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GALAXIES

The Future Utilisation of Schmidt Telescopes
ASP Conference Series, Vol. 84, 1995
J. M. Chapman, R. D. Cannon, S. J. Harrison and B. Hidayat (eds)

The Study of Stellar Populations and Dynamics in the Small Magellanic Cloud using the UKST

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Abstract. The combination of the wide field of Schmidt telescope photographic plates with fast measuring machines such as COSMOS and APM, had a major impact on the study of the global properties of the Magellanic Clouds. Results (based on UKST data) regarding the stellar populations and dynamics of the Small Magellanic Cloud are described here in some detail. The stellar content and kinematics of the intercloud region are also outlined, with particular emphasis on the importance of this region in understanding the interaction between the Magellanic Clouds.

1. Introduction

The history of evolution of the Magellanic Clouds is believed to have been markedly different from that of the Galaxy. The SMC, in particular, is a typical dwarf irregular galaxy, two orders of magnitude less massive than our own and with the low metal content and high gas-to-total mass fraction that generally characterize less evolved systems. Apart from offering a unique opportunity to study at close hand the star formation processes in such systems, the SMC is also the least massive, and hence the most likely to be disturbed, member of the triple interacting system consisting of the two Magellanic Clouds and the Galaxy.

The operation of the two 1 m class Schmidt telescopes in the Southern Hemisphere (one at Siding Spring, in Australia, and one at ESO, in Chile) had a significant impact on the study of the Magellanic Clouds, which are sufficiently close to require the large field of view of a Schmidt telescope for the determination of their structure and evolution. In the last 25 years there has been a continuous evolution in the methods used to analyse Schmidt telescope photographs, ranging from visual inspection of the plates to sophisticated analyses of plate scans by fast measuring machines such as COSMOS (Edinburgh) and APM (Cambridge).

In the following sections, some results on the stellar content and dynamics of the SMC, based on UKST plates, will be briefly described. For reviews on the subject of the Magellanic Clouds, the reader is referred to the two recent conferences devoted entirely to the Magellanic Clouds, namely, the IAU Symposium 148 (1990) and the Second European Meeting on 'Recent Developments in Magellanic Cloud Research' (1992). Finally, a review of even more recent and

https://doi.org/10.1017/S0252921100022260 Published online by Cambridge University Press

on-going research in both Clouds using wide-field techniques can be found in Hatzidimitriou (1994).

2. Stellar Populations in the SMC

2.1. Colour Magnitude Diagrams over 130 square degrees

Using *COSMOS* digitisations of a total of 38 blue (J) and red (R) deep UKST photographic plates, a large grid of $\simeq$ 150 colour magnitude diagrams (R vs $B-R$, hereafter CMDs) was constructed covering an area of 130 square degrees in the 'outer regions' of the SMC, i.e. at projected distances larger than 2 kpc from the optical centre (Hatzidimitriou, Hawkins & Gyldenkerne 1989 (Paper I), Hatzidimitriou & Hawkins 1989 (Paper II), Gardiner & Hawkins 1991 (Paper III), Gardiner & Hatzidimitriou 1992 (Paper IV)). The basic data set comprises colour ($B-R$) and magnitude (R) information for 1.1×10^6 stars. The instrumental COSMOS photometry was calibrated using a grid of CCD sequences. The limiting magnitude of the survey was $R = 20$ mag, and the completeness was better than 90 % down to $R = 19.5$ mag. Details on the accuracy and completeness of the data-set and on the methodology of the analysis can be found in Papers I and IV. The same data-set was also used for the study of the line-of-sight depth of the SMC, discussed in §3. It should be mentioned that similar studies, using COSMOS measurements of UKST plates, have been conducted earlier as well (Hawkins & Brück 1982; Brück, Cannon & Hawkins 1985), but they covered only about 1–2 % of the area of the survey described here.

A detailed description of the CMDs can be found in Paper I. Briefly, a typical CMD consisted of a conspicuous clump/red-horizontal branch at $R \simeq 19$ mag, the red giant and subgiant branches, and a usually sparsely populated main sequence (with the exception of the Wing region, where the main sequence dominates the CMD) with the magnitude of its 'tip' varying as a function of position in the SMC.

Due to the magnitude limit of the survey, the detectable main sequence stars essentially corresponded to populations younger than 1–2 Gyr (assuming a distance modulus of 18.8 for the SMC, and using the Revised Yale Isochrones to derive ages from main-sequence fitting). The overall projected distribution of these younger populations consisted of, as expected, the SMC 'Bar', the 'outer arm' and the 'Wing' region, and it correlated well with the neutral hydrogen (HI) distribution (e.g. Mathewson & Ford 1984). There appeared to be a significant NE extension of the outer contour well beyond the outer arm; however, there may be some admixture of somewhat older stars in the registered counts of main sequence stars in these areas, due to the generally shorter mean distance modulus in the NE (see §3.1 and Paper II).

The luminosity function of the observed main sequence generally corresponded to mixtures of stellar populations with only two identifiable discrete (and localized) star formation events: the well-known very young population in the Wing ($\tau \simeq 5 \times 10^7$ yr, see also Irwin, Demers & Kunkel (1990)) and a 4–6 $\times 10^8$ yr population most conspicuous in the NE area (near the 'outer arm', also identified by Brück & Marsoglu 1978). The stellar content of the Wing and NE outer arm has also been studied on the basis of the distributions of spectral

https://doi.org/10.1017/S0252921100022260 Published online by Cambridge University Press

types of their brighter stars (from UKST prism plates) by Kontizas et al. (1988), who reached generally similar conclusions.

Finally, there was evidence that the mean age (of populations younger than 1–2 Gyr) increased with increasing distance from the optical centre of the SMC (assuming a global initial mass function). A detailed analysis can be found in Paper IV.

Regarding the older stellar component of the SMC, the distribution of clump/red horizontal branch (RHB) stars was examined. These stars belong to populations with ages ranging from $\simeq 10^8$ yr to $\simeq 10$ Gyr, although most are older than 1–2 Gyr, as can be deduced from a comparison of the observed numbers of main sequence stars ($\tau < 1$–2 Gyr) and of clump/RHB stars on the same CMD with stellar evolution predictions.

A contour map of the surface number density of the clump/RHB stars revealed a smooth ellipsoidal distribution with no conspicuous features. However, there was some indication of a distortion of the outer contour levels in the NE direction (also noted by Brück 1980); as will be seen in §3.1, in these same areas there is a large depth along the line-of-sight. The two effects may well be related. Projected surface density profiles were computed for various power-law and exponential relations. As an example, for a northern direction (20°) an exponential law ($N \simeq e^{-r/l}$, where l is the scalelength) truncated at 10 kpc and with a scalelength of 1.2 kpc was found to give the best fit to the radial fall-off of the numbers of clump/RHB stars (Paper III).

In order to further refine the age-resolution of this study, the colour properties of the clump/RHB were used:

1. using the colour difference between the clump/RHB and the red giant branch at the level of the clump/RHB as a *median* age indicator (see Hatzidimitriou 1991 for the definition and calibration of the indicator), it was found that beyond 2–2.5 kpc from the optical centre, the SMC field has a *median* age of 10 ± 2 Gyr;

2. there is a weak 'horizontal extension' of the main clump towards bluer colours (but still redward of the instability strip). This can be interpreted (using the above age indicator) as belonging to a population older by 2–3 Gyr than the median population represented by the main clump. These older stars would account for $\simeq 7\,\%$ of the stellar mass in these regions. Finally, it is also worth mentioning that there is no indication of a blue horizontal branch in the regions studied.

2.2. Carbon Stars

Carbon stars, with ages generally between $\simeq 0.8$–8 Gyr, are excellent tracers of intermediate age populations in local group galaxies. Morgan & Hatzidimitriou (1994) conducted a visual search for carbon stars (on the basis of their pronounced Swan C_2 band at 5165 Å) on UKST prism plates in the outer parts of the SMC. The survey covered a total area of $\simeq 200$ square degrees, and yielded a total of $\simeq 1400$ carbon stars, out of which $\simeq 1000$ were new ones. The projected spatial distribution of these stars together with carbon stars in the SMC Bar identified by Rebeirot, Azzopardi & Westerlund (1993), shows the SMC as ellipsoidal, with a northward distortion of the outer contours. The distribution agrees in detail with the distribution of clump/RHB stars described in §2.1. The diameter of the outermost contour is of the order of 11.5 degrees. It is worth noting that there is a spiral-arm-like extension of the outer contour southwards at projected distances larger than 4 kpc from the optical centre.

2.3. RR-Lyrae variables

RR-Lyrae variables are particularly useful tracers of old populations ($\tau \geq 10$ Gyr) and excellent distance indicators and thus tracers of the structure of a galaxy. In the SMC only two surveys of RR-Lyraes have been published to date. Both regions searched for RR-Lyraes (near the cluster NGC121 by Graham (1975) and near the cluster NGC361 by Smith, Baird & Graham (1992)) are located at very similar distances from the dynamical centre of the SMC (they virtually lie on the same clump/RHB isopleth) and therefore cannot give us much information about the radial profile of the distribution of the old stellar population of the SMC. In a recent search for RR-Lyraes over an area of 13 deg^2 in the western outer regions of the SMC (at projected distances between 3–6 kpc from the SMC centre), using a series of UKST blue plates, Hatzidimitriou & Hawkins (1994) found that RR-Lyraes seem to have the same spatial distribution as the (generally younger) clump/RHB and carbon stars described in §2.1 and §2.2, suggesting that all populations older than $\simeq 1$ Gyr are well mixed spatially and form an ellipsoidal structure.

3. Structure and Dynamics of the SMC

The structure and dynamics of the SMC have been the subject of numerous investigations, since one of the pioneering studies on the subject by de Vaucouleurs & Freeman (1972).

It is now generally recognized that the gravitational interaction between the LMC, the SMC and the Galaxy must be taken into account in order to interpret the structure and kinematics of the SMC in particular. The fact that the two Clouds are actually much bigger than originally thought (the LMC has a diameter $\simeq 20°$ according to Irwin (1991), while the SMC is reported as having a diameter $\simeq 16°$ by Irwin, Demers & Kunkel (1990)) reinforces the above statement. In the following, the role of the UKST in revealing some of the aspects of the structure of the SMC and of its interaction with the LMC, is outlined.

3.1. Line-of-sight distribution of old populations

As mentioned in §2, a significant proportion of the stellar mass of the SMC is in populations older than 1–2 Gyr. Therefore, to understand the dynamics of the SMC, we need to know the three-dimensional distribution and kinematics of older populations, particularly of those located in the outer, least strongly bound regions.

It was immediately obvious (Paper II) from the appearance of the clump/RHB in the CMDs described in §2.1, that the N and NE outer regions were significantly different from the W regions, in that the clump/RHB in the N and NE had a much larger 'size' along the magnitude axis of the CMDs (i.e. larger luminosity dispersion). This observation was confirmed recently with accurate CCD CMDs in selected regions (Mateo & Hatzidimitriou 1992 and 1994). This larger 'size' of the clump/RHB (in magnitude) could be due to either an admixture of younger stars, or to differential reddening, or to a large depth along the line-of-sight of the stars.

Differential reddening could be ruled out easily, since it would affect the distribution in colour of the clump/RHB as well, which was not the case.

Age (and metallicity), on the other hand, posed a much more subtle problem. Mateo & Hodge (1985) found empirically that for ages larger than several 10^8 yr the mean magnitude of the clump/RHB remains constant with age. The contribution of young populations (with $\tau \leq 1$ Gyr) in the majority of the areas where the large size of the clump/RHB was observed was minimal (as indicated by the absence of an observable main sequence on the CMDs). Therefore, we can interpret the clump/RHB size in terms of the depth along the line-of-sight. As additional confirmation of the Mateo & Hodge (1985) empirical result, Mateo & Hatzidimitriou (1994) calculated the Seidel, Demarque & Weinberg (1987) model predictions for the dependence of the clump/RHB mean magnitude and intrinsic size on age and metallicity and convolved the derived curves with the age-metallicity relation of the SMC (e.g. Da Costa & Hatzidimitriou 1994). For ages between 2–11 Gyr it was confirmed that only a small part of the observed effect could be attributed to age (Mateo & Hatzidimitriou 1994).

Therefore, the 'size' of the clump/RHB was used as a relative indicator of the line-of-sight depth, while its mean magnitude was used as a measure of the mean distance modulus of the particular area. The following general conclusions (for details see Papers II and III) were thus reached for the 3-dimensional distribution of stars with $\simeq 2 < \tau < 10$ Gyr in the outer areas of the SMC (i.e. beyond 2 kpc in projection from the optical centre):

1. The whole Western region of the SMC studied ('away' from the LMC) has a uniform distance modulus and a small depth along the line-of-sight of < 10 kpc. This result is consistent with the study of RR-Lyrae variables near NGC 121 by Graham (1975), and with the study of a small number of giants in the same general area by Suntzeff et al. (1986).

2. In the N–NE there is an abrupt transition to large line-of-sight depths, larger by 9–13 kpc than those found in the W regions (Papers II and III).

3. The NE regions have shorter distance moduli than the W regions. There appears to be a continuous decrease of the mean distance modulus with increasing projected radial distance from the SMC centre in these regions (Paper II).

3.2. Kinematics of RHB stars in the NE

The large depth observed in certain regions of the SMC (§3.1) led us to study the kinematics of old stars in these same areas, in an attempt to interpret dynamically the results. Radial velocities for a sample of clump/RHB stars in a 40 arcmin field in one of the 'deep' regions in the NE (at a projected radial distance of 2.7 kpc from the optical centre) were obtained, using the multifibre spectroscopic facility Autofib at the 3.9 m AAT (Hatzidimitriou, Cannon

& Hawkins 1993). The derived velocity distribution had a significantly higher velocity dispersion, of $33 \pm 4\,\mathrm{kms}^{-1}$, than the $18 \pm 5\,\mathrm{kms}^{-1}$ dispersion found by Suntzeff et al. (1986) for a sample of red giants in a W field (which is shallow along the line-of-sight). More importantly, there was a well-defined correlation between radial velocity and distance along the line-of-sight for these stars (estimated as in §3.1), with a slope of $8.1 \pm 0.4\,\mathrm{kms}^{-1}\mathrm{kpc}^{-1}$, corresponding to a timescale (assuming all stars were at the same distance along the line-of-sight in the past) of $1.2 \times 10^{8}\,\mathrm{yr}$, which coincides with the period of the last close encounter between the two Clouds, according to Fujimoto & Murai (1984) and Gardiner, Sawa & Fujimoto (1993). This result, in conjunction with the large depth in extended areas in the N and NE, seems to confirm that the recent close encounter between the LMC and the SMC had a profound effect on the dynamical stability of the latter. It is worth mentioning that Mathewson, Ford & Visvanathan (1988) found a similar correlation between radial velocity and distance for a sample of cepheid variables.

3.3. The intercloud region

The presence of HI gas in the intercloud region has been known for over 30 years (Hindman, Kerr & McGee 1963). However, it is only recently that a young stellar component was discovered in this gaseous 'bridge' linking the two clouds, using APM scans of UKST plates (Irwin, Demers & Kunkel 1990). This stellar 'bridge' consists of OB stars and associations, apparently coeval, less than $16 \times 10^{6}\,\mathrm{yr}$ old (Grondin, Demers & Kunkel 1992), and with radial velocities intermediate between the SMC and the LMC systemic velocities (Irwin, Demers & Kunkel 1990). Interestingly, the stellar bridge appears to have a large line-of-sight depth near the tip of the SMC Wing. In a recent report, Demers & Irwin (1993) announced the measurement of the radial velocities of over 200 newly identified carbon stars in the intercloud region and on the periphery of both the LMC and the SMC. They found a large velocity spread of $\simeq 100\,\mathrm{kms}^{-1}$ which is excessive for any bound elliptical orbit of the SMC about the LMC. They interpret this result together with the Hatzidimitriou, Cannon & Hawkins (1993) result mentioned in §3.2, as indicating a disruptive tidal impulse which happened between 0.05 and 0.2 Gyr ago according to the age of the OB associations, and $\simeq 0.1$ Gyr ago from the timing argument in Hatzidimitriou, Cannon & Hawkins (1993).

4. Conclusions

The UKST has played an important role in unraveling the complexities of the star formation history and the dynamics of the Small Magellanic Cloud and of the effects of its interaction with the Large Magellanic Cloud and the Galaxy. There is a lot of work yet to be done along similar lines, especially in the LMC. Some of the science that can be done with Schmidt Telescopes on the subject of the Magellanic Clouds (e.g. construction of good quality CMDs) will benefit from the possible future introduction of CCD mosaics as detectors in lieu of the photographic emulsion. I would also like to emphasize the great importance of the type of data produced from the combination of Schmidt telescope plates with COSMOS and APM-type machines, for the selection of targets (as well as for providing the necessary astrometry) to be studied with the various multi-fibre spectrographs now available at most Southern observatories, and, particularly, with the 2-degree field instrument to be commissioned soon at the 3.9 m Anglo-Australian Telescope.

Acknowledgements

I would like to thank the scientific organizing committee of the IAU Col. 148 for inviting me to give this talk. I would also like to acknowledge the most important contribution of my collaborators (R.D. Cannon, G.S. Da Costa, L.T. Gardiner, M.R.S. Hawkins, M. Mateo, D.H. Morgan) in the various projects that I described, the results from some of which have not been published yet.

References

Brück M. T., 1980, A&A, 87, 92

Brück M. T. & Marsoglu A. 1978, A&A, 68, 193

Brück M. T., Cannon R. D. & Hawkins M. R. S., 1985, MNRAS, 216, 165

Da Costa G. S. & Hatzidimitriou D., 1994, in preparation

Demers S. & Irwin M. J., 1993, BAAS, 25, 1414

Fujimoto M. & Murai T., 1984, Proc. IAU Symp. 108, S. van den Bergh & K. S. de Boer, eds, (Reidel, Dordrecht), p. 115

Gardiner L. T. & Hatzidimitriou D. 1992, MNRAS, 257, 195 (Paper IV)

Gardiner L. T. & Hawkins M. R. S., 1991, MNRAS, 251, 174 (Paper III)

Gardiner L. T., Sawa T. & Fujimoto M., 1994, MNRAS, 266, 567

Graham J. A., 1975, PASP, 87, 641

Grondin L., Demers S. & Kunkel W. E., 1992, AJ, 103, 1234

Hatzidimitriou D., 1991, MNRAS, 251, 545

Hatzidimitriou, D. 1994, Proc. IAU Symp. 161, H.MacGillivray & E. Thompson, eds, in press

Hatzidimitriou D., Hawkins M. & Gyldenkerne K., 1989, MNRAS, 241, 645 (Paper I)

Hatzidimitriou D. & Hawkins M. R. S., 1989, MNRAS, 241, 667, (Paper II)

Hatzidimitriou D. & Hawkins M. R. S., 1994, in preparation

Hatzidimitriou D., Cannon R. D. & Hawkins M. R. S., 1993, MNRAS, 261, 873

Hawkins M. R. S. & Brück M. T., 1982, MNRAS, 198, 935

Hindman J. V., Kerr F. J. & McGee R. X., 1963, Aust.J.Phys., 16, 570

Irwin M. J. 1991, Proc. IAU Symp. 148, R. Haynes & D. Milne, eds, (Kluwer, Dordrecht), p.453

Irwin M.J., Demers S. & Kunkel W. E., 1990, AJ, 99, 191

Kontizas E., Morgan D. H., Kontizas M. & Dapergolas A., 1988, A&A, 201, 208

Mateo M. & Hodge P., 1985, PASP, 97, 753

Mateo M. & Hatzidimitriou D., 1992, Proc. IAU Symp. 149, B. Barbuy & A. Renzini, eds, (Kluwer, Dordrecht), p.454

Mateo M. & Hatzidimitriou D., 1994, in preparation

Mathewson D. S. & Ford V. L., 1984, Proc. IAU Symp. 108, S. van den Bergh & K. S. de Boer, eds, (Reidel, Dordrecht), p.125

Mathewson D. S., Ford V. L. & Visvanathan N., 1988, ApJ, 333, 617

Morgan D. & Hatzidimitriou D., 1994, Proc. IAU Symp. 161, H.MacGillivray & E. Thompson, eds, in press

Rebeirot E., Azzopardi M. & Westerlund B. E., 1993, A&AS, 97, 603

Seidel E., Demarque P. & Weinberg D., 1987, ApJS, 63, 917

Smith H. A., Baird S. R. & Graham J. A., 1992, AJ, 104, 1430

Suntzeff N. B., Friel E., Kremola A., Kraft R. P. & Graham J. A., 1986, AJ, 91, 275

de Vaucouleurs G. & Freeman K. C., 1972, Vistas in Astr., 14, 163

Discussion

Reid: HI maps of the SMC also show a striking bimodality in velocity in certain regions. How does this tie in with your measurements of the morphology of the horizontal branch?

Hatzidimitriou: The range of radial velocities obtained for the sample of 30 RHB stars in a 40° region in the NE "halo" of the SMC, coincides with the range of velocities (from $\sim$ 100 to $\sim$ 200 km/s) found in HI measurements. However it is not at all clear that we are looking at two different components in the RHB star distribution, as the sample is too small and the velocity accuracy and distance-moduli accuracy too poor. It could be a "wing-like" structure.

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