THE AGE-ABUNDANCE RELATIONS AND AGE DISTRIBUTIONS FOR THE STAR CLUSTERS OF THE MAGELLANIC CLOUDS.

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ABSTRACT. A sample of Large Magellanic Clouds (LMC) and Small Magellanic Clouds (SMC) clusters for which ages have been directly determined from main sequence turnoff photometry has been compiled. According to this sample, the LMC and SMC cluster age distributions are very different. The LMC contains a large population of 1 to 3 Gyr old clusters as well as a small number of clusters that appear to be as old as the Galactic halo globular clusters. Surprisingly however, only a single cluster is known with an age in the interval between 3 Gyr and the age, taken as 15 Gyr, of the oldest clusters. The SMC age distribution, on the other hand, is much broader. It extends back to approximately 12 Gyr but there appear to be no SMC clusters as old as the oldest in the LMC. The sample of clusters is also used to discuss the age-abundance relations for both galaxies. Little can be learned for the LMC but it appears that the chemical evolution of the SMC differed in form from that experienced in the solar neighbourhood. The first results of an imaging survey designed to find LMC clusters with ages exceeding 3 Gyr are also described.

1. Introduction

Studies of the star clusters of the Magellanic Clouds find application in many areas of astronomy, from stellar evolution to discussions of the formation and evolution of the parent galaxies. In particular, the contribution of cluster studies to the subjects of chemical evolution and star formation history in the Magellanic Clouds is potentially large, since it is easy (at least relative to individual field stars) to determine cluster ages and abundances. The age-abundance relation determined by the clusters is thus widely used in discussions of the chemical evolution of both the LMC and the SMC. Similarly, the cluster age distribution, suitably corrected for disruption processes, can reveal much about the history of star formation over the lifetime of these galaxies. In this contribution, the observed age-abundance relations for the LMC and SMC cluster populations are reviewed and discussed, with emphasis on the differences that are apparent between the Large and Small Clouds. At the same time the differences in cluster age distribution are highlighted. In the final section, the first results of a survey designed to find LMC clusters with ages greater than 3 Gyr are presented. Such clusters are conspicuously absent from the LMC but are found in the SMC.

It is worth emphasizing right at the outset however, that throughout this paper it is the observed age distribution that is under discussion: i.e. no allowance is made in any quantitative sense for completeness as a function of magnitude, the fading of clusters as they age and so on. Elson and Fall (1988 and the references therein) describe in some detail how these and other processes can be allowed for. However, in the present contribution, the discussion is focused on those clusters for which an age has been directly determined from photometry of the cluster's main sequence turnoff.

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This avoids the extra complication of deriving ages from integrated colours, a process which is far from straightforward for clusters older than about 1 Gyr. Fortunately, as a result of the advent of CCD detectors, the sample of clusters with directly determined ages is now quite large and thus can be discussed on its own without introducing any substantial bias. Indeed a survey of the literature leads to a sample of some 70 or so clusters (mostly in the LMC) where the photometry reaches sufficiently faint magnitudes to reveal the main sequence turnoff. These clusters form the sample discussed in this contribution.

2. Results for the LMC

In Figure 1, the adopted cluster age is plotted against the abundance for the LMC clusters in the sample. Before discussing this diagram and its implications however, it is necessary to make some comments concerning the procedures used to determine the cluster ages and abundances. Regarding the cluster ages, they are based on an assumed distance modulus for the LMC of 18.2 (18.8 for the SMC) and on the isochrones of VandenBerg (1985). These isochrones are based on "conventional" stellar evolution in which overshoot from the convective core is not included. If, instead, use is made of isochrones which include convective overshoot (e.g. Bertelli *et al.* 1986), then the ages for the younger clusters become significantly older. However, for clusters older than about 1 Gyr, the effect is relatively minor since by this age the turnoff stars no longer have substantial convective cores. In any case, none of the results to be discussed here are dependent upon the particular value of the LMC distance modulus used or on the set of isochrones adopted.

For the cluster abundances, direct measurements (i.e. spectroscopy or photometry in abundance sensitive system) have been used whenever available. The majority of the abundances however, come from the c-m diagrams themselves via parameters such as the giant branch colour or from the actual isochrone fits. In this latter case, the abundances are often quite uncertain and a generous error bar has been assigned. Fortunately, much new work is going on in the area of Magellanic Cloud cluster abundances (see, for example, Geisler *et al.*, 1990) and many more accurate values will soon become available.

Figure 1 also includes the seven "old" clusters (NGC 1466, 1786, 1835, 1841, 2210, 2257 and Hodge 11)[1] associated with the LMC. All these clusters, except Hodge 11 which has only blue horizontal branch stars, possess RR Lyrae variables. Those which are in fields that permit photometry are known to have blue horizontal branch morphology and where available (e.g. Walker 1990), deep photometry reveals faint main sequence turnoffs. In the absence of any evidence to the contrary therefore, it seems reasonable to conclude that these clusters are analogues of the galactic halo globular clusters. They have then been *assigned* an age of 15 ± 2 Gyr. The abundances of these clusters are all relatively well established and are all quite metal-poor; the mean abundance is -2.0 ± 0.1 dex. This value is significantly less than the mean abundance (-1.58 dex) for the galactic halo globular clusters.

On even the most casual inspection of Figure 1, one is immediately struck by two things: the apparent lack of LMC clusters with ages between 3 Gyr and the 15 Gyr age assumed for the oldest clusters, and the unique location of the cluster ESO121-SC03. The deficiency of clusters older than 3 Gyr is made all the more apparent by the relatively large number (~30) of clusters with ages in the 1 to 3 Gyr interval. Although the cluster sample used here is highly inhomogeneous in that it is restricted to those clusters with turnoff photometry, it seems highly unlikely that selection effects could have conspired to produce such an unexpected age distribution. Similarly, it seems

[1]The Reticulum Cluster should probably also be included in this list. Its properties (Gratton and Ortolani 1987) are very similar to those described for the other 7 clusters.

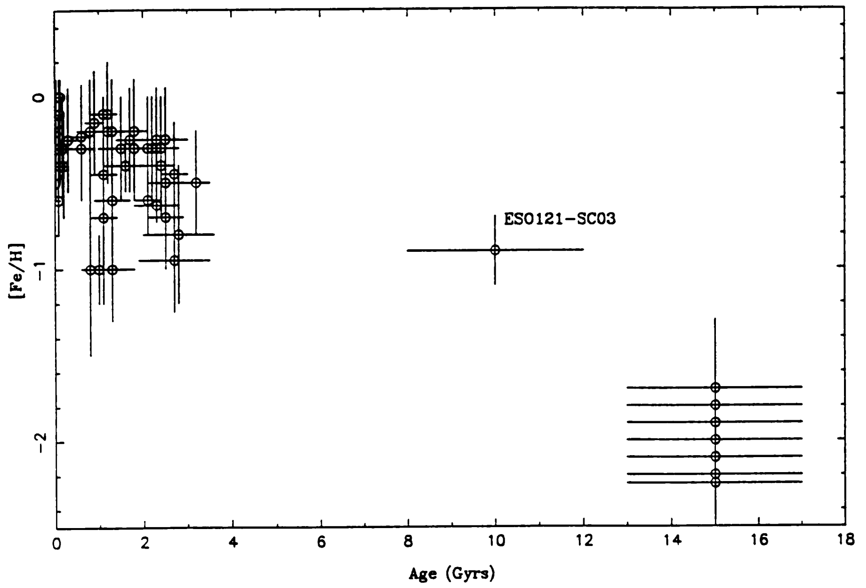

Figure. 1. The Age-Abundance relation for LMC clusters with ages determined from main sequence turnoff photometry. The "old" clusters however, have been assigned an age of 15 ± 2 Gyr.

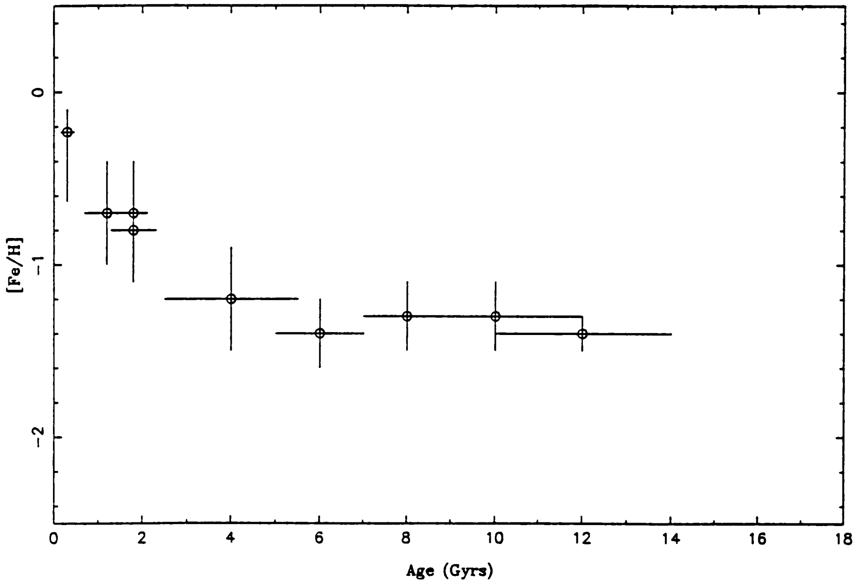

Figure. 2. The Age-Abundance relation for SMC clusters with ages determined from main sequence turnoff photometry.

improbable that any cluster disruption process could produce such an abrupt cutoff. The implications of this LMC cluster age distribution will be discussed further in Section 4, but it is perhaps relevant to review here the properties of the only known cluster in the "age gap"; ESO121-SC03. This cluster, studied by Mateo, Hodge and Schommer (1986), lies some 10° from the center of the LMC and it is a rather inconspicuous object with an integrated magnitude of only V=14.3. It is thus some 1 to 2 magnitudes fainter than the majority of the 1 to 3 Gyr old clusters in Figure 1.

As regards the chemical evolution of the LMC, it is evident that the star cluster data in Figure 1 impose only weak constraints. The "present-day" mean cluster abundance is approximately -0.3 dex, while the mean abundance for the 1 to 3 Gyr old clusters is slightly lower at about -0.5 dex. Both these abundances are considerably more metal-rich than the "old" cluster mean abundance. However, because of the lack of observed clusters with ages older than 3 Gyr, at the present time there is no way to decide (from cluster data alone) whether the LMC mean abundance rose rapidly initially and then remained approximately constant (cf. the solar neighbourhood) or whether the rate of enrichment was more gradual. We simply do not have, as yet, the required data.

3. Results for the SMC

In Figure 2 the equivalent results for the SMC are presented. Although there are many fewer clusters, it is obvious that the age distribution of the SMC clusters differs markedly from that of the LMC. This difference is manifested in two ways. First, unlike the LMC, there are SMC clusters in the 3 to 12 Gyr age range; indeed they appear to be relatively numerous. Second, again unlike the LMC, there are no SMC analogues of the galactic halo globular clusters. The oldest SMC cluster, NGC121, has been shown by Stryker *et al.* (1985) to be younger than the galactic globular clusters of similar abundance.

The chemical evolution of the SMC suggested by Figure 2 is also rather unusual in that the rate of enrichment, following a presumed initial burst that brought the abundance up to approximately -1.3 dex, has been very low over most of the lifetime of the SMC. However, an increase in the enrichment rate seems to have occurred some 2 to 3 Gyrs ago bringing the mean cluster abundance up to the present-day value of approximately -0.6 dex. This sort of age-abundance relation, and the chemical evolution it implies, is very different from that of the solar neighbourhood. It also differs substantially from that expected from a simple model of chemical evolution: if such a model is scaled to the present-day abundance and gas fraction of the SMC, then the predicted abundances for the clusters in the 3 to 12 Gyr age range are much higher than those observed. Thus modelling this age-abundance relation is likely to produce interesting results.

4. Discussion

The results presented in Figures 1 and 2 indicate that the SMC cluster age distribution, as observed, is fundamentally different from that of the LMC in that it is apparently much more uniform, while that for the LMC is peaked at 1 to 3 Gyr. This difference has been noted before (e.g. Mould and Aaronson 1982) but the present data, since the cluster ages are directly determined rather than inferred from integrated colours for example, are the most illustrative of this difference. Elson and Fall (1988 and references therein) have argued that the LMC cluster age distribution, when corrected to a mass limited sample and after allowance for cluster fading, is a smoothly decreasing function with no statistically significant deviations. That is, they find no evidence for any LMC-wide increases or decreases in the cluster formation rate. Mateo (1988) on the other hand, finds evidence in his study of a magnitude limited sample of clusters in a single region in the northern outskirts of the LMC, for a significant increase in the cluster formation rate some 2 to 4 Gyr ago. The rarity of LMC clusters older than 3 Gyr and the surfeit of clusters with 1 < age < 3 Gyr in the sample presented here certainly seems to support Mateo's results, the only caveat being the inhomogeneous nature of the present sample. If further work confirms his suggestion, then the fact that a surplus of 1 to 3 Gyr clusters is seen in the LMC, but not the SMC, has one immediate consequence. Whatever the origin of the enhanced LMC cluster formation rate, its source was most likely to have been internal to the LMC rather than external, since any plausible external process (e.g. tidal interactions) should have had at least an equal effect on the SMC, and that is not observed.

5. A Search for LMC Clusters with Age > 3 Gyr

It is evident from the above discussion that the discovery of additional LMC star clusters with ages exceeding 3 Gyr is required before the LMC cluster age-abundance relation can be meaningfully used to constrain chemical evolution models for this dwarf galaxy. It is also apparent that the search technique must be efficient since it is quite likely that many clusters will have to be surveyed. This suggests the use of integrated photometry since the derivation of c-m diagrams from broad-band imaging to directly determine ages is a time consuming process. As shown by Chiosi *et al.* (1988) for example, the UBV system has insufficient age sensitivity to isolate clusters uniquely in this age range, but as illustrated in Figure 3, the Q(ugr), Q(vgr) diagram first introduced by Searle *et al.* (1980) apparently has the necessary age sensitivity. This diagram plots the Q(ugr) and Q(vgr) values from Searle *et al.* (1980) for those clusters with a turnoff age available. Clearly, the Type V and Type VI clusters are all 1 to 3 Gyrs old and are well separated from the Type VII clusters which are all at least 4 Gyr old. Hence a program of integrated uvgr photometry of a suitable set of candidate clusters will yield a reliable age classification and any Type VII clusters discovered would be prime candidates for the sought-after clusters with ages exceeding 3 Gyr. A colour-magnitude diagram reaching the main sequence turnoff however, would be required to determine the actual age.

The author has begun such a search using a CCD camera on the 1.5m telescope at CTIO to image the candidate clusters and the surrounding field. The advantages of using a CCD are twofold: a better sampling of the field near the cluster and the ability to optimize the choice of the measurement aperture. The candidate sample consists of a list of clusters in the outer parts of the LMC chosen, by inspecting them visually on the SRC Sky Survey films, to have faint apparent magnitudes for the "brightest blue stars". This criterion is sufficient to eliminate clusters younger than approximately 500 Myr. The first observing run occurred in December 1989 and data were obtained for six clusters of known SWB type and known age to check that the CCD system reproduced that of SWB, four clusters of known age but which lacked SWB classification, and six clusters from the candidate sample. The CCD system was found to reproduce the SWB system well and the four clusters of known age, when placed in the Q,Q diagram by the new photometry, fell in their expected locations. Specifically, the SMC cluster Kron 3 (age ~ 8 Gyr) is a found to be a Type VII cluster and the clusters NGC1651, NGC2203 and Hodge 4, all of which have ages near 2.5 Gyr, fall near the Type V-Type VI boundary in the Q,Q diagram. However, perhaps not surprisingly, none of the six previously unstudied clusters is of Type VII. As illustrated in Figure 4, five are of Type V and are undoubtedly additional members of the large class of 1 to 3 Gyr old LMC clusters. The sixth cluster, while still classified as a Type VI, lies closer to the LMC Type VII clusters than any other LMC cluster yet identified and it will be followed-up to determine the

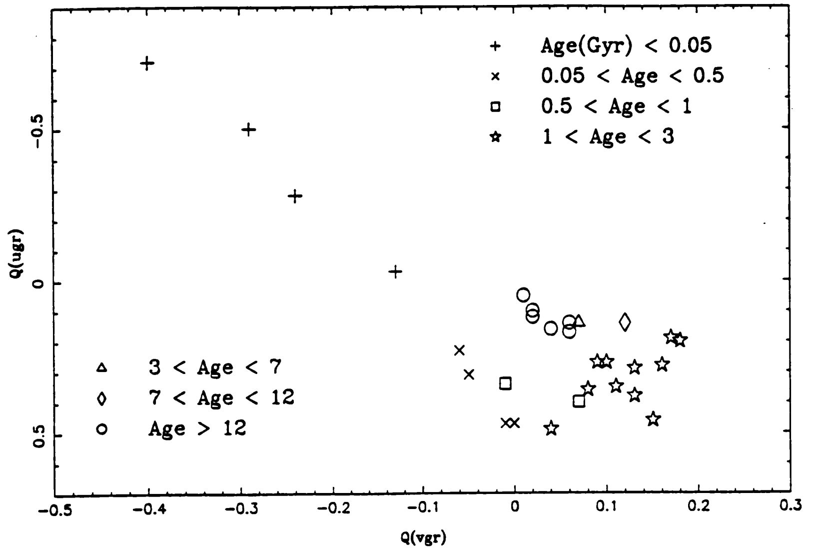

Figure. 3. The Q(ugr), Q(vgr) diagram of Searle *et al.* (1980) for the clusters of known age. Notice the clean separation of the clusters older than 4 Gyr (Type VII) from the 1 to 3 Gyr old clusters (Types V and VI). The equivalent UBV diagram does not show this same separation.

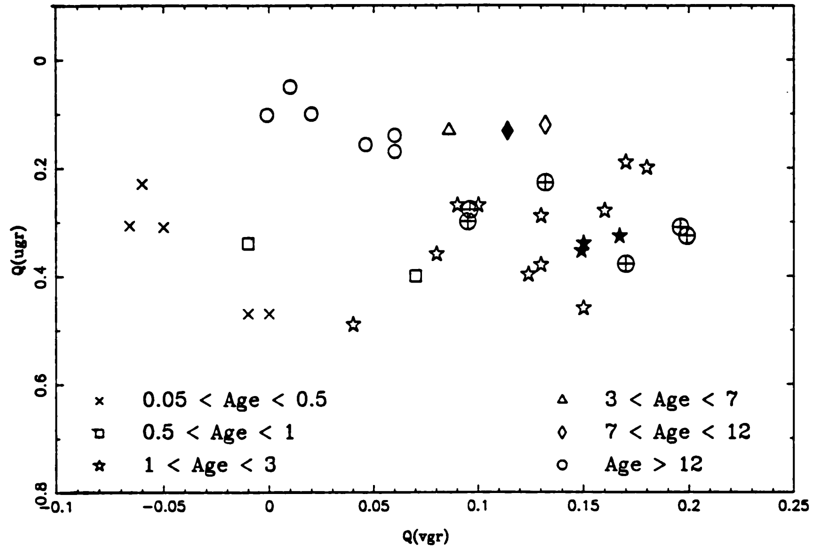

Figure. 4. An enlarged version of the lower part of Fig. 1 to which 4 clusters of known age (filled symbols) but which were not studied by Searle *et al.* (1980) have been added. Also shown are six previously unstudied clusters (circled plus-signs). The uvgr photometry for these 10 clusters comes from CCD observations.

actual age. Additional uvgr photometry of further candidates is planned for the coming observing season.

6. Summary

The principle results of this analysis of the sample of LMC and SMC clusters of known age can be summarized as follows:
a) The age distributions of the LMC and SMC clusters are very different, with the SMC showing a more continuous distribution of ages. The oldest clusters however, are found only in the LMC.
b) The apparent paucity of LMC clusters with ages exceeding 3 Gyr, together with the surplus of 1 to 3 Gyr old objects, suggests that the idea of an enhanced rate of cluster formation in the LMC some 2 Gyr or so ago should be given serious consideration.
c) The current sample of LMC clusters with known ages reveals very little about the chemical evolution of the LMC over most of its lifetime, while for the SMC, the clusters suggest that the rate of enrichment was different in form from that of the solar neighbourhood.

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