New Views of the Magellanic Clouds
IAU Symposium, Vol. 190, 1999
Y.-H. Chu, N.B. Suntzeff, J.E. Hesser, and D.A. Bohlender, eds.

Intermediate-age and Old Populations in the Small Magellanic Cloud

D. Hatzidimitriou

Physics Department, University of Crete, P.O. Box 2208, Heraklion 71003, Crete, Greece

Abstract. The star formation history and kinematics of intermediate-age and old populations in the Small Magellanic Cloud are the subject of this brief review. New results confirm the occurrence of a period of enhanced SF about 8-10 Gyr ago in the SMC. Younger populations are confirmed to be more centrally concentrated than older ones. The SMC, at least in the areas studied (which *do not* include the Bar) seems to have had a different history of star formation from the LMC. Although the kinematics of the SMC have been extensively studied, it is still unclear if there are distinct Bar, disk and halo components, or if all populations share the same kinematics.

1. Introduction

As a dwarf irregular galaxy distinguished by its membership of a closely interacting system of galaxies, the Small Magellanic Cloud (SMC) is able to provide us with insights into the evolutionary development of dwarf irregular galaxies as well as the role of external dynamical interactions in stimulating star formation (SF) and modifying dynamical evolution.

Intermediate-age and old populations constitute most of the mass locked in stars in the SMC, and therefore understanding their history of formation is of the utmost importance. Ideally, one would like to address the following still unresolved questions:

- What is the age of the first (identifiable) generation of stars in the SMC? Is it as old as the oldest population in the Galaxy?
- Has SF been more or less continuous, or did it proceed in several major bursts? If the latter is the case what is the duration and strength of these bursts? In the Large Magellanic Cloud (LMC), such a global burst of SF occurred some 2-4 Gyr ago (e.g., Elson et al. 1997). Did a similar event take place in the SMC?
- Does the SF history depend on location?
- Is there any correspondence between major events in the SF history of the SMC and close passages with either the LMC or the Galaxy?
- Is there a kinematic halo in the SMC?

- Is the so-called Bar of the SMC a distinct dynamical entity, and if yes when was it formed?
- How has the dynamical state of the SMC evolved with time?

In the following, some recent developments will be briefly presented (for an older comprehensive review see Olszewski et al. 1996).

2. Star Formation History of Intermediate-age and Old Populations

Some general characteristics of the star formation (SF) history can be readily obtained (Hatzidimitriou 1997) by comparing the mean SF rate (total mass in stars divided by 15 Gyr) $< SFR >= 0.09\mathrm{M}_\odot\ \mathrm{yr}^{-1}$, with the current SF rate (derived from Hα emission measurements) $SFR_o = 0.05\mathrm{M}_\odot\ \mathrm{yr}^{-1}$ and the "initial" SF rate (estimated from the RR-Lyrae variable star content) $SFR_i = 0.03 - 0.08\mathrm{M}_\odot\ \mathrm{yr}^{-1}$. All these values are very similar within a factor of 2 (as is the case in other dwarf irregulars), and they are all a factor of 5 lower than the corresponding values for the LMC. It is noteworthy that the $< SFR >$ is almost a factor of 2 higher than the current SFR_o, suggesting that there may have been some period(s) of increased SF activity at intermediate ages. There is also little doubt that at earlier times active SF extended to larger distances from the Galactic center than it does at the present time. This is clearly demonstrated in Figure 1, where the median age of the field populations (derived from the clump-age indicator of Hatzidimitriou 1991) is plotted against projected radial distance from the optical center of the SMC. The same effect is apparent in the distribution maps of clump/horizontal branch stars and young main sequence stars produced by Gardiner & Hatzidimitriou (1992, hereafter GH92), of carbon stars (Morgan & Hatzidimitriou 1995) and of RR-Lyrae variables (Hatzidimitriou 1994). This radial aging -also seen in other dwarf irregulars- is probably reflecting a gradual decrease of the gas density in the outer regions below a critical value necessary for SF. The issue will become more complicated if the SMC is proved to be a system consisting of different components (disk, halo, and Bar) superimposed, rather than a system where all populations share similar kinematics (see next section).

Table 1. Field Color-Magnitude Diagrams in the SMC.

Source	V_{lim}	Area (sq.deg)	references
UKST	≃20.5	130	Gardiner & Hatzidimitriou 1992
OGLE	≃21.2	2.4	Udalski et al. 1998
CTIO	≃23.5	0.06	Hatzidimitriou et al. 1999
CTIO	≃23.5	0.015	Suntzeff et al. 1999
HST	≃27.0	0.001	Holtzman et al. 1999

Derivation of the detailed SF history is not an easy task. It requires well-sampled and sufficiently deep color-magnitude diagrams (CMDs), as well as adequate knowledge of the age-metallicity relation (cf. Da Costa 1999) and of the

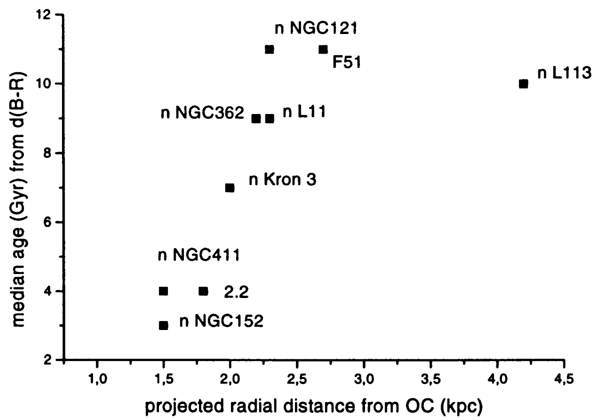

Figure 1. Median age of field populations as a function of projected radial distance from the optical center. Most points are for fields near star clusters (see references in GH92). The point marked as 2.2 corresponds to the CTIO 4-m observations of an inner disk field (Hatzidimitriou et al. 1999+) shown in Fig.2, and the point marked as F51 refers to the area F51:2.4 studied in detail in GH92.

metallicity distribution, because the CMDs are degenerate in age and metallicity. Range in reddening and line-of-sight distance must also be taken into account. Table 1 summarizes recent color-magnitude-diagram (CMD) studies of field regions in the SMC. A compilation of studies prior to 1992, which include mostly regions close to star clusters, can be found for example in GH92.

All recent studies in Table 1 are still in progress. Preliminary analysis of the Hatzidimitriou et al. (1999) data (see Figure 2 for an example) indicates that at least the disk fields studied lack the strong intermediate-age component (2-4 Gyr) found to be prominent in the LMC. Applying the Bertelli et al. (1992) method, we derived the R_1, R_2 and R_3 ratios for the four fields studied. These ratios depend in different ways on the relative strengths of populations of different ages, and they are compared with SF history models by Bertelli et al. It is remarkable how different these ratios are (Table 2) in the SMC (from Hatzidimitriou et al. 1999) from the LMC (from Bertelli et al. 1992).

Table 2. Comparison of the R-ratios in the SMC and the LMC field

	R_1	R_2	R_3
SMC	1.6-1.8	1.2	8.2-30.6
LMC	2.6-5.0	1.9-3.3	3.7-8.5

They also seem to suggest that a significant period of SF (of uncertain duration) occurred more than 8 Gyr ago in the SMC fields studied. There is a very marked difference in the history of SF of the inner and outer disk fields, as

https://doi.org/10.1017/S007418090011808X Published online by Cambridge University Press

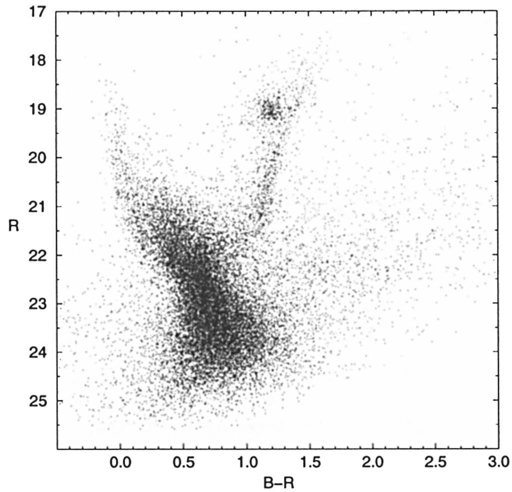

Figure 2. Color-magnitude diagram of a 200 square-arcmin field in the inner disk of the SMC, taken with the CTIO 4m-telescope (Hatzidimitriou, Smecker-Hane & Croke, 1999, in preparation).

exemplified by a comparison of the main sequence luminosity functions in the two regions (Figure 3). The outer field is older in the mean, as expected from earlier studies. Suntzeff et al. (1999) have produced a similar deep CMD near NGC 121, also using the CTIO 4-m telescope. Their main conclusion is that at least in this area active SF occurred between $\simeq$ 15 Gyr ago (the age of old Galactic globular clusters) and 9 Gyr ago, in agreement with the Hatzidimitriou et al. result.

3. Kinematics

In recent years there has been a significant qualitative and quantitative improvement of kinematical studies of young and intermediate age populations in the SMC. A compilation of these studies is presented in Table 3.

The intermediate age and old populations (upper panel of Table 3) do not seem to participate in any rotational motion (Hardy et al. 1989; Hatzidimitriou et al. 1997).

There is clear evidence of streaming motions in certain locations: along the Wing (Hardy et al. 1989), and along the line-of-sight in the NE outer regions (Hatzidimitriou et al. 1993). These streaming motions are believed to result from tidal interactions with the Large Magellanic Cloud and the Galaxy. It is important to note at this point that intermediate-age stars have been recently discovered in the inter-cloud "Bridge" (e.g., Kunkel et al. 1997), thus confirming the tidal origin of the feature.

Except for these distinct cases, the radial velocity dispersion values of Table 3 indicate that within the observational uncertainties all populations, including young "Pop I", have similar kinematics, regardless of age and location. However,

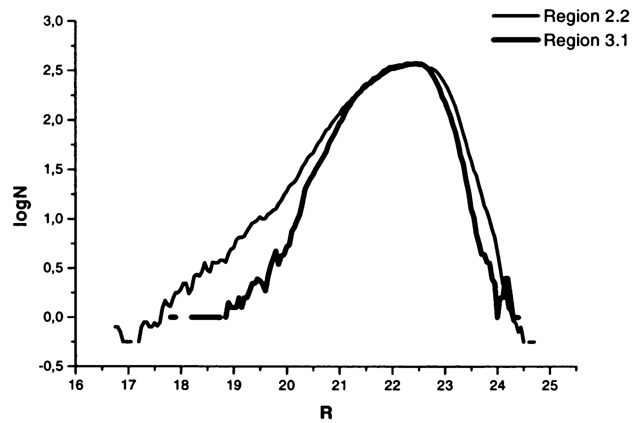

Figure 3. Main Sequence Luminosity Functions for two regions studied with the CTIO 4m-telescope. The two regions are located in the inner (2.2) and outer (3.1) disk (halo?) west of the Bar.

careful analysis of the existing data and comparison with N-body simulation predictions (Gardiner & Hatzidimitriou 1999+) seem to favor halo kinematics for the older stars. Clarification of this very important issue has to await new extended observations. Lastly, it must be emphasized that there is no kinematical information about the older stellar component, traced by RR-Lyrae variables. Time consuming as it may be, identification and subsequent kinematical study of RR-Lyraes, with good spatial coverage, will be instrumental in deciphering the dynamics of the SMC.

Table 3. Recent kinematical studies of field populations in the SMC.

Type	Region	n	<RV>	σV	references
clump stars	NE outer	30	151(6)	33(4)	Hatzidimitriou et al. 1993
				18(5)[a]	
red giants	NW outer	36	135	26	Suntzeff et al. 1999
planetary nebulae	central	44	146(4)	25(3)	Dopita et al. 1985
carbon stars	central	131	148(2)	27(2)	Hardy et al. 1989
carbon stars	outer	70	149(3)	25(2)	Hatzidimitriou et al. 1997
		62[b]	145(3)	21(2)	
star clusters		7	138(6)	16(4)	Da Costa & Hatzidimitriou 1998
PopI	central				Maurice et al. 1989
cepheids	main	61	149(3)	22(3)	Mathewson et al. 1988
HI shells	main	501	155(1)	25(1)	Staveley-Smith et al. 1997

[a] Same as previous row, but after having removed the radial velocity versus line-of-sight distance correlation.

[b] Same as previous row, but without including stars belonging to the Wing.

Acknowledgments. The author is grateful to B.F. Croke and T. Smecker-Hane who were instrumental in analysing the CTIO-4m data in time for the meeting. This work was partially supported by a grant from the American Astronomical Society.

References

Bertelli, G., Mateo, M., Chiosi, C., & Bressan, A. 1992, ApJS, 388, 400

Da Costa, G.S. 1999, in this volume

Da Costa, G.S., & Hatzidimitriou, D. 1998, AJ, 115, 1934

Dopita, M.A., Ford, H.C., Lawrence, C.J., et al. 1985, ApJ, 296, 390

Elson, R.A.W., Gilmore, G.F., & Santiago, B.X. 1997, MNRAS, 289, 157

Gardiner, L.T., & Hatzidimitriou, D. 1992, MNRAS, 257, 195

Hardy, E., Suntzeff, N.B., & Azzopardi, M. 1989, ApJ, 344, 210

Hatzidimitriou, D. 1991, MNRAS, 251, 545

Hatzidimitriou, D. 1994, in Astronomy from Wide-Field Imaging, eds. H.T. MacGillivray et al., Dordrecht:Kluwer, 489

Hatzidimitriou, D. 1997, in Star Formation Near and Far, eds. S. Holt & L.G. Mundy, AIP: New York, 561

Hatzidimitriou, D., Cannon, R.D., & Hawkins, M.R.S. 1993, MNRAS, 241, 667

Hatzidimitriou, D., Croke, B.F., Morgan, D.H., & Cannon, R.D. 1997, A&AS, 122, 507

Hatzidimitriou, D., Smecker-Hane, T., & Croke, B.F. 1999, in preparation

Holtzman J.A., Mould J.R., & Gallagher, J.S. 1999, in this volume

Kunkel, W.E., Irwin, M.J., & Demers, S. 1997, ApJ, 488, 129

Maurice, E., Martin, N., & Bouchet, P. 1989, A&AS, 78, 445

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

Morgan, D.H., & Hatzidimitriou, D. 1995, A&AS, 113, 539

Olszewski E.W., Suntzeff N.B., & Mateo M. 1996, ARA&A, 34, 511

Staveley-Smith L., Sault R.J., Hatzidimitriou D., Kesteven, M.J., & McConnell D. 1997, MNRAS, 289, 225

Suntzeff, N.B., Walker, A.R., Smith, V.V., Kraft, R.P., Klemola, A., & Stetson, P.B. 1999, in this volume

Udalski, A., Szymanski, M., Kubiak, M., Pietrzynski, G., Wozniak, P., & Zebrun K. 1998, AcA, 48, 147

Discussion

Lance Gardiner: What significance do you attach to the similar velocity dispersions seen in the H I, Cepheids, carbon stars and HB/clump? I believe that they are largely coincidental - the H I is affected by the kinematic effects of star formation activity, whereas we are probably seeing a kinematic halo in the outer parts.

Hatzidimitriou: That is one possibility. Or, the velocity dispersion in the solar regions could be increased because of streaming motion in some locations. Or, it could be that all populations share the same kinematics.

Carme Gallart: I would like to comment on your reference to the synthetic CMD technique to recover SFH's, and to the fact that there are a large number of parameters to be taken into account. I want to remark that it is difficult and a lot of work but it can be done. I would like to refer to the work I am presenting on Leo I, where I explore a considerable volume of the parameter space, including IMF, Z(t) and binary function, and I do find a "unique" and statistically significant solution. This kind of work can be done for the MC if good enough data is used. Deep CTIO 4m data, for example, is perfect for this purpose.

Hatzidimitriou: I agree. I just wanted to emphasize that whatever solutions one derives from the CMD's, they must be consistent with the age-metallicity relation, element ratios (e.g. [O/Fe]) etc.

Hans Zinnecker: The finding that the LMC experienced a significant increase in its star formation rate 2-4 Gyr ago while the SMC did not provokes the following question: was there an LMC/SMC close encounter then or where exactly were the two Magellanic Clouds with respect to each other at this critical time? Do we know?

Hatzidimitriou: I am not all that certain that there is no enhancement of the SF rate in the central regions of the SMC ("Bar") at 2-4 Gyr ago. We just do not know. Different models predict somewhat different epochs for past close encounters. So, we do not really know.