INTERMEDIATE-AGE MAGELLANIC CLOUD GLOBULAR CLUSTERS

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ABSTRACT. In this paper, I discuss some of the new facts that have been learned about Magellanic Cloud clusters, mostly thanks to new detectors and associated reduction code. I first show the extent of the LMC cluster system, in order to note that studies of age, abundance, and kinematics of the cluster system have been missing clusters to the north and south of the Hodge and Wright atlas, and to point out that star formation has gone on in places far from present day neutral hydrogen. I will concentrate on the intermediate age clusters (10^8-10^{10} y) in the discussion concerning new stellar evolution results, neglecting the 10^7 y clusters and 30 Doradus. I further restrict my choice of topics to 1) the luminosity of clump giants, 2) the youngest possible RR Lyrae stars, and 3) the patterns and history of cluster formation. The discussion of abundances of Cloud clusters leads readers to the excellent poster papers presented at this meeting.

1. THE EXTENT OF THE MAGELLANIC CLOUD CLUSTER SYSTEMS

I will start this discussion by reminding readers what the Magellanic Clouds look like, and how far out the cluster systems extend. Our typical conception of the LMC, for instance, is shown in Figure 1 of Alcaino and Liller (1984), which shows the LMC bar, the 30 Doradus region, and goes north to slightly beyond Shapley's Constellation III. Another example, the color picture in Sky and Telescope (April, 1984, p304) shows an even more restricted region. Casual inspection of the SRC J plates will also lead to a similar conclusion, for the ionized gas is most evident near the bar, and the density of stars drops off rapidly south, east, and west of the bar, and a couple of degrees north of Constellation III.

This picture of the LMC is incomplete, as the following three pictures will show. The first is in Schommer, Olszewski, and Aaronson (1986), and is a reproduction of two Canterbury Atlas (Doughty, Shane, and Wood 1972) prints on which we have labelled some clusters. What I want to mention here, for I will return to the cluster E2 below, is

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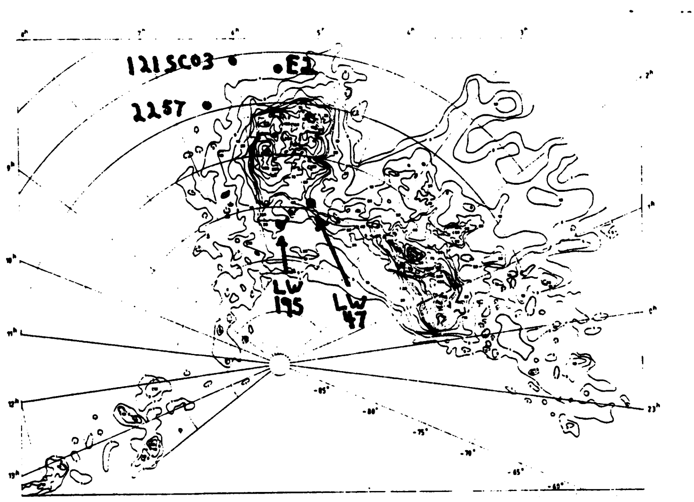

Fig. 1. This is the Magellanic Cloud H I distribution shown by Mathewson and Ford in IAU Symposium 108. I have added the positions of the clusters E2, 121SC03, NGC 2257, LW 47, and LW 207, which are mentioned in the text.

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that there are LMC clusters many degrees from the bar, far beyond the picture of the LMC described above. Lynga and Westerlund (1963, their Figure 1) showed this more than 20 years ago. They also noted that a southern 'gap' in clusters followed by a more southerly increase in cluster density corresponded in position with features noted in de Vaucouleurs' (1955) low resolution deep photographs. The second picture, which I reproduce here as Figure 1, is the LMC and SMC neutral hydrogen distribution given in Mathewson and Ford (1984), with some of the clusters from this review marked. Note that the northernmost clusters extend beyond the detected neutral hydrogen (the limit is 10^{19} atoms cm^{-2}). The third picture, Figure 2, is reproduced from Freeman, Illingworth, and Oemler (1983), which was a compendium and analysis of the kinematics of the LMC cluster system. I have added to their figure the outline of the Hodge and Wright (1967) atlas, NGC and IC clusters outside the atlas, the clusters in the Olszewski, Harris, and Schommer (1987) catalog of outer LMC clusters, the region studied in Mateo's paper in this symposium, and the Reticulum system.

I think that there are two important points about LMC clusters to be made here. The first is that while the more populous clusters inside the boundaries of the Hodge and Wright atlas are reasonably well sampled, though not complete, there are 18 NGC and IC clusters outside the atlas. The boundaries of the atlas were chosen by the available plate material, which covered 'most of the recognized area of the LMC.' The publications resulting from Hodge's thesis (1960, 1961) identified the red and blue clusters within the atlas as well as a few others (e.g., NGC 1868). Aside from NGC 2257, 1466, and 1841, which were

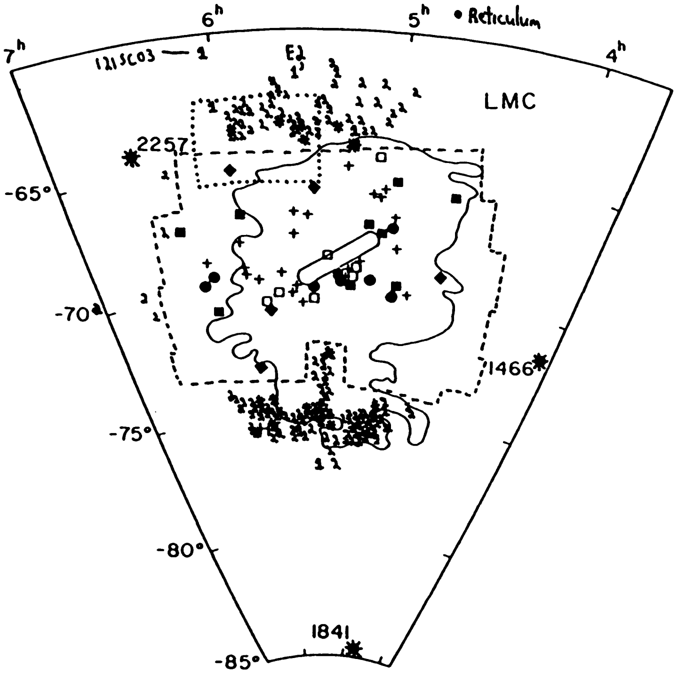

Fig. 2. A map of the LMC, taken from Freeman, Illingworth, and Oemler (1983). The dashed line is the boundary of the Hodge and Wright (1967) atlas; stars are NGC and IC clusters outside the Hodge and Wright atlas; ones are outer clusters mentioned in the text; twos are outer clusters from Olszewski, Harris, and Schommer (1987); the dotted line is the approximate boundary of the Mateo (this volume) study.

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already well known clusters, essentially all of the clusters in the Freeman, Illingworth, and Oemler (1983) and Searle, Wilkinson, and Bagnuolo (1980) studies are within the boundaries of the atlas or from Hodge's thesis. What of these other NGC and IC clusters? Many are as bright as representative inner clusters, and are in less crowded fields. It seems to me that the problem was a lack of suitable chart material (the SRC J plates have only recently become available; without marked charts finding clusters is tedious), and I think the lack of recognition of the value of the Lyngå and Westerlund survey. I hope that this 'Hodge Atlas bias' can be corrected in future work.

The second point is that with the detector revolution of the past few years, we can relatively easily measure CMDs and velocities of any clusters, not just the most populous ones. It is not necessary to restrict studies to the clusters which have colors compiled in van den Bergh (1981), which in general represent some linear combination of the least crowded and most luminous subset of the subset of clusters within the Hodge and Wright atlas. Mateo (this volume) has surveyed all clusters in a small northern region of the LMC, determining accurate ages from isochrone fitting, and deriving an age-metallicity relation for this spatially defined sample. In this way, one can avoid sampling the tail of the cluster distribution.

I have generally ignored the SMC in the above discussion. The Hodge and Wright (1977) SMC atlas does seem to cover the entire SMC, as represented by the clusters. In order to have a more complete sample of the clusters, however, higher resolution plates must be examined (SRC J) or obtained (Hodge 1987). In the SMC, almost all of the clusters which are reasonably populous and reasonably uncrowded now have CCD color-magnitude diagrams, mostly thanks to Da Costa, Mould, and collaborators. Some of the results will be mentioned below. Most of the SMC clusters are in or near the bar, which makes CMD work very difficult, and cluster membership hard to deduce.

My last point about the clusters in the context of the two galaxies as a whole is illustrated by de Vaucouleurs and Freeman's (1972) review. Their Figure 9a, if we did not know was of the LMC/SMC, is of some galaxies which have obviously undergone some strong interaction (among other things, remember that the SMC has a 'wing' and that the Magellanic Stream exists). I don't mean to make this case too strongly, but I think that we should remember that the LMC and SMC do not exist as island universes in majestic isolation. If we truly wish to understand the cluster system in the Clouds, we need to look for evidence that interactions (see the cover of IAU 108) have affected the clusters, perhaps helping to make the outermost clusters, and almost certainly influencing the outer cluster dynamics. We should also remember that projection effects can distort our picture and that dispersion along the line of sight may be significant, especially for the SMC.

2. STELLAR EVOLUTION

In this section, I will discuss some results which have come from a number of good CMDs of Cloud clusters. We now can actually look at specific stages of stellar evolution in clusters of different age, which finally vindicates the optimism which Magellanic Cloud workers have had for the potential of the confrontation of observation with stellar evolution theory. Perhaps surprisingly, most of the data to be discussed come from SMC clusters.

2.1 Clump Giants

The clump giants are the more massive, hence younger, analog of the globular cluster horizontal branch, and are burning helium in their cores. As we do for the horizontal branch stars, in order to understand the clump, we need to ask questions like: 1) how do clump giant magnitudes vary with metallicity; 2) how do magnitudes and masses (or mass loss from main sequence star to clump giant) vary with age; 3)

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how does the morphology of the clump vary with metallicity or mass; 4) how well do models predict the observed features and can the model results be reconciled with our prejudices; and 5) can the study of clumps help solve other fundamental questions about the Clouds? I don't think that we can answer all these questions, but a good start has been made.

The questions about metallicity really must await more clusters, and of course are entwined with the question of age. Mateo and Hodge (1985) have argued that M_V(clump) is a constant, if the cluster in question has an age > 3×10^8 y. Olszewski, Schommer, and Aaronson (1986) have tested this hypothesis by plotting the apparent mean R magnitude of the clump of six SMC clusters versus age. The clusters span an age of 1.5 - 12 Gyr; the results are shown in Figure 3, both for the short SMC modulus of 18.7, and for this modulus corrected for the presumed tilt of the SMC at the position of each cluster. Using the

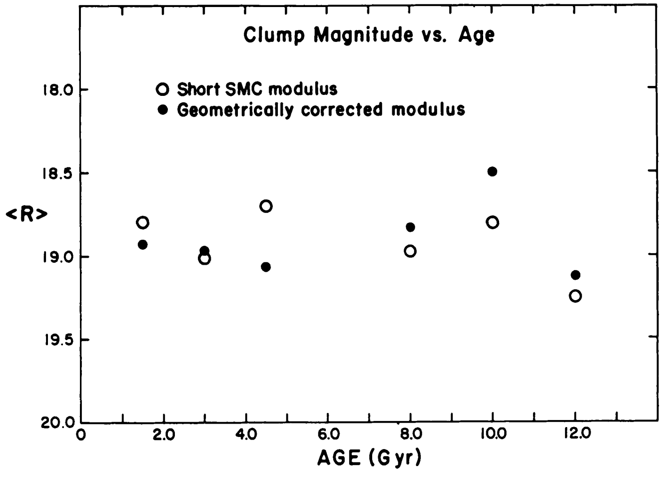

Fig. 3. A plot of the apparent R magnitude of the giant branch clump versus derived cluster age for several SMC clusters. Open circles are measured from CMDs, while filled circles are magnitudes corrected for the presumed geometry of the SMC.

data in Seidel, Da Costa, and Demarque (1986) gives similar results. Formally, m_R(clump) = ~ 18.8 + ~ 0.02* (age in Gyr), with a correlation coefficient of ~ 0.4. As Olszewski, Schommer, and Aaronson, and Seidel, Da Costa, and Demarque point out, the severe tilt of the SMC can cause interpretative problems for individual clusters. At present there is little evidence for a variation of M_V(clump) with age; more CMDs need to be made, and much more work needs to be done on the distances to and the tilts of the Magellanic Clouds.

Seidel, Da Costa, and Demarque (1987) have gathered CMDs made by Da Costa and collaborators to investigate clump giants, determining

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their masses, and the amount of mass loss as a star evolves from the main sequence to the clump. The mass loss is calculated by determining the turnoff mass from conventional isochrone fits to CMDs, while the clump mass comes from a new grid of models of core helium burning stars.

If the short modulus to the SMC is adopted, the older clusters seem to lose ~ 0.2 $M_{\odot}$ of material, while the ~ 1 Gyr clusters lose ~ 0.6 $M_{\odot}$. This latter large mass loss is somewhat unexpected, but is consistent with the conclusion in Aaronson and Mould (1985) that quantitative agreement between the observed luminosity of the AGB with theory is possible if mass loss on the AGB increases with increased luminosity for initial masses greater than 1.5 $M_{\odot}$. I point the reader to the lengthy discussion in Seidel, Da Costa, and Demarque.

Not only did the Seidel, Da Costa, and Demarque study teach us about clump giants and mass loss, but it was able to make a consistency argument about the correctness of the long and short distance moduli to the Clouds. If the long moduli are adopted, the derived clump giant masses are in general larger than their progenitor masses. Either the theory is wrong, or more likely, another reason exists for believing the short scale. (I point out that the poster papers at this conference discussing Galactic RR Lyraes also point to the short scale.)

2.2 The Youngest Known RR Lyrae Stars

This discussion is adapted from that given in Olszewski, Schommer, and Aaronson (1987). The problem can be stated simply: Lindsay 1 has an age of ~ 10 Gyr and has no RR Lyraes while NGC 121 is ~ 12 Gyr old and contains them. Have we discovered the approximate age of the onset of the RR Lyrae phenomenon, and is there any evidence for 'young' RR Lyraes in other galaxies? Again, remarkably, we are dealing with SMC clusters.

The CMDs of L1 (Olszewski, Schommer, and Aaronson 1987) and NGC 121 (Stryker, Da Costa, and Mould 1985), both have well defined main sequence turnoffs; their ages are as well determined as for any other Magellanic Cloud clusters. That either cluster contains RR Lyraes is somewhat surprising, since the giant branch clumps are quite red. Both clusters have approximately the same metal abundance.

The absence of RR Lyrae stars in L1 is based on the unsuccessful blinking of plates by Gascoigne (1966); no modern study such as Graham and Nemec (1984) has been made for this cluster. If we accept this pair of clusters as representative, we conclude that a cluster can make RR Lyrae stars at an age of 10 Gyr $< t_{RR} <$ 12 Gyr, for [Fe/H] ~ - 1.3.

Evidence for young RR Lyraes in other galaxies includes the metal rich disk RR Lyraes in the Milky Way (Taam, Kraft, and Suntzeff 1976; Strugnell, Reid, and Murray 1986). These form a kinematically distinct sample of RR Lyraes, which can best be called 'old disk.' Current

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wisdom maintains that the old disk is several billion years younger than the Galactic globular clusters.

The Carina dwarf galaxy provides evidence which the present set of observations cannot unambiguously interpret. Mould and Aaronson (1983) deduced that the bulk of the stellar population of Carina was ~ 7 Gyr old, with only a small old population. Saha, Monet, and Seitzer (1986) have now found ~ 50 RR Lyraes in Carina, which can either argue for a (small) old population or for younger RR Lyrae stars.

Clearly, the Magellanic Cloud clusters provide the best limits on the youngest possible age of RR Lyrae stars. Comments about increasing the sample of L1-, N121-aged clusters will be made below.

2.3 Post-AGB Stars

In the oral version of this paper, I presented a crude argument which suggested that for every 10 AGB stars we should expect one post-AGB star, and asked the question, 'where are the post-AGB stars?' Renzini made a comment which can be read in the questions following this paper which said that my numbers were far too optimistic. This section is therefore revised.

Renzini and Voli (1981) estimate the AGB lifetime of ~ 1 $M_{\odot}$ stars to be ~ 2×10^6 y. Paczynski (1970) calculated lifetimes of post-AGB stars (nuclei of planetaries in his case) to be approximately a few x 10^4 y. Given the total number of ~ 1-2 x 10^2 AGB stars found in the extensive surveys of Mould and Aaronson (see Aaronson and Mould 1985), and the total luminosity surveyed of ~ 3 x 10^6 $L_{\odot}$, we expect to have ~ 1 post-AGB star in these ~ 60 clusters. What post-AGB stars will look like is not clear to me. Will they be hot, blue cores of stars which have lost their envelopes (planetary nebulae nuclei) or stars highly obscured by their own dusty ejected atmospheres (RAFGL objects)? Do the latter evolve into the former?

3. PATTERNS AND HISTORY OF STAR FORMATION

3.1 The Strange Age Distributions of the Oldest Clusters

Figure 4 shows the spatial distribution of the oldest clusters in the SMC, those with B-V > 0.5, U-B > 0.0, from van den Bergh's (1981) compilation of integrated colors. To this figure, I have added the cluster names and ages, the latter determined in most cases from isochrone fits. Note two important properties of these clusters: 1) NONE are as old as Galactic globular clusters; and 2) most have ages between 3-12 Gyr.

This age distribution of the oldest populous clusters is very different from that in the LMC. If we examine Hodge's (1984) list of 'genuine' globulars, we find that NGC 1466 may not be an LMC member; NGC 1841 is very distant in projection, with no CMD to the level of the

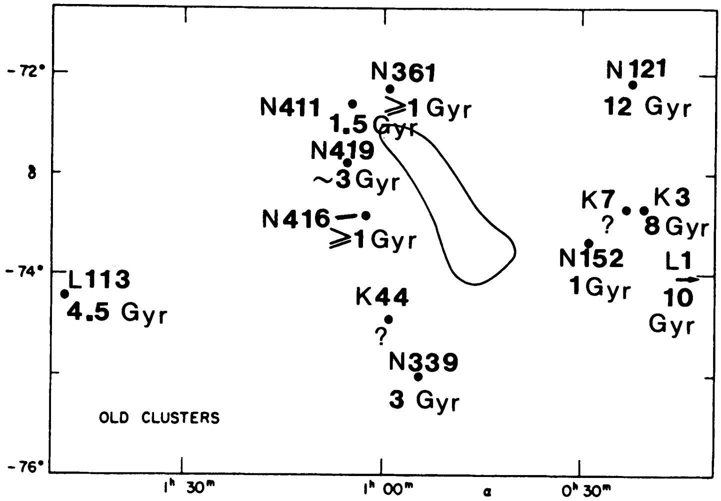

Fig. 4. The distribution of the oldest SMC clusters, from van den Bergh (1981). I have added the cluster identifications and derived ages.

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main sequence yet published; NGC 2257 and 2210 have not yet been published with isochrone fits; NGC 1786 and 1835 are not being attempted; and NGC 121 (SMC) is significantly younger than Galactic globulars. Given the discussion of RR Lyraes above, there is currently no compelling evidence for globular-cluster-aged clusters in either Cloud, although NGC 2257 is probably that old.

Of all the other populous LMC clusters studied, none are older than 3-4 Gyr; I know of no good candidates for populous clusters in the 5-10 Gyr age range. Why are there no such clusters in the LMC, yet several in the SMC? Perhaps cluster destruction is more important in the LMC for even these most populous clusters. It would be nice to have good models of the LMC tidal field and of cluster destruction (but note Schommer's comments in this conference on observed vs. computed tidal radii of Cloud clusters).

To slightly complicate matters, Mateo, Hodge, and Schommer (1986) have shown that the sparse cluster ESO 121SC03, the northernmost LMC cluster, has an age of ~ 10 Gyr. This cluster is not in any list of integrated photometry. Uncovering more of these (seemingly) rare clusters will not be easy, but is necessary if we are to understand both cluster destruction and possible bursts in cluster formation.

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3.2 The E2, 121SC03, N2257 Region

As Figure 2 shows, the clusters E2 (Schommer, Olszewski, and Aaronson 1986), ESO 121SC03 (Mateo, Hodge, and Schommer 1986), and NGC 2257 (see Hesser, McClure, and Harris 1984) all exist far to the north of the LMC bar, beyond measured neutral hydrogen. E2 is ~ 2 Gyr old, 121SC03 ~ 10 Gyr, and NGC 2257 ~ 15 Gyr. How this region of the LMC has made clusters at such different epochs is hard for me to understand. Could some tidal mechanism be at work?

3.3 A Catalog of Distant LMC Clusters; CMDs of Distant LMC Clusters

Olszewski, Harris, and Schommer (1987) have compiled a catalog of clusters outside the Hodge and Wright (1967) atlas, from examining SRC J plates. This catalog contains ~ 150 clusters, most rather sparse, but 18 of which have NGC or IC numbers. This catalog is virtually identical to the subset of Lyngå and Westerlund clusters which are outside the Hodge and Wright atlas, with a few important additions to the north.

We present here (Figure 5) CMDs of LW 177, 195, 399, 47, and 207, the first three to the north, and the last two to the south of the Hodge and Wright atlas. Along with E2, we now have six clusters all with ages 2-3 Gyr. These clusters were picked to be reasonably populous, very distant, and reasonably uncrowded, excepting E2, which was observed because E1 and E3 were amusing clusters.

Mateo (this volume) has derived ages for ~ 30 clusters in his northern LMC region; he finds a peak at 2-3 Gyr as well. This may be the most fundamental and least ambiguous way to see if there were bursts of cluster formation. Certainly if we continue to find many 2-3 Gyr clusters it will be hard to accept the results of Elson and Fall (1986), which are based on very poorly determined ages.

3.4 Metallicities and the Age-Metallicity Relation

This section would best be written in a year or two, for the poster papers at this meeting show that many different techniques are being successfully used to derive metallicities of Magellanic Cloud clusters. I will state a prejudice, advertise some of the work presented at this meeting, and point out a result that astonishes me.

At the Schenectady meeting in 1981, we saw three attempts to derive ages and/or abundances of Magellanic Cloud clusters: Searle and Smith (1981), who derived their results from integrated spectrosopy; Hodge (1981), who attempted to compile and evaluate ages and abundances from all available techniques; and Cohen (1981), who measured spectral indices of individual stars. The clusters in these studies are scattered all about the face of the LMC; they are essentially the clusters measured by Freeman, Illingworth, and Oemler (1983) which are displayed in Figure 2. I've always been baffled by what is meant by an

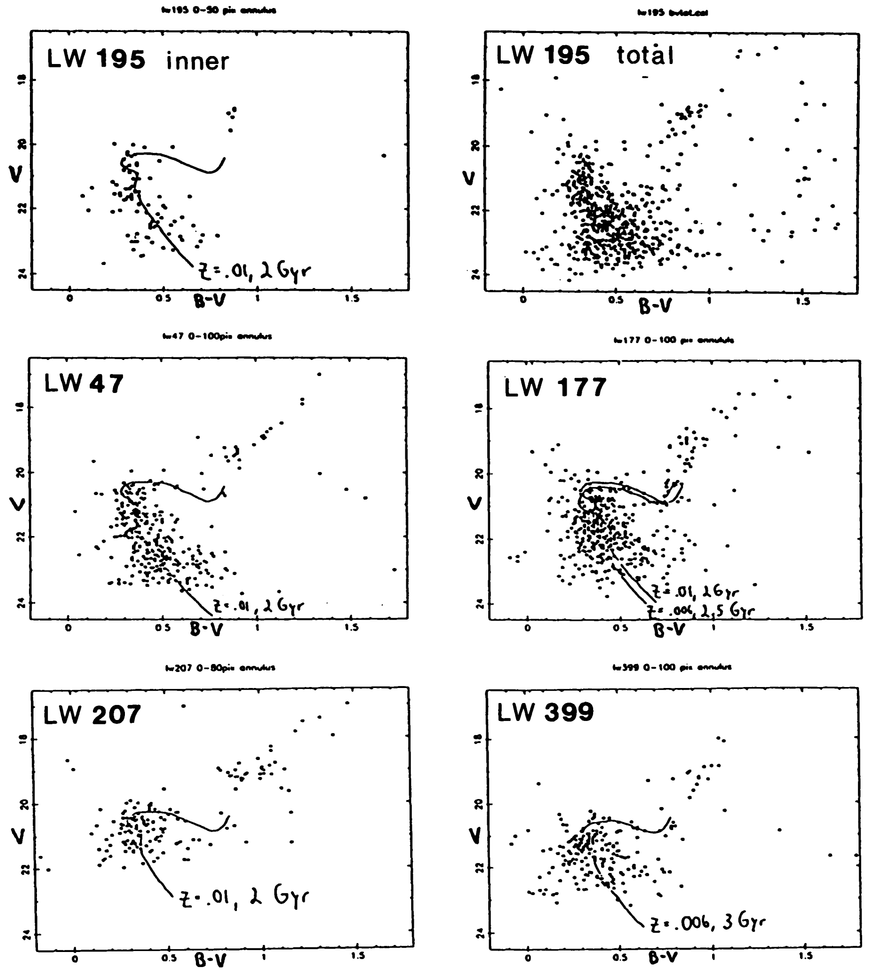

Fig. 5. CMDs of several distant LMC clusters, whose positions are given in Figure 2. These plots are from work being done by Olszewski, H. Harris, and Schommer.

age-metallicity relation for the entire LMC, given that star formation seems to appear in a place for a while then disappear (Hodge 1973). Are we assuming something very simplistic about the LMC, or is it well enough mixed, or is the time-averaged rate of star formation constant enough that there is one age-metallicity relation?

Good ages are getting easy to come by, with many good CCD CMDs, the understanding of the limitations of SWB class, and better analysis of integrated spectra (Smith, Searle, and Manduca, this volume). Abundances are also now getting more certain, partly because of new instrumentation, which allows new spectral regions to be profitably used (see Armandroff, this volume); partly because of better calibrations and wider understanding of special photometric systems (Geisler, this volume; Schommer and Geisler, this volume); and partly because of the number of complementary techniques being used. I note that all the studies are giving similar abundances for clusters of similar age, excepting the work of Richtler and Seggewiss (this volume).

Mateo (this volume) reports on a study of all the star clusters, populous or otherwise, in a small northern section of the LMC (see Figure 2). He derives ages for ~ 30 clusters and metallicities for ~ 16, from CCD CMDs, isochrone fitting, and integrated colors. The resultant age-metallicity diagram can be seen in his poster paper in this volume; this diagram has a variety of other authors' relations sketched in. I am astonished at the similarities between the two data sets. Mateo's region is far from the LMC bar, with part of the region beyond detectable neutral hydrogen. There had to be a lot of star formation in this remote piece of the LMC or a lot of mixing. When we understand how this particular age-metallicity relation came to be, we'll be a lot closer to an understanding of the LMC.

Bob Schommer and I have worked closely together on many of the topics discussed here. I'd like to specially thank both him and Paul Hodge for help and influence for the past twelve years. This paper came into being by assimilating the work of many people, especially Mario Mateo and Gary Da Costa. Hugh Harris, Jim Hesser, and Marc Aaronson have also contributed in many ways. I appreciate a travel grant from the IAU which helped defray some of my costs of attending IAU 126, and acknowledge NSF grant AST 83-16629 for support of all my research.

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DISCUSSION

MCCARTHY: First, tell us what is the globular cluster distribution to the east and west of the Hodge Wright Atlas of the LMC. Why are there so few to the east and west and so many to the north and south? Second, How do your RV measures of stars in ESO 121-03 compare with the RV for the Magellanic Clouds.

OLSZEWSKI: The LMC cluster system extends outside the Hodge and Wright atlas in the north and south, but not in the east and west. We searched outside the Atlas in all directions for several degrees beyond the last discovered cluster. Our discovery of clusters to the north and south is mostly an artifact of the plates Hodge and Wright chose to put in their atlas, and partly because of the better resolution of the SRC plates. In answer to your second question no velocities are known; we have time in Jan. 1987.

SCHOMMER; I would like to mention that many of these outer clusters had been catalogued by LW, that is Lynga and Westerlund in 1963 (MNRAS). We found some additional, fainter, objects, but I'm afraid some of us had failed to read this paper before, or at least appreciate its significance.

LYNGA: I can mention that the LW survey was made over a field of 15 x 15° where we tried to find all clusters with a plate scale of 2 min of arc/mm.

OLSZEWSKI: Most of the clusters we found were in your list; we found ~ 25 new ones, mostly again due to improved resolution.

RENZINI: To answer your question about the absence of Post-AGB stars in the Magellanic Cloud clusters; one expects to find one of such star for every five million solar luminosities of cluster light. One should then expect to inspect about 100 clusters before finding just one Post-AGB star.

SMITH: It is worth noting that the most metal poor SMC stars yet identified are field red giants and RR Lyraes. Perhaps the absence of SMC clusters older than 12 Gyr is telling us that star formation took place outside of large clusters before that time.

OLSZEWSKI: Most of the old SMC clusters seem to have [Fe/H] ~ -1.3!

RICHER: The nearby galactic globulars show almost dispersionless main sequences down to a few magnitudes below the turnoff. The CM diagrams you showed have very wide main sequences. An honest error for the ages of the galactic globulars is at least ±3 Gyr. What error would you attach to the ages of the LMC clusters you discussed?

OLSZEWSKI; I can't quantify this, but it's my feeling that anyone in the audience who works in Magellanic Cloud cluster CM diagrams would get the same age to ± 1 or 2 Gyr, given the same data and isochrones. It's my impression that systematic errors are what's discussed most in Galactic globular cluster age determinations.

DiFAZIO: If we inspect more closely the graph where you compared J. Cohen's metallicity-age relation to the data, since you only have one point in the lower-right end of the graph, and given the shape of the distribution of the other points, I think Cohen's relation cannot be said to fit the data very well; which I think can be fitted pretty well by a straight line too. Do you agree?

OLSZEWSKI; All I wanted to state was my amazement that this distant place in the LMC had an age-metallicity relation similar to that given by Cohen for the inner clusters. There had to be a lot of star formation in the last 10 Gyr, which qualitatively contradicts our Astronomy 101 notion of where the important star formation in the LMC occurs.