STELLAR POPULATIONS IN THE MAGELLANIC CLOUDS

M.W. FEAST
Department of Astronomy, University of Cape Town,
Private Bag, Rondebosch 7700, South Africa
(mwf@uctvax.uct.ac.za)

Abstract. There seems to be no strong evidence that the young globular clusters in the MC have metallicities differing significantly from the metallicities of MC field stars of the same age. The old globular clusters in the LMC are of the same age as, or slightly younger than, those in the outer halo of our Galaxy. It is suggested that the increase in the SFR in the LMC ~ 4 Gyr ago was related to the collapse of the system to a plane. Evidence for a spread in metallicities amongst young stars in either Cloud remains tentative. There is no strong evidence for bursts of star formation being triggered by LMC-SMC-Galaxy interactions but the possibility is raised that the SFR in the SMC has been strongly affected by this interaction.

1. Introduction

From the very large amount of current work on the Magellanic Clouds (MC) this paper discusses four topics which seem particularly relevant to the concept of stellar populations. These are, star clusters, overall structure, chemical abundances and star formation rates (especially in relation to possible bursts of star formation).

2. Clusters

In the study of stellar populations, no group of objects has caused quite as much confusion as the globular clusters, both old and young, in the MC. Thackeray's discovery that the brightest stars in the LMC globular cluster NGC 1866 were blue and that the cluster contained Cepheids, led

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Baade (1951) to conclude that the LMC was a "pure" population I system. The idea of "pure" population I and "pure" population II was reinforced in Baade's mind (l.c.) by Thackeray's further work in establishing that the variables in the Sculptor dwarf spheroidal were RR Lyraes, whilst it was the belief of the time (Baade 1951, Shapley 1951) that there were no RR Lyraes in the MC since Harvard workers had failed to find any. It was against this climate of belief that Thackeray and Wesselink searched to fainter limits and found RR Lyraes in some MC clusters. This work, announced at the same time as Baade's work on M31 (IAU General Assembly, Rome, 1952) not only gave the best quantitative estimate for the required revision of the extragalactic distance scale, but rather clearly suggested that the MC, though very different in size and apparent structure from our Galaxy, probably contained examples of all the sorts of objects that make up our Galaxy and thus made them a particularly illuminating place for the study of stellar populations.

It has been felt by some workers that the term "globular" should not be applied to the young globular clusters in the MC. However the clusters are globular in form and there is little doubt, providing our ideas of stellar evolution are approximately correct,that some at least of them will evolve into objects with masses and luminosities similar to those of galactic globulars (cf. Mateo 1993). In contrast to this van den Bergh (e.g. 1993a) has stressed that whilst the systems of (old) globular clusters in our own and other galaxies have a roughly Gaussian luminosity function, the luminosity function of open clusters (of all ages) is quite different both in our Galaxy and the MC, showing a power-law increase to fainter luminosities (e.g.Elson and Fall 1985). The young MC globulars fit rather well on the high luminosity tail of this distribution and van den Bergh suggests that this sets them apart from globular clusters. However it does not seem possible to rule out a model in which the halo globular cluster population of our own and other galaxies originally contained many lower mass objects which were subsequently destroyed by evaporation or other processes. The suggestion (Elson *et al.* 1987, 1989) that young massive clusters in the LMC have large unbound haloes may be related to this problem. This issue is not merely one of semantics since it has relevance for our ideas of globular cluster formation, the origin of field stars in the haloes of galaxies and the use of globular-cluster luminosity functions as distance indicators. The distribution of ellipticities of the cluster population (all ages) in the MC is different from that of Galactic (old) globulars, the mean ellipticity being higher in the MC group (Frenk and Fall 1982, van den Bergh 1991, Kontizas *et al.* 1989). It is not clear whether this has significance for the above problem since the ellipticities of clusters are expected to decrease with age due to evaporation and other processes (Agekian 1958, Lightman and Shapiro

1978, Weinberg 1993).That we do not see young globular clusters in our Galaxy might be due to the shearing effects of differential galactic rotation preventing their formation.

Suggestions have been made that the young globular clusters in the MC are metal deficient by a factor of about five compared with MC field stars of the same age. Work has particularly focused on NGC 330 in the SMC and NGC 1818 in the LMC. However recent work throws considerable doubt on these conclusions. There may have been crowding problems with the Strömgren photometry on which the initial conclusions were based and the temperatures used in the spectroscopic analyses came from colours which seem likely to have been undercorrected for reddening (Bessell 1993). Abundances of B-type stars in NGC 330 and NGC 1818 reported by Jüttner (1993) do not show significant differences from field stars nor does spectral synthesis for cool supergiants in the two clusters (Jasniewicz and Théverin 1994; see also Russell 1992).

The old globular clusters in the LMC are of key importance in deciding whether the outer halo of our Galaxy can have formed from the accumulation of LMC-like systems subsequent to the initial epoch of cluster formation in them. Suntzeff *et al.* (1992) point out that the metallicities and the numbers of RR Lyraes per unit cluster luminosity are similar in the LMC old globular clusters to those in the galactic outer halo and that the ratios of mass in the old clusters to that in the field halo-type populations are also about the same (0.02). At least the conditions in these two places seem to have been rather similar when the oldest stars were formed. However the relation between horizontal branch morphology and metallicity (data from Lee *et al.* (1994) (Galaxy); Walker (1992) (LMC); Zinn (1993) (Fornax)) can be interpreted as showing either that the old LMC clusters are not significantly different from those in the outer Galactic halo or that the clusters in the inner halo, outer halo, LMC and Fornax form an age sequence (Fornax clusters being the youngest). As evidence against the accumulation hypothesis it has been pointed out (van den Bergh 1990) that the old LMC clusters are more flattened than those in our Galaxy. This does not appear to be a conclusive argument both because the number of very old LMC clusters (i.e. those with RR Lyrae variables) is only five, making the statistics uncertain and also because the ellipticities of clusters can be significantly reduced subsequent to formation by environmental effects (e.g. Weinberg 1993). Thus the important issue of the formation of the Galactic halo remains unresolved.

3. Structure

The detailed spatial and kinematic structure of the MC is quite complex. However, at least for the LMC, there are a number of overall features which are relatively easy to understand. Certain of these are reminiscent of those in our own Galaxy but on a smaller scale. De Vaucouleurs' model of a tilted, planar, structure holds at least for the younger parts of the population.The expected elliptical contour on the sky is nicely shown by the distribution of clusters (e.g. Irwin 1991;see also the review by Westerlund 1990). That this does indicate a tilted near-circular disc is shown by the Cepheids which indicate that the NE edge is nearer to us than the SW one and that the tilt is about 34° (Caldwell and Laney 1991). The system seems to have evolved by contraction. Old clusters are more spread out on the sky than young ones (e.g. van den Bergh 1991, Fig. 5). One imagines this contraction will have been both towards the centre of the LMC and towards a plane. Velocity dispersion studies suggest a marked flattening to the plane with time. Young objects (supergiants, HII regions) have a velocity dispersion of only $\sim$ 10 km s^{-1} about a mean rotation curve. Planetary nebulae with an age of $\sim$ 3.5 Gyr have a velocity dispersion of $\sim$ 22 km s^{-1} and short period Mira variables (mean period 180d) which have ages similar to those of the disc globular clusters in our Galaxy have a velocity dispersion of 33 km s^{-1} (see e.g. Feast 1989b, 1992; Meatheringham *et al.* 1988; Hughes *et al.* 1991). The 13 oldest clusters (SWB class VII) have a velocity dispersion of $\sim$ 24 km s^{-1} (Schommer *et al.* 1992) not significantly different from the short period Miras. Of these clusters only five have RR Lyraes and this is too small a number to entirely rule out a dispersion of 40 to 50 km s^{-1} for the oldest population which would indicate a pressure supported, non-rotating system. However a somewhat flattened, rotating system seems likely even at the oldest age. In principle the RR Lyraes could settle this issue. The apparent magnitude dispersion of field RR Lyraes (Graham 1977,Walker 1989) is $\sim$ 0.15 mag. which seems too small to allow any great extention in depth when one considers the effects of observational error, differential reddening and a possible spread in absolute magnitudes. A flattened distribution thus again seems likely though a near spherical distribution with a line-of-sight scale height of about $\sim$ 2 kpc cannot be ruled out. The surface distribution of RR Lyraes in the LMC could be explained by a spherical space distribution with a radial density gradient close to $R^{-3.5}$ (i.e. a straight line fit of slope –2.5 in Fig. 4 of Kinman *et al.* 1991).Curiously this is the radial density gradient in the outer halo of our Galaxy (see Kinman 1992). But the LMC data can also be fitted with an exponential disc model of scale length $\sim$ 2.6 kpc (Kinman *et al.* 1991).

One would like to probe the oldest structure of the LMC with some easily found objects which are brighter than the RR Lyraes. Hartwick and Cowley (1988; also Cowley and Hartwick 1991) pointed out that CH stars (halo carbon stars) could be such objects. The stars they selected as candidates, though of considerable interest in their own right (Feast and Whitelock 1992; Suntzeff *et al.* 1993) turn out to be the most massive rather than the least massive C stars in the MC. It remains to be seen whether there are any halo type CH stars in the MC.

The structure of the SMC is quite different from the LMC. The three dimensional structure of the young population is best delineated by a limited number of Cepheids with well determined distances from a PLC relation (Caldwell and Coulson 1986; Caldwell and Maeder 1992). These indicate a body much extended in the line of sight (a depth of 15 to 20 kpc). Other estimates of depth are not inconsistent with this (see Feast 1989b, 1991). An important investigation (Hatzidimitriou *et al.* 1989; Hatzidimitriou and Hawkins 1989; Gardiner and Hawkins 1991) has used the luminosity spread of stars in the giant branch clump to measure the depth of an older population (a few Gyr in age). This depth varies over the SMC reaching its greatest extent in the NE where the depth can reach 23 kpc and averages $\sim$ 17 kpc. Radial velocity measurements of some of these stars show a correlation with estimated distance confirming the reality of a depth spread (Hatzidimitriou *et al.* 1993).

It seems clear that these complex SMC structures and the Magellanic Stream result from the interaction of the MC with each other and with our Galaxy. But there is still no final certainty as to whether the observed structures can be explained entirely in terms of tidal forces or whether gas dynamic effects are involved (see Wayte 1991; Gardiner *et al.* 1994).The latter workers have recently had some success with the tidal model. On the basis of a number of plausible assumptions they obtain distributions of test particles which approximately reproduce the Magellanic Stream and the distribution of Cepheids in the SMC. They also predict that the tidal effects on the shape of LMC will be relatively small. It remains to be seen whether further work on these lines can satisfactorily model the distribution of the older SMC population. An interesting feature of the tidal model is that it incorporates the effects of a massive dark halo for our Galaxy (cf. Tremaine 1976) so that refinements of the model might eventually provide significant constraints on the properties of such a halo at the distance of the MC.

4. Metallicity

The few old globular clusters in the LMC have a range of metallicities ([Fe/H] = −1.7 to −2.3). The oldest cluster in the SMC (NGC 121) may be a few Gyr younger and has an [Fe/H] of about −1.4 (Stryker *et al.* 1985). The overall increase of metallicity with decreasing age has been discussed frequently in the past (e.g. Da Costa 1991) but it is still not clear whether at any given age there is a real spread in metallicity in either Cloud. A recent review of the chemical composition of young MC objects (Russell 1992) suggests an [Fe/H] (or overall metal abundance) of about −0.2 for the LMC and −0.5 for the SMC from spectroscopic studies, very similar to results obtained by less direct means (e.g. Feast 1989a). Russell concluded that in view of the scatter in the data there was no strong evidence for non-solar abundances of other metals relative to Fe except perhaps that heavy, neutron-capture elements in the SMC might be enriched. He also concluded that nitrogen might be anomalously underabundant in the SMC. Carbon,once thought to be underabundant in the MC seems normal. Russell also concluded that there is no really strong evidence for a metallicity spread amongst the youngest objects in either Cloud, despite a number of recent claims to the contrary in the case of the LMC (McWilliam and Williams 1991; Luck and Lambert 1992=LL). A range of abundances in the LMC would be interesting especially in the case of the Cepheids studied by LL, one of which (HV5497, period 99d) they find to have a greater than solar metallicity ([Fe/H] = +0.2). It would be particularly desirable to confirm this result taking into account the cautions on the spectroscopic side mentioned by Russell. In addition the following points are relevant to the use of infrared colours by LL to derive temperatures. (1) Different results would have been obtained if the reddenings of Caldwell and Coulson (1985) had been adopted. (2) Whilst the SMC Cepheids studied by LL have many JHK observations,mainly from one homogeneous source (Laney and Stobie 1986), their LMC Cepheids have in general less well covered IR light curves with data from a variety of telescopes. (3) Of the LMC Cepheids studied, HV953, HV1003 and HV5497 are noted by Payne-Gaposchkin (1971) as having variable periods so phasing of the spectroscopic work with IR data obtained several years earlier is difficult. For instance Dr C.D.Laney (private communication) finds that a re-evaluation of the infrared-spectroscopic phasing and other considerations suggest [Fe/H] to be ~ -0.1 rather than $\sim +0.2$ for HV 5497. Thus whilst it is quite possible that the SMC could be more chemically homogeneous than the LMC due to its smaller size and the fact that it may have been kept well mixed by interaction with the LMC and the Galaxy, the observational evidence on this matter is not yet conclusive. Furthermore it is worth recalling that the [O/H] ratio in MC HII regions shows no evidence for a significant abundance spread in either Cloud (a dispersion, uncorrected for observational scatter, of 0.09 dex in both Clouds (Pagel *et al.* 1978)).

5. Bursts of Star Formation?

There has been much discussion in recent years as to whether there were bursts of star formation in the MC and, if there were, whether they were triggered by interactions of the MC and the Galaxy. The well known work of Butcher (1977), the review by Stryker (1984a) and other investigations (e.g. Bertelli *et al.* 1992) strongly suggests that in the outer regions of the LMC the SFR was relatively low until a few Gyr ago (2 to 5 Gyr). The extreme outer regions of the LMC may be dominated by a somewhat older ($\sim$ 7 Gyr) population (Stryker 1984b). Butcher's result is nicely mirrored in the age distribution of clusters (e.g Da Costa 1991) though selection effects (and cluster destruction) complicate the quantitative interpretation of the frequency distribution of cluster ages. However it is a little difficult to think of this as due to an interaction-induced burst of star formation. One reason for this is that the SFR has been quite different in the SMC. This is shown by the different distribution of clusters with age in the SMC compared with the LMC (Da Costa 1991). The clusters suggest a rather constant rate of production in the SMC (or perhaps a smooth decline if we take into account the dissolution of older clusters). These results are consistent with the discovery that the outer regions of the SMC are dominated by a $\sim$ 10 Gyr age population (cf. Stryker 1984a). A more complete discussion of the age of the dominant populations in the outer parts of the SMC by Gardiner and Hatzidimitriou (1992) broadly confirms this result. They interpret their photometric data in terms of a very old component (age $\sim$ 15 Gyr) which comprises $\sim$ 7 percent of the mass of the outer regions of the SMC together with a dominant population of age $\sim$ 10 Gyr.

Possibly one should think of the increase in SFR in the LMC $\sim$ 4 Gyr ago as the result of a collapse to a more planar structure, the equivalent phase in our Galaxy having taken place earlier ($\sim$ 10 Gyr ago), at least in the vicinity of the Sun. If the interaction of the MC with each other and with our Galaxy has played any part in determining SFRs in the MC it may perhaps have been in keeping the SMC stirred up and preventing collapse to a plane. Against this interpretation must be set the work of Frogel and Blanco (1983, 1990) who find a non-uniform distribution of LMC M-type stars in an infrared c-m diagram. They interpret this in terms of two bursts of star formation. One a few Gyr ago and presumably associated with the general increase in SFR at that time, and one $\sim 10^8$ years ago, possibly associated with an MC - Galaxy interaction. However Wood (private communication) has pointed out that theoretical HR diagrams with tracks for stars of different mass (e.g. Vassiliadis and Wood 1993, Fig. 2) suggest the possibility that gaps such as that found by Frogel and Blanco could occur even with a constant SFR. This seems to be the point being made by

Frantsman and Schmeld (1994).

In principle, element ratios (e.g. [O/Fe]) can give clues to major variations in past SFRs (e.g. Gilmore and Wyse 1991). This follows since the relative contributions of SN I and II to the enrichment of the interstellar medium depend on the past SFR and the two types of SN produce elements in different relative proportions. The [O/Fe] ratio in the MC remains uncertain although according to Russell (1992) and Pagel (1993) the best current values in both Clouds are not significantly different from the solar value. This matter seems far from settled (cf. Hill 1994) but element ratios do not at present provide any strong evidence for bursts of star formation.

6. Conclusions

Contrary to earlier suggestions there is no strong evidence that the young globular clusters in the MC have metallicities which differ from those of field stars of the same age. These objects give us a valuable opportunity to study the early development of a system of globular clusters. It is not clear whether the old globular clusters in the LMC are of the same age or slightly younger than those in the outer halo of our Galaxy. Thus it is still uncertain whether the outer galactic halo could have formed from the accumulation of MC-like systems subsequent to globular cluster formation.

Despite many little-understood irregularities the LMC may well have evolved overall in much the same way as in the ELS model of our Galaxy (i.e. by collapse to a plane) with only minor effects due to interaction with the SMC and our Galaxy. However if it began as a more-or-less spherical object, the formation of globular clusters and the oldest stars probably did not begin until the initial stages of collapse and flattening had started. In this picture the main disc formation episode took place $\sim$ 4 Gyr ago compared with $\sim$ 10 Gyr ago in solar neighbourhood of our Galaxy.

Evidence for any significant spread in the metallicities of young objects in either Cloud remains quite tentative. There is also no compelling evidence that there have been bursts of star formation on a galaxy-wide scale in either Cloud associated with LMC-SMC-Galaxy interactions. It is however possible that the star and cluster formation rates in the SMC and its chemical evolution have been strongly affected by such interactions.

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VAN DEN BERGH: You suggested that some of the globulars in the outer halo of the Galaxy might have been derived from LMC-like objects. An argument against this is that almost all LMC globulars (and those associated with the Fornax dwarf) have half-light radii that are *much* smaller than those of the globulars in the outer Galactic halo.
FEAST: This is an interesting point. If I remember correctly you found the opposite effect using Galactic globular clusters (in your Russell lecture). However, apart from the small mumber of objects involved when one restricts oneself to very old clusters in the LMC (due to selection effects) one has to bear in mind that environment may have significant effects on clusters during their lives.
TAYLER: Is it possible that the LMC disk did not collapse suddenly about 4 Gyr ago, but that it took until then to build up a threshold for star formation? In addition, if most of a disk has accumulated before the threshold occurs, star formation may be more episodic than if infall is still very important. The input of energy from the first generation of stars may have a much more disruptive effect.
FEAST: I agree that the relation between collapse and SFR is not necessarily very straightforward since big threshold effects are probably involved.
ALCAINO: Independently in both the Large and the Small Magellanic Cloud, is there a connection of the ellipticity of the clusters with either age, metallicity or position in the Cloud?

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FEAST: There is really too little information to discuss metallicity or positional differences. The data are also probably too uncertain to decide whether at a given cluster mass there is a dependence of ellipticity on age.

FABER: You showed us the cluster age distribution in the LMC, which shows the well-known gap between, say, 4 and 12 Gyr. Yet you also mentioned that the average age of the LMC filed *halo* stars is 7 Gyr, right in the middle of this gap. Could you comment?

FEAST: It seems probable that there are stars of all ages to be found in the LMC. We have however little quantitative information as to what the relative proportions of stars of different ages are or how these proportions vary over the LMC. The cluster data cannot easily be interpreted due to the effects of dissolution of smaller clusters and the different volumes sampled for clusters of different ages. It does appear however that the big increase in SFR at ≈ 4 Gyr did not occur in the outer parts of the LMC, though stars of a few Gyr ages are in these regions as well as older populations.