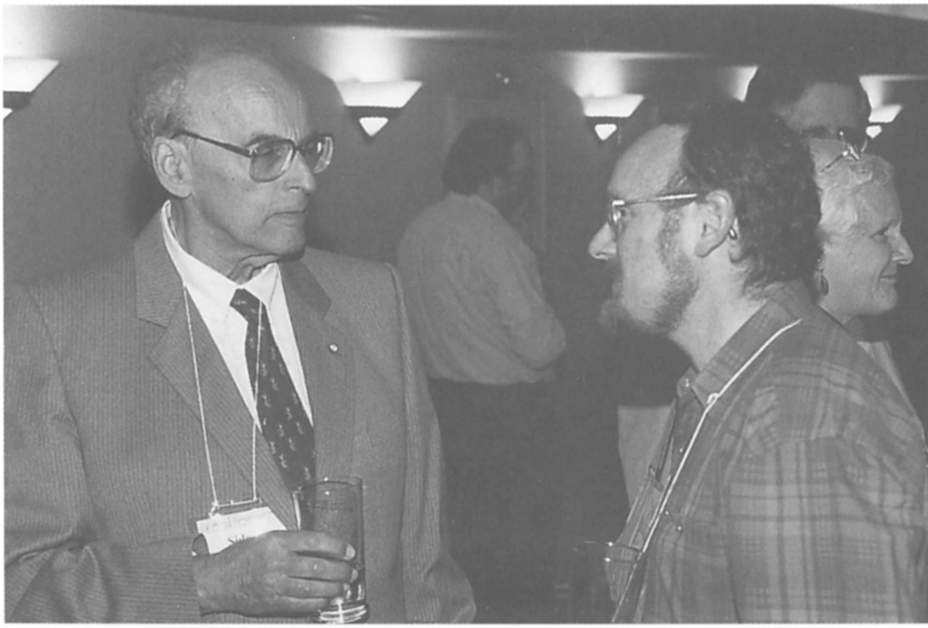
Part 6. Stellar Clusters

Section A. Invited Reviews



(Top) Sidney van den Bergh and Gary Da Costa and (bottom) Sally Oey and Don Garnett exchanging reactions to Symposium presentations.

https://doi.org/10.1017/S0074180900118406 Published online by Cambridge University Press

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.

Star Clusters in the Magellanic Clouds

G. S. Da Costa

Mt. Stromlo & Siding Spring Observatories, Private Bag, Weston Creek Post Office, ACT 2611, Australia

Abstract. Recent results for the old and intermediate-age star clusters of the Magellanic Clouds are reviewed. Highlights include new evidence that the LMC old clusters are as old the Galaxy's halo globular clusters and the persistence of the LMC *cluster* "Age Gap" despite *field star* evidence for significant star formation during the cluster age gap epoch. For the SMC new data confirm the lack of significant change in cluster abundances with age prior to ~4 Gyr ago.

1. The Old LMC Clusters

The current sample of LMC clusters considered analogues of the Galactic halo globular clusters consists of 13 objects (Suntzeff et al. 1992). Like their Galactic halo counterparts, for existing abundance estimates the LMC clusters show no radial abundance gradient (e.g., Da Costa 1993). Yet kinematically the LMC cluster system is quite different from that of the Galactic halo. It shows "disk-like" motions with $V_{circ} \approx 60$ kms^{-1} and $\sigma \approx 25$ kms^{-1} (Schommer et al. 1992). This kinematic difference might suggest that the LMC old clusters are somewhat younger than the Galactic halo clusters. Such a suggestion, however, is difficult to substantiate from the ground because, while ground-based estimates of LMC old cluster main sequence turnoff luminosities do indicate similar ages to Galactic halo clusters, they lack the ± 1 Gyr precision required to be certain of any age differences. Horizontal branch (HB) morphology – abundance diagrams, on the other hand, do suggest that some LMC old clusters are younger than the inner Galactic halo clusters (e.g., Da Costa 1993). However, the interpretation of such diagrams in terms of age differences is a process fraught with uncertainty.

The question of the age of the LMC old clusters relative to Galactic halo clusters, however, can be settled with WFPC2 data. Two groups report their results in these proceedings. Olsen et al. (1998 and these proceedings, hereafter O98) derive age estimates from main sequence photometry for five "inner" clusters while Johnson et al. (these proceedings) studied three "outer" objects. Both groups find the same result: *the LMC clusters are as old as their Galactic halo counterparts and there is no evidence for any age range in excess of ~1 Gyr.* Thus the proto-Galaxy and the proto-LMC began forming stars at similar epochs.

The new results have two interesting consequences. First, O98 have increased significantly the number of LMC old clusters that can be plotted in the HB morphology – abundance diagram. If we adopt the "age is the second param-

https://doi.org/10.1017/S0074180900118406 Published online by Cambridge University Press

eter" interpretation of this diagram, then the location of the clusters NGC 1898, 1754, 2019, 2005 and Hodge 11 (see O98, Fig. 17a) suggests that these clusters should have the same age, and moreover, that this age should be comparable to that of the inner Galactic halo clusters. This prediction is in excellent accord with the new WFPC2 results. The same interpretation applied to the clusters Reticulum, NGC 1466, 2257 and 1841 would require these clusters to be ~3 Gyr younger than the first group. However, from the Johnson et al. results we know that this younger age interpretation is not correct, at least as regards NGC 1466 and NGC 2257. This suggests strongly that the "age is the second parameter" interpretation of HB morphology – abundance diagrams is not always valid. This is consistent with recent WFPC2 results for the Galactic halo, in which outer halo clusters with red HBs have been found to be somewhat younger than inner halo clusters of similar abundance, but the observed age difference is somewhat less than that expected from the HB morphology difference (see Hesser et al., these proceedings).

The second consequence follows from the abundances derived by O98. They apply the "simultaneous metallicity and reddening" technique which, given their well defined cluster giant branches, should result in abundances that are more reliable than existing estimates. These latter estimates come mostly from CaII spectroscopy but are often based on only a single star per cluster (Olszewski et al. 1991). For NGC 1754, 1835 and 1898 the agreement between the two techniques is satisfactory (and this is also the case for the three clusters studied by Johnson et al.), but for NGC 2005 and 2019 the new abundances are ~0.6 dex higher than the earlier estimates. If we now use the O98 abundances in a plot of abundance versus projected radial distance for the LMC clusters, as is illustrated in Fig. 1 (cf. the upper panel of Fig. 3 of Da Costa 1993), it is evident that there is now support for the existence of a *radial abundance gradient in the LMC old cluster system.* Given the implications of such a result, it is important to have spectroscopic confirmation of the O98 abundances, and an improved abundance estimate for NGC 1916, the innermost metal-poor system. O98 could not derive an abundance for this cluster because of differential reddening; the abundance in Fig. 1 is based on a CaII measurement for a single cluster star only.

2. The LMC Cluster Age Gap – An Update

Geha et al. (1998, see also many contributions in these proceedings) have used deep WFPC2 images to analyze the LMC field star formation history. They find that their data are most consistent with a star formation rate that is approximately constant for most of the LMC's history but which increases by a factor of ~3 approximately 2 Gyr ago. This history produces a stellar population with approximately equal numbers of stars older and younger than ~4 Gyr. This result contrasts strongly with the observed *cluster* age distribution in which only a single cluster with an age between ~3 Gyr and the age of the oldest clusters is known, despite the existence of numerous 1 – 3 Gyr old clusters. Consequently, unless there is a mechanism to disrupt LMC clusters older than ~3 Gyr, which seems unlikely, the star formation history implied by the (relatively luminous) LMC cluster population is *not* that followed by the field population. Given the

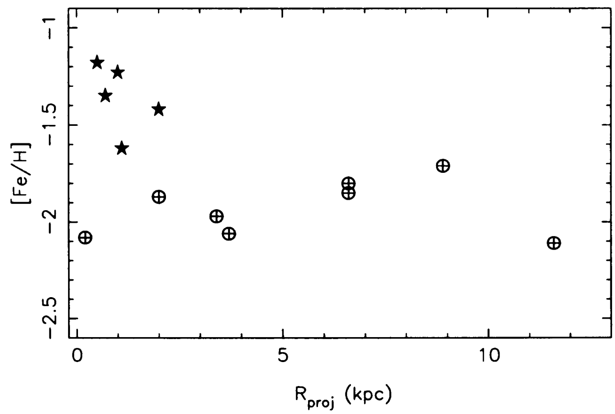


Figure 1. Abundance versus projected radial distance for the LMC old cluster population. Star symbols represent new abundances for five inner clusters from Olsen et al. (1998), while the circled plus sign symbols are abundances from Suntzeff et al. (1992 and references therein).

implications of this result, it is not surprising that there have been additional searches for LMC star clusters that fall in the "Age Gap".

The first of these is that of Geisler et al. (1997, see also these proceedings) in which candidate clusters were selected on the basis of integrated UBV colors or low metallicity. The clusters were imaged to produce c-m diagrams and the age estimated from the magnitude difference between the red clump and the main sequence turnoff. Observations of the ~9 Gyr old cluster ESO121-SC03 were included as a check. For the 23 candidates for which an age estimate could be obtained, *none* proved to be older than ~2.5 Gyr. This result rather strongly reinforces the status of the cluster Age Gap: there are now more than 40 clusters known, via main sequence turnoff photometry, to have ages between ~1 and 3 Gyr! Sarajedini (1998), however, has reported the serendipitious discovery of three LMC clusters somewhat older than 3 Gyr. The data are archival WFPC2 short exposure images and isochrone fits suggest ages of ~4 Gyr for the clusters, slightly older than any previously age-dated LMC intermediate-age cluster. The results require confirmation from better data, especially as the Sarajedini (1998) abundance estimates differ significantly from those of Olszewski et al. (1991) for the two clusters in common. Nevertheless, independent of the Sarajedini (1998) results, ESO121-SC03 remains a unique LMC cluster and we are yet to find (if they exist) the LMC equivalents of SMC clusters like Kron 3, NGC 361 and 416, clusters with ages between ~5 and 8 Gyr.

The search for clusters in the Age Gap is important because, without such objects, the LMC Age-Metallicity relation (AMR) remains virtually unconstrained in the epoch between ~3 Gyr and the formation of the oldest clusters. Despite this, Pagel & Tautvaisiene (1998) have used the existing LMC cluster AMR to constrain analytical models for the chemical evolution of the LMC. Their models can incorporate variations in the star formation rate and they find the cluster AMR can be fit with a model that has a star formation history quite similar to that determined observationally by Geha et al. (1998) from deep WFPC2 observations of field regions. The Pagel & Tautvaisiene (1998) result can be then interpreted as further evidence for significant LMC star formation in the ~3 – 10 Gyr interval that is apparently not reflected in the cluster age distribution. If these field star formation histories are assumed to apply to the cluster formation history also, then based on the current size of the known ~1 – 3 Gyr cluster population, we expect there should be perhaps a dozen LMC clusters with ages in the ~3 – 10 Gyr age range, even allowing for evolutionary fading and some cluster disruption. At the present time we know definitely of only one such cluster in this age range; perhaps the Sarajedini (1998) objects may represent one or two more. While searches for such clusters should continue, it is apparent that the deficiency of age $\geq \sim 3$ Gyr clusters in the LMC is probably real. In that case we must address the fact that prior to the large increase in star formation ~3 Gyr ago, the LMC did form significant numbers of field stars but did not form any relatively luminous (i.e., massive) star clusters (other than the old clusters). Identification of the star formation conditions under which this can occur (or perhaps better, the conditions under which massive cluster formation *does* occur) is best left to theorists. But they should not forget that such clusters have been forming approximately continously in the SMC.

One final point deserves mention. In Fig. 1 there is a strong suggestion of a radial abundance gradient in the old LMC cluster system. It is of relevance to the LMC enrichment history to ask if such a gradient is also present among the intermediate-age cluster population which, like the old clusters, has disk kinematics. The extensive work of Olszewski et al. (1991) found a slight difference between "inner" ($r \leq 5°$) and "outer" clusters, in the sense that the outer clusters were marginally more metal-poor. There was, however, considerable overlap in the total abundance range. On the other hand, Bica et al. (1998, see Geisler, these proceedings) have provided (photometric) abundance estimates for the 13 most distant of the intermediate-age clusters studied by Geisler et al. (1997). They find generally lower abundances than Olszewski et al. (1991) for the clusters in common and their results hint at the existence of a radial abundance gradient. A comprehensive investigation of this question is clearly called for.

3. SMC

In the SMC star cluster AMR shown in Da Costa (1991), the cluster ages were determined from main sequence turnoff luminosities but the abundances were mostly based on giant branch colors. Recently, however, there have been both new abundance determinations and new age estimates for an increased sample of SMC clusters. Thus a reinvestigation of the SMC cluster AMR is appropriate.

As regards cluster abundances, Da Costa & Hatzidimitriou (1998) have published estimates for six old and intermediate-age clusters based on spectroscopy at the CaII triplet of typically five individual red giant members per cluster. Similarly, Mighell et al. (1998 and these proceedings) have determined "photometric" abundances for seven old and intermediate-age clusters by applying the "simultaneous reddening and metallicity" and the "red giant branch slope" methods to cluster c-m diagrams. Finally, de Freitas Pacheco et al. (1998) have

https://doi.org/10.1017/S0074180900118406 Published online by Cambridge University Press

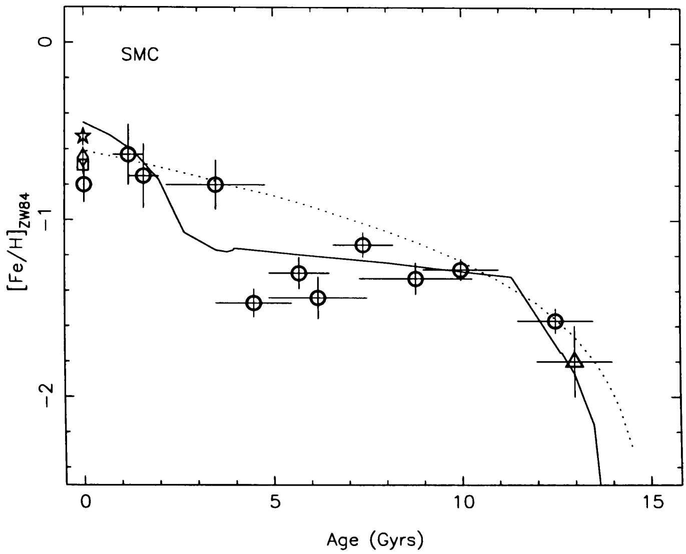


Figure 2. The SMC age-metallicity relation. Star clusters are shown as circles, the field RR Lyrae results of Butler et al. (1982) by the triangle and present-day field star results by the star, diamond and square symbols. The dotted line is the prediction of a simple (closed box) chemical evolution model while the solid line is that for the "bursting" model of Pagel & Tautvaisiene (1998). Note that this latter model has a very low star formation rate in the ~4 to 12 Gyr interval, which is in conflict with the numbers of clusters found in this age range.

determined abundances for six old and intermediate-age clusters from integrated cluster spectra. Their technique involves the measurement of Lick system indices calibrated via single stellar population models. The agreement between these independent abundance determinations is generally quite good. Thus they can be combined to produce improved abundance estimates for a total of 10 old and intermediate-age SMC star clusters.

As regards cluster ages, Mighell et al. have used archival WFPC2 short exposure images to estimate ages for several clusters using the color difference between the red clump and the red giant branch as an age indicator. Similarly, de Freitas Pacheo et al. have used their single stellar population models to derive age estimates from their integrated cluster spectra. The agreement between these data and the ages available from (ground-based) determinations of the main sequence turnoff luminosities is usually reasonable, so that the values can be combined to produce improved age estimates.

The SMC cluster AMR based on these new data is shown in Fig. 2. Somewhat surprisingly perhaps, the "morphology" of this relation isn't greatly different from that in Da Costa (1991), although the cluster data are undoubtedly more reliable. What are we to make of this relation? First, we can compare the

https://doi.org/10.1017/S0074180900118406 Published online by Cambridge University Press

data to the predictions of a simple (closed box) chemical evolution model; such models are often assumed to apply to dwarf galaxies like the SMC. The prediction of such a model, scaled to the present-day SMC abundance and gas fraction, and assuming an age of 15 Gyr, is shown as the dotted curve in Fig. 2. The fit is clearly not satisfactory: it might be adequate for the earliest epochs but the model generally predicts abundances that are too large for the intermediate-age clusters. An alternative approach is that adopted by Pagel & Tautvaisiene (1998). As noted above, in their models these authors allow for variations in the star formation rate (SFR). For the SMC they find that if large variations in the SFR are included, then age-metallicity relations can be generated that are more representative of the cluster data. In particular, they associate the period of little obvious enrichment with a long interval in which the SFR is very low. They then use a large increase in the SFR at ~4 Gyr to "explain" the rapid rise in cluster abundance. The solid line in Fig. 2 shows the AMR for one of these "bursting" models, and it does appear to be representative of the cluster data. However, the assumed star formation history underlying this model is problematic. It assumes that the SFR is very small over the ~4 – 12 Gyr interval, yet, while the current sample of SMC clusters is undoubtedly biased by various selection effects, most observed clusters in fact formed during this postulated "quiescent" period, an inconsistency with the model assumptions.

As a guide then to future modellers of these cluster data, and to SMC observers, two salient features of Fig. 2 should be noted. First, the rapid rise in cluster abundance at ~3 – 4 Gyr seems inescapable. Tighter constraints on the SMC star formation history, from both field star and additional cluster studies, are required however, to gain insight into the origin of this sharp abundance rise. Second, among the SMC intermediate-age clusters there is a definite abundance range, but with little obvious correlation between age and abundance. For example, contrast the clusters NGC 339 and NGC 416 with [Fe/H] ≈ -1.45 at ~5 Gyr with Kron 3 at [Fe/H] ≈ -1.15 at ~7.5 Gyr. The existence of this abundance range is somewhat unexpected given that in dwarf galaxies lacking significant systematic rotation, such as the SMC, enrichment products are expected to be well-mixed over galaxy-wide scales on timescales considerably less than a Hubble time. Certainly the present-day abundances in the SMC are homogeneous: studies of HII regions and young stars suggest the present-day abundance dispersion is $\lesssim$0.1 dex. In this context it is also worth noting that there is no apparent spatial – abundance correlation in these SMC cluster data; e.g., there is no evidence for a radial abundance gradient.

These results suggest that the chemical evolution of the SMC was (and is) quite complex. In particular, it is becoming increasingly clear that we must relax the simplfying assumption that the SMC has evolved as an isolated system, and no longer ignore the effects of interactions with the LMC and the Galaxy.

4. Summary

The latest data for old and intermediate-age clusters in the Magellanic Clouds seem to have raised as many questions as they have supplied answers as regards the star and cluster formation histories and the chemical evolution of these galaxies. Clearly a variety of complex processes are involved. We can but look forward to the impact the new large telescopes in the Southern Hemisphere will have on these subjects. For example, it will be possible to study quantities such as the [α/Fe] element ratio in red giants in Magellanic Cloud clusters of different ages. The results of such studies will tell us a lot about the details of the enrichment processes in these galaxies. Indeed, at the next Magellanic Clouds IAU Symposium, we'll undoubtedly be discussing the new puzzles that the new large telescope data will reveal.

References

Bica, E., et al. 1998, AJ, 116, 723

Butler, D., Demarque, P., & Smith, H.A. 1982, ApJ, 257, 592

Da Costa, G.S. 1991, in The Magellanic Clouds, IAU Symp. 148, eds R. Haynes and D. Milne (Kluwer, Dordrecht), p. 183

Da Costa, G.S. 1993, in The Globular Cluster – Galaxy Connection, eds G.H. Smith and J.P. Brodie (ASP, San Francisco), ASP Conf. Ser. 48, p. 363

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

de Freitas Pacheco, J.A., Barbuy, B., & Idiart, T. 1998, A&A, 332, 19

Geha, M.C., et al. 1998, AJ, 115, 1045

Geisler, D., et al. 1997, AJ, 114, 1920

Mighell, K.J., Sarajedini, A., & French, R.S. 1998, AJ, 116, 2395

Olsen, K.A.G., et al. 1998, MNRAS, 300, 665

Olszewski, E.W., et al. 1991, AJ, 101, 515

Pagel, B.E.J., & Tautvaisiene, G. 1998, MNRAS, 299, 535

Sarajedini, A. 1998, AJ, 116, 738

Schommer, R.A., et al. 1992, AJ, 103, 447

Suntzeff, N.B., et al. 1992, AJ, 104, 1743

Discussion

van den Bergh: In the dwarf irregular galaxy IC 1613 we see lots of star formation, but no cluster formation. This shows that the specific cluster forming frequency is $\geq 10^2$ times higher in the LMC *now* than it is in IC 1613.

Da Costa: Yes, this further illustrates the point I was trying to make in regard to the LMC. We shouldn't assume that the formation history of relatively luminous (massive) star clusters necessarily tells us about the star formation history of the general population. The formation of such clusters may require special conditions and so the lack of such clusters doesn't necessarily mean no star formation at all.

Hans Zinnecker: The jump in metallicity in the SMC some 3 Gyr ago strikingly agrees with the onset of enhanced star formation rate in the LMC! Something must have happened then, some common trigger. Perhaps a close encounter with the Milky Way?

https://doi.org/10.1017/S0074180900118406 Published online by Cambridge University Press

Rebecca Elson: Are there any constraints from field star studies on the star formation history in the 4-10 Gyr gap where the Pagel et al. model shows no star formation?

Jon Holtzman: Our deep HST data near the bar of the SMC appear to be inconsistent with the predictions of the Pagel model. Comment: Note that it may still be possible for a star formation history which matches that of LMC clusters to fit the deep luminosity function if one allows for a steeper IMF.

Norbert Langer: Pagel & Tautvaisiene's model for the chemical evolution of the SMC points out that there may be a fundamental problem with the interpretation of the age-metallicity data from clusters in the SMC: a constant metallicity for a time interval of about 5 Gyr seems to imply that there was no significant star formation during that time (at least in a closed box model), in contrast with the existence of clusters with these ages.

Da Costa: Yes, the lack of enrichment shown by the SMC clusters over the $\sim$4 to 10 Gyr interval, assuming the formation of clusters is indicative of general on-going star formation throughout this period, requires either the outflow of metal-enriched gas, which seems unlikely unless the star formation was very vigorous, or the infall of primordial, or at least low abundance, gas.