ASTRONOMY FROM WIDE-FIELD IMAGING

Part Ten:

THE MAGELLANIC CLOUDS

https://doi.org/10.1017/S007418090004794X Published online by Cambridge University Press

NEW RESULTS ON THE MAGELLANIC CLOUDS

D. HATZIDIMITRIOU
Department of Physics, University of Crete
GR 714 09
Heraklion, Crete
Greece

ABSTRACT. Recent results on global properties of the Magellanic Clouds are reviewed, with particular emphasis on the impact of wide-field techniques on their study. The subjects discussed include large-scale surveys of different tracers of intermediate age and old populations in the Clouds and new data on their chemical evolution, kinematics and spatial motion.

1. Introduction

Due to their proximity, the Magellanic Clouds offer an excellent opportunity to study in detail galaxies less evolved than our own; they have lower present-day chemical abundances (e.g. Thevenin & Jasniewicz 1992) and high gas-to-total mass ratios. They are also gravitationally interacting with each other and with the Galaxy (e.g. Fujimoto & Murai 1984), thus allowing us to test at close hand theories of galaxy interactions and their effects on galaxy evolution. Moreover, the Magellanic Clouds constitute excellent laboratories for the study of the physics of several classes of object, by alleviating (at least in the case of the LMC) one of the major constraints of such studies in our own Galaxy, that of the often poorly known distances to the objects.

The subject matter on the Magellanic Clouds (MC) has increased enormously in the last few years. Suffice it to mention that two recent conferences were dedicated entirely to their study (the IAU Symposium 148 in 1990, in Sydney, and the ESO workshop on Magellanic Cloud research, in 1992, in Heidelberg). In this paper, due to the lack of space and the enormity of the subject, I shall limit the reviewed matter to studies that were published (or completed) since the last Magellanic Cloud conference in 1992. For information on earlier work, the reader is referred to the proceedings of the previously mentioned meetings. Greater emphasis will be given to the intermediate age and old populations and to results originating in wide-field imaging and/or related to global properties of the Clouds. Finally, only observations in the optical wavelength region will be discussed.

The study of the global properties of the Magellanic Clouds depends largely (due to their proximity) on wide-field techniques. In the optical region, digitisation of wide-field photographic plates with measuring machines such as APM (Cambridge), COSMOS (Edinburgh) and MAMA (Paris), play an important role in studying the structure and stellar populations of the Clouds. On the other hand, in the near future, CCD mosaics (see e.g. Sekiguchi 1993) will start being

H. T. MacGillivray et al. (eds.), Astronomy from Wide-Field Imaging, 489–496.

customarily used for *deep* imaging of the Clouds, providing a significant improvement on areal coverage over even the largest single CCD chips currently available.

Another relatively new — but of continuously increasing importance — aspect of wide-field imaging in the Magellanic Clouds, is its use in conjunction with multi-fibre spectrographs, now available at most large telescopes in the Southern Hemisphere. Both the selection of targets (and their coordinates) and the subsequent interpretation of the results from such spectroscopic studies, depend on the availability of wide-field imaging data.

In the following, the reviewed matter will be grouped in four sections: first, stellar population surveys; second, structure and kinematics; third, chemical evolution; and finally, new results on the space motion of the Clouds.

2. Surveys

Large-scale surveys in the MCs serve the dual purpose 1) of producing large complete samples of particular classes of object, thus providing excellent test-beds for theories of their governing physical processes, and 2) of determining the large scale distribution of populations, which coupled with kinematical studies can inform us about the dynamics and history of evolution of the MCs.

2.1 RR-LYRAE VARIABLES

RR-Lyrae variables are tracers of populations older than $\simeq$ 10 - 12 Gyr, and they are consequently paramount in determining the distribution and dynamics of the early stellar generations in the Clouds.

In the *Small Magellanic Cloud*, since the study by Graham (1975) of field RR-Lyraes near the cluster NGC 121, only one other such study has been published, near the cluster NGC 361, by Smith et al. (1992). Both of these samples are located at very similar distances from the dynamical centre of the SMC (they lie almost on the same isopleth of clump/red horizontal branch stars, given by Gardiner & Hatzidimitriou 1992), and therefore do not give us much information about the shape of the spatial distribution of the old stars in the SMC. In an attempt to derive this spatial distribution, Hatzidimitriou & Hawkins (1993) conducted a search for RR-Lyraes over an area of 13 deg^2 to the west of the SMC centre (in the ESO/SERC survey field 28) and at projected distances between 3 - 6 kpc from it. This study is based on COSMOS measurements of UKST photographic plates, and thus it is essentially limited to higher amplitude variables (because of the limited photometric accuracy that can be achieved with this method). Preliminary results from this study showed that at least in this region of the SMC, the RR-Lyraes, i.e. populations older than 10 - 12 Gyr, seem to have the same radial distribution as the red giant clump stars in the same area (Gardiner & Hatzidimitriou 1992), which are generally younger than $\simeq$ 10 Gyr (Fig. 1). As will be seen in the next subsection, carbon stars have a similar spatial distribution as well. Therefore, intermediate age and old populations in the SMC are well mixed spatially, and would thus be expected to share similar kinematics as well.

In the *Large Magellanic Cloud*, Reid and Freedman continue their long term goal of identifying RR-Lyraes over large areas of the LMC, using photographic plates (and large format CCDs). In Reid & Freedman (1993), they present their results from a test region near NGC 2210, where they identified (using CCD observations) $\simeq$ 50% more RR-Lyrae variables than given by

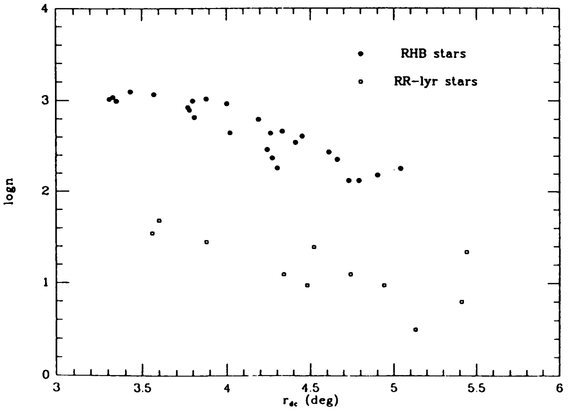

Figure 1. Radial distribution of RR-Lyr candidates (□) and of RHB/clump stars (•) in the ESO/SERC survey field 28. A constant was added to $\log n_{RR\text{-}Lyr}$, for illustration purposes; r_{dc} is the radial (projected) distance from the dynamical centre of the SMC.

Kinman et al. (1991). It should be mentioned that the MACHO project (e.g. Marshall 1993), which uses multiple CCD observations of LMC fields to identify micro-lensing events, is also expected to produce a large number of RR-Lyrae variables in these fields. Studies of RR-Lyraes in LMC globular clusters continue (Walker 1993), producing large samples of well observed such variables. Finally, of particular interest on the subject of the automated techniques used for the identification of RR-Lyrae variables, is the work by Welch & Stetson (1993), who propose a robust identification scheme for stellar variability.

2.2 CARBON STARS

With ages between $\simeq$ 0.8 - 8 Gyr, carbon stars typify the intermediate age (i.e. the dominant) populations in the MCs. Being bright and numerous, they are excellent test particles for kinematical and dynamical studies.

In the case of the Small Magellanic Cloud, there has been a great deal of progress in the last couple of years: the entire area of the SMC, including its outermost regions, has now been completely searched for carbon stars (Azzopardi 1993; Morgan & Hatzidimitriou 1993). The carbon star distribution thus derived, has an outermost contour of $\simeq$ 12 kpc in diameter, and the same radial distribution as other intermediate age populations such as RHB/clump stars. The remotely located carbon stars are expected to play a significant role in studies of the dynamics of the SMC outer regions (often referred to as the SMC 'halo').

Finally, Demers et al. (1993) have identified a number of carbon stars in the outer halos of the MCs and possibly in the intercloud region; a small number of carbon stars in the intercloud region were also found by Hazard & Morgan (1993, private communication).

2.3 OTHER SURVEYS

In the Large Magellanic Cloud, Hughes & Wood (1993, private communication) are in the process of extending their survey of *long period variables* (LPVs) to the Eastern and Western areas of the LMC, using UKST plates measured with COSMOS, with the purpose of determining the shape and kinematics of the LMC 'halo'. They are also monitoring in the infrared (J and K) LPVs from their 1991 survey (Hughes et al. 1991).

Morgan (1993) completed a survey of *planetary nebulae* (PNe) in the LMC, while Hughes & Wood (1993, private communication) are conducting a new survey of PNe to the North of the LMC, using UKST plates in OIII and Hα. Morgan (1993) found a total of 265 PNe, defining a system with a 13° diameter. He also found a 1° offset between the outer contour of the PNe distribution and the Bar.

Meyssonnier & Azzopardi (1993) have produced a new catalogue of *Hα emission-line stars* and small nebulae in the SMC; Marcelin (1993) and his collaborators, on the other hand, have produced *Hα maps* of the MCs, which should be particularly useful, e.g. for kinematical studies in the Clouds.

The *star-cluster systems* of the Clouds are widely used to determine global properties of their parent galaxies, such as their chemical evolution (section 3) and kinematics (section 4), as well as to derive broader conclusions about the formation (e.g. Richtler 1993) and other properties (e.g. the initial mass function, reviewed by Mateo 1993) of star clusters in general. Van den Bergh (1993) recently discussed the use of the MC clusters as tracers of the star-forming histories of the MCs. A recent review of the properties of MC clusters older than 1 Gyr can be found in Da Costa (1993) while some general characteristics of the LMC cluster system are discussed in Kontizas & Kontizas (1993), in this volume. It appears (Covino & Pasinetti Fracassini 1993) that the LMC clusters form a more heterogeneous system than the clusters of M 31 and the Galaxy.

Finally, wide-field imaging is of great importance in studying *star formation* (SF) processes in the MCs. Recent examples of such studies are the one by Vallenari et al. (1993), who studied the SF history of the young association NGC 1948 in the LMC, and the continuing study of young LMC associations (DeGioia-Eastwood et al. 1993) with the ultimate purpose of deriving the initial mass function of massive SF in the MCs. In the future, the use of large-format CCDs and CCD mosaics should greatly improve our knowledge of the SF history (not only recent SF) of the MCs, by providing us with high-quality deep colour-magnitude diagrams and luminosity functions over large areas and at different locations within the MCs.

3. Chemical Evolution

The age-metallicity relation of star clusters has traditionally been used to determine the chemical enrichment history of the Magellanic Clouds. In the SMC, there seemed to be a period of $\simeq$ 10 Gyr in its history (e.g. Da Costa 1991) when very little chemical enrichment took place. Such a result would require significant infall of unenriched gas. On the contrary, in the LMC chemical enrichment apparently proceeded at a quicker pace, although the 10 Gyr age gap (e.g. Da Costa 1993) in the cluster distribution does not allow us to trace its chemical evolution successfully, using this method.

Very recently, new spectroscopic measurement of Ca abundances of clusters in both Clouds have led to a refinement of the previous results. Olszewski (1993) and his collaborators have

https://doi.org/10.1017/S007418090004794X Published online by Cambridge University Press

rederived the age-metallicity relation of the LMC using a sample of 80 well observed star clusters with spectroscopic abundances and main sequence turnoff ages. Their results confirmed that the age-gap in the LMC cluster age distribution is accompanied with a metallicity gap and that the rise of metallicity with age has been rapid. They also compared 'inner' to 'outer' regions and concluded that — although in its outer regions the LMC has little present day gas content and very low surface brightness of stars — the outer regions apparently have the same heavy element formation as the inner regions.

Because of the age-gap in the cluster distribution of the LMC, we need to turn to the field populations, to improve our understanding of the chemical evolution of the LMC. Preliminary results on this subject in a distant field (8.5° from the centre) were reported by Olszewski (1993), while work is still in progress by his and other groups. It would appear, that most LMC giants in this field have $-1.6 < [Fe/H] < 0$, i.e. although the surface brightness of the field is very low, substantial enrichment has apparently occurred.

In the SMC, Da Costa & Hatzidimitriou (1993) have derived spectroscopic calcium abundances for 5 clusters (with main sequence turnoff ages) spanning an age-range of approximately 10 Gyr. The resulting age-metallicity relation for the SMC is shown in Fig. 2, along with the simple model prediction scaled to the present day gas content and metal abundance of the SMC.

Although any conclusions are bound to suffer from small-number statistics (there are very few aged massive star clusters in the SMC), the following preliminary statements can be made: first, the age-metallicity relation of Fig. 2 does not display the characteristic plateau that was apparent in the older data; second, the simple model provides a reasonably good fit; finally, there are indications that there may be a significant metallicity dispersion of $\simeq 0.4$ dex at all epochs. If the latter proves to be the case, then the discrepantly low abundance of the cluster NGC 330 in comparison with the corresponding field stars in its surroundings (e.g. Grebel & Richtler 1992) may be just a manifestation of this effect. The implication is that the chemical enrichment in the SMC has not been uniform and therefore that the star-forming gas was not well mixed.

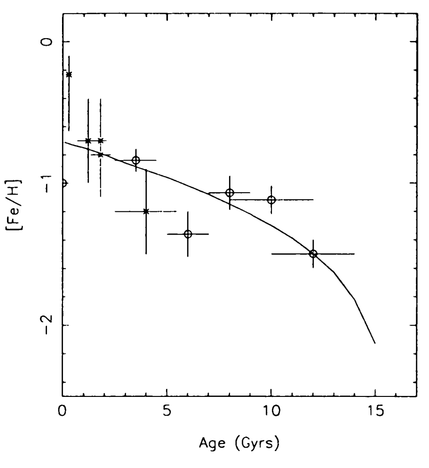

Figure 2. Age Metallicity Relation of the SMC. Star clusters with spectroscopic abundances are symbolised with o, while clusters with RGB-abundance estimates, with *.

https://doi.org/10.1017/S007418090004794X Published online by Cambridge University Press

4. Kinematics

The kinematics of the Clouds are of particular interest, not only because they reveal the internal dynamics of these galaxies, but also because they may give us clues about the possible effects of the tidal interactions taking place.

In the *Large Magellanic Cloud*, the consensus of most recent results is that all populations (including the old clusters in the outer regions!) belong to the same disk structure and share the same rotation (Olszewski 1993 and references therein). The velocity dispersion (about the best planar solution) of the oldest clusters is found to be 23 km/s, while a line-of-sight velocity dispersion of 45 - 55 km/s would be required for a hot halo (Olszewski 1993). However, there is evidence of spheroidal-like kinematics in the old long period variable population (Hughes et al. 1991), with a velocity dispersion of 33 km/s and little rotation.

Although more work needs to be done, the new cluster data dispense with twisted disks and warps, which were often introduced in the past in order to interpret the observed cluster kinematics, and which were assumed (at least by some) to have arisen from the LMC-SMC interactions. This probably comes as no surprise, given the results of new numerical simulations of the LMC-SMC interaction (Gardiner et al. 1993), which show that the LMC remained largely undisturbed by even the closest and most powerful of its encounters with the SMC. Interestingly, new HI (21 cm) data (Luks & Rolphs 1992) seem to be adequately modelled with a flat disk in differential rotation, without the need of a warp, which was usually introduced in the past to interpret the heliocentric radial velocity distribution of the disk.

In the Small Magellanic Cloud, there is still a paucity of kinematical information about intermediate age and old populations, especially in the outer regions. Hardy et al. (1993) reported a substantial increase (to 500) of the number of SMC carbon stars with accurate radial velocities, in the central regions of the SMC. They find no evidence of the rotation, or of the velocity splitting demonstrated by the young stars and gas in the same areas (e.g. Torres & Carranza 1987). They derive a large velocity dispersion of 26.6 $\pm$1.0 km/s for their sample.

On the other hand, Da Costa & Hatzidimitriou (1993) have measured the radial velocities (with an accuracy of to 2 - 5 km/s) of 5 intermediate age and old clusters in the SMC. The 4 clusters on the western side of the SMC (L1, L11, L113 and NGC 121) have a mean radial velocity of 127 km/s and a remarkably low velocity dispersion of $<$ 10 km/s! The fifth cluster, L113, has a higher radial velocity by 40 km/s, but it lies near the Wing and may therefore belong to a different kinematical system. However, a much larger sample is necessary, to determine reliably the velocity dispersion of the cluster system of the SMC.

To complicate the picture even further, a recent study of the kinematics of red horizontal branch stars in a field situated at 3.3 kpc to the NE of the SMC centre (Hatzidimitriou et al. 1993), revealed a well defined correlation between (what is interpreted as) line-of-sight depth and radial velocity, corresponding to 8 km/s/kpc, probably the result of the recent encounter between the LMC and the SMC. The velocity dispersion around this correlation was $\simeq$ 15 km/s.

We are still far from understanding the kinematics of the Clouds, and of the SMC in particular; the answers may come from accurate velocity measurements for large samples of objects at known distances and distributed over extended areas, which is obviously a task for multifibre spectrographs.

https://doi.org/10.1017/S007418090004794X Published online by Cambridge University Press

5. Proper Motions

The space motion of the Clouds, in connection with the LMC-SMC-Galaxy interactions, is a long-standing problem. In the last year, there have been reports on two attempts to measure the spatial motion of the LMC, by Kroupa et al. (1993) and by Lin et al. (1993), while there is ongoing work by other groups (e.g. Tucholke et al., private communication). Kroupa et al. used LMC members from the PPM catalogue to derive a proper motion of 1.7 ±0.9 mas/yr for the LMC, corresponding to a galactocentric transverse velocity of 335 ±200 km/s. The large error is mostly due to the small number of stars used. However, there may be additional systematic errors in the PPM catalogue (which may be corrected in the future with reference e.g to the Hipparcos proper motions).

Lin et al. using photographic plates of the remote LMC cluster NGC 2257 (~9 kpc from the centre), derived a transverse velocity of 220 ±61 km/s, by using background galaxies in the field to define the inertial system of reference. Significant corrections may have to be applied to this result, if the rotational curve of the LMC extends to the distance of NGC 2257.

Both these results are consistent — within the errors — with the new models of Gardiner et al. (1993), which predict a transverse velocity of 287 km/s for the LMC. However, as noted by Kroupa et al., in order to discriminate between different models of the mass distribution in the outer parts of the Galaxy (and therefore to better model the processes involved in the interactions between the Galaxy and the Clouds) the proper motion of the Clouds should be known to $\simeq$ 0.1 mas/yr, which is not achieved yet.

Acknowledgements

I would like to thank L. Gardiner, E. Hardy, S. Hughes, P. Kroupa, D. Morgan and N. Reid for sending preprints and/or communicating results in advance of publication. Moreover, I would like to thank my collaborators G. Da Costa, M. Hawkins and D. Morgan for allowing me to present some of our results prior to publication.

References

Azzopardi, M., 1993. These proceedings.

Covino, S. and Pasinetti Fracassini, L.E., 1993. *Astron. Astrophys.*, **270**, 83.

Da Costa, G.S., 1991. IAU Symp. No. 148, eds. R. Haynes and D. Milne, Kluwer Academic Publishers, Dordrecht, p. 183.

Da Costa, G.S., 1993. 'The Globular Cluster-Galaxy Connection', ASP Conference Series, Vol. 48, eds. G.H. Smith and J.P. Brodie, p. 363.

Da Costa, G.S. and Hatzidimitriou, D., 1993. In preparation.

DeGioia-Eastwood, K., Meyers, R.P. and Jones, D.P., 1993. *Astron. J.*, **106**, 1005.

Demers, S., Irwin, M.J. and Kunkel, W.E., 1993. *Mon. Not. R. astron. Soc.*, **103**.

Fujimoto, M. and Murai, T., 1984. IAU Symp. No. 108, eds. S. van den Bergh and K.S. de Boer, Reidel, Dordrecht, p. 115.

Gardiner, L.T. and Hatzidimitriou, D., 1992. *Mon. Not. R. astron. Soc.*, **257**, 195.

Gardiner, L.T., Sawa, T. and Fujimoto, M., 1993. Nagoya University Preprint **93-07**.

Graham, J.A., 1975. *Publ. Astron. Soc. Pacific*, **87**, 641.

Grebel, E.K. and Richtler, T., 1992. *Astron. Astrophys.*, **253**, 359.

Hardy, E., Beauchamp, D and Suntzeff, N.B., 1993. Proc. of 3rd DAEC Meeting on 'The Feedback of Chemical Evolution on the Stellar Content of Galaxies', Meudon, France, October 1992, in press.

Hatzidimitriou, D., Cannon, R.D. and Hawkins, M.R.S., 1993. *Mon. Not. R. astron. Soc.*, **261**, 873.

Hatzidimitriou, D. and Hawkins, M.R.S., 1993. In preparation.

Hughes, S.M.G., Wood, P.R. and Reid, I.N., 1991. *Astron. J.*, **101**, 1304.

Kinman, T.D., Stryker, L.L., Hesser, J.E., Graham, J.A., Walker, A.R., Hazen, M.L. and Nemec, J.M., 1991. *Publ. Astron. Soc. Pacific*, **103**, 1279.

Kontizas, M. and Kontizas, E., 1993. These proceedings.

Kroupa, P., Roeser, S. and Bastian, U., 1993. *Mon. Not. R. astron. Soc.*, in press.

Luks, Th. and Rolphs, K., 1992. *Astron. Astrophys.*, **263**, 41.

Lin, D.N., Jones, B.F. and Kremola, A.R., 1993. AAS meeting, Berkeley, 1993.

Marcelin, M., 1993. These proceedings.

Marshall, S., 1993. These proceedings.

Mateo, M., 1993. 'The Globular Cluster-Galaxy Connection', ASP Conference Series, Vol 48, eds. G.H. Smith and J.P. Brodie, p. 387.

Meyssonier, N. and Azzopardi, M., 1993. *Astron. Astrophys. Suppl.*, in press.

Morgan, D.H., 1993. *Astron. Astrophys. Suppl.*, in press.

Morgan, D.H. and Hatzidimitriou, D., 1993. These proceedings.

Olszewski, E.W., 1993. 'The Globular Cluster-Galaxy Connection', ASP Conference Series, Vol. 48, eds. G.H. Smith and J.P. Brodie, p. 351.

Reid, I.N. and Freedman, W., 1993. *Mon. Not. R. astron. Soc.*, in press.

Richtler, T., 1993. 'The Globular Cluster-Galaxy Connection', ASP Conference Series, Vol. 48, eds. G.H. Smith and J.P. Brodie, p. 375.

Sekiguchi, M., 1993. These proceedings.

Smith, H.A., Baird, S.R. and Graham, J.A., 1992. *Astron. J.*, **104**, 1430.

Thevenin, F. and Jasniewicz, G., 1992. *Astron. Astrophys.*, **266**, 85.

Torres, G. and Carranza, G.J., 1987. *Mon. Not. R. astron. Soc.*, **226**, 513.

Vallenari, A., Bomans, D.J. and de Boer, K.S., 1993. *Astron. Astrophys.*, **268**, 137.

van den Bergh, S., 1993. 'The Globular Cluster-Galaxy Connection', ASP Conference Series, Vol. 48, eds. G.H. Smith and J.P. Brodie, p. 346.

Walker, A.R., 1993. *Astron. J.*, **105**, 527.

Welch, D.L. and Stetson, P.B., 1993. *Astron. J.*, **105**, 1813.