRIUS and deep-2MASS are two near-infrared surveys of the MCs which will reach a magnitude fainter sources compared to the original 2MASS survey, these surveys have been completed very recently and will represent a step further in the study of near-infrared stellar populations in the MCs until the much deeper VISTA data will become available;
- SAGE and S3MC are two surveys currently ongoing from the Spitzer Space Telescope, they focus on obscured sources like embedded late-type stars and star forming regions in the MCs, many of these objects do not have a near-infrared counterpart and are too obscured to be detected at optical wavelength, this aspect severely limits their classification and study and VMC data will therefore be extremely valuable;
- MOSAIC is a deep optical survey of the outer MCs from 7° to 20° from the centre, the overlap with VMC data will be minimum but both surveys will be highly complementary;
- AKARI is a mid-infrared space telescope which is currently observing the MCs via an all sky survey but also via dedicated observations. These data, analogous to the Spitzer data, will characterise dusty sources for which VMC counterparts will prove highly useful.
- STEP is an optical survey of the SMC and the Bridge components of the Magellanic System to be performed with the VLT survey telescope (the VST), these data will provide unique periods for short period variables located in the Bridge and will also reach sources as faint as VMC will do across the SMC;

- GAIA is an astrometric survey which is due to begin within the next decade, it will measure the accurate proper motion of the MCs, the kinematics and metallicity (via the Ca II triplet) of all bright giant stars, these informations combined with VMC data as well as with optical data of a similar sensitivity will provide the necessary ingredients to study the evolution of the Magellanic System, the propagation of star formation as well as the interaction with the Milky Way galaxy.

4 Conclusions

The Magellanic System has yet many challenging aspects that new surveys, with the increased quality of the coming data and new theoretical models and their ability to explain detail observations, aim to resolve in the next decade.

Prior to new facilities like GAIA, JWST and ALMA we need to exploit data from VISTA and similarly powerful telescopes at other wavelengths. Surveys like VMC will provide unique and high quality data for science and training of young astronomers.

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