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OLD AND INTERMEDIATE-AGE STELLAR POPULATIONS IN THE MAGELLANIC CLOUDS

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ABSTRACT

The Magellanic Clouds have galactocentric distances of 50 and 63 kiloparsecs, making it possible to probe the older populations of clusters and stars in some detail. Although it is clear that both galaxies contain an old population, it is not yet certain whether this population is coeval with the date of formation of the oldest globulars in the Milky Way. The kinematics of this old population in the Large Magellanic Cloud (LMC) are surprising; no component of this old population is currently measured to be part of a hot halo supported by velocity dispersion. Spectroscopy of field stars is beginning to show the existence of a small population of stars with abundances [Fe/H] less than -1.4. These stars will help to unravel the star-formation history when the next generation of telescopes are commissioned. Asymptotic giant branch stars, long-period variables, planetary nebulae, and horizontal-branch clump stars can be used to trace the extent and kinematics of the intermediate-age population. Deep color-magnitude diagrams can be used to derive the relative proportions of stars older than 1 Gyr.

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The age distribution of populous clusters and the age-metallicity relation are used to compare the evolution of the two Magellanic Clouds to each other. The issue of where the LMC's metals originated is explored, as is the question of what triggers star formation in the Clouds.

1. INTRODUCTION

The notion of a "stellar population" is now so commonly used that we generally do not challenge ourselves to provide a specific definition for what really constitutes a population of stars. In the IAU Symposium 164, a range of possible definitions was offered, but perhaps the simplest is that a stellar population in a galaxy comprises the stars formed during a major event in the life of a galaxy (King 1995, Mould 1995). It has long been tacitly assumed, especially for the earliest stages of star formation in galaxies, that there exist some populations that are coeval for all disk galaxies, or perhaps even for all galaxies. What evidence do we really have that there was a substantial early episode of star formation in all galaxies? Are there characteristics of a young galaxy that determine the subsequent star-formation history or do external factors play a substantial role? To begin to answer such questions we can study distant galaxies or protogalaxies (e.g. Koo 1986, Djorgovski 1992), the formation of spheroids and disks (e.g. Schechter & Dressler 1987), or the special population of faint blue galaxies seen in faint galaxy number counts (Kron 1980, Tyson 1988, Colless et al 1993). Local galaxies can provide important details to galaxy evolution models, which makes the star-formation histories of the nearest galaxies a source of interest for cosmological questions. We are able to combine stellar photometry with spectroscopy to determine the fundamental population characteristics: the stellar luminosity function, spatial distribution, age, chemical abundance, and kinematics. The only external galaxies for which we can currently hope to make such detailed observations are the Magellanic Clouds and the Local Group dwarf spheroidal galaxies. This review focuses on the Magellanic Clouds.

Many of the characteristics that we attribute to a stellar population are strongly influenced by the properties of the Milky Way. For instance, we use the words "halo," "metal-poor," "high velocity," and "old" interchangeably to describe a certain population in our Galaxy, yet these words in the context of other galaxies are not necessarily interchangeable. As we will see, the "old" stars in the Large Magellanic Cloud (LMC) are not "halo" stars, and the "metal-poor" stars in the Small Magellanic Cloud (SMC) are not necessarily "old." We hope to show the reader that the Magellanic Clouds, with their relatively low metal abundances and large numbers of star clusters of all ages, can provide an instructive contrast to the notions of the stellar populations in our Galaxy. In addition, by studying the Magellanic Clouds, we may begin to better understand the characteristics of the stellar populations in a vigorously evolving system: systems that may have at some earlier epochs been similar to our Galaxy, but have subsequently evolved very differently.

In this review we concentrate on a quite limited set of questions that relate to these issues in the context of the Magellanic Clouds. What old populations are there in the Magellanic Clouds? How old is the oldest population in each galaxy and how do these populations compare to the Milky Way? Are the oldest populations in the Magellanic Clouds simply scaled versions of the halo of the Milky Way? What are the age-metallicity relations in each galaxy? What is the history of star formation from the earliest populations to the population characterizing the Clouds about 1 Gyr ago? Does the history of star formation as seen in the clusters reflect the history of star formation as seen in the field stars of the Magellanic Clouds?

We show that the available evidence suggests that the LMC really did lie relatively dormant for a substantial fraction of a Hubble time, while the SMC seems to have experienced a more constant star-formation rate. We know of no compelling observation that will tell us why the LMC resumed making stars several billion years ago. Although it is tempting to use the current dynamical models of Cloud–Milky Way interactions as a vehicle for understanding the LMC and SMC star-formation histories, these models are just beginning to predict the times of major episodes of star formation in the intermediate and old populations.

We approach these questions by summarizing the recently published observations of the field stars and of the rich luminous star clusters of the Magellanic Clouds. We also point out observations currently being made and observations that could and should be made in the future. It is our feeling that we are on the verge of a deep understanding of the general evolution of the Clouds, based on expected new data from the *Hubble Space Telescope* (*HST*), the southern 6.5–8-m class telescopes, proper motion surveys, wide-field optical and infrared surveys, and multifiber spectroscopy.

To make this review tractable, we have chosen to take Westerlund's (1990) review as our starting point. Unless it is important to our argument, we assume that Westerlund (1990) and other reviews and symposia (Feast 1995; Olszewski 1988, 1993, 1995; Da Costa 1993; many papers in Baschek et al 1993; many papers in Haynes & Milne 1991; Suntzeff 1992a,b; Mateo 1992; Graham 1988) can lead the reader to the earlier literature on the Magellanic Clouds.

2. THE OLDEST POPULATIONS OF THE MAGELLANIC CLOUDS

2.1 *Definition and Nomenclature*

The population that we are interested in describing here should more rightly be called the oldest observable population or the first substantial population in the Large and Small Magellanic Clouds (we use MC when referring to both Clouds). If there were a small tail of stars more metal poor than [Fe/H] $= -3.0$ in the MCs, therefore presumably older than the first major population, it would be impossible to detect it given currently available sample sizes, just as stars in the Milky Way halo with [Fe/H] < -3.0 have only been found by heroic efforts to search large numbers of Galactic halo stars (e.g. Beers et al 1992). We do not call the oldest major population in the MC "Population II" or the "halo population," as these words have connotations of abundance, age, and kinematics that may be inappropriate for the oldest MC populations. The word "halo" is used when these connotations are intended.

In this section we concentrate on describing the properties of the oldest population, including the mean age and kinematics. It is important to determine with certainty whether this "ancient" population exists in either Cloud or if the first dominant population is demonstrably younger in those galaxies than in the Milky Way. By an ancient population we mean a population coeval with the oldest globular clusters in the Milky Way, currently believed to be ~ 15 Gyr old. We acknowledge that the age scale may change in the future, but we believe that the age ranking of populations within the two Magellanic Clouds and relative to the Milky Way globulars will remain secure.

2.2 *The Old Cluster Population*

The Magellanic Clouds have a number of red clusters long suspected of being analogues to the Galactic globular clusters. A list of these old LMC clusters is given in Suntzeff et al (1992) and is repeated in Table 1 with a few revisions. Reticulum, NGC 1841, and NGC 1466 have at times been considered to be Milky Way globulars (e.g. Webbink 1985). All three have now been shown from color-magnitude diagrams (Gratton & Ortolani 1987, Walker 1992a for Reticulum; Walker 1990 for NGC 1841; Walker 1992b for NGC 1466) and velocities (Storm et al 1991, Suntzeff et al 1992, Olszewski et al 1991) to be LMC members. The few old clusters in the SMC are also listed in Table 1. The lower age cutoff in Table 1 is about 8 Gyr.

While the early papers of Arp (1958a, 1958b), Tifft (1962), and Hodge (1960) were among those that first showed that some of the redder Magellanic Cloud clusters were similar to Galactic globulars, direct evidence for the old ages of the red clusters comes only from deep color-magnitude diagrams (CMD),

Table 1 The oldest cluster in the Magellanic Clouds[a]

Cluster	[Fe/H]	M_V	n(RR)	Notes[b]
		LMC		
Hodge 11	– 2.1	– 7.0	0	1,2
NGC 1466	– 1.8	– 7.9	38	1,2
NGC 1754	– 1.5	– 7.1	—	1,2
NGC 1786	– 1.9	– 7.9	9	1,2
NGC 1835	– 1.8	– 9.2	35	1,2
NGC 1841	– 2.1	– 7.1	22	1
NGC 1898	– 1.4	– 7.4	—	1
NGC 1916	– 2.1	– 9.0	—	1,2
NGC 2005	– 1.9	– 7.5	—	1,2
NGC 2019	– 1.8	– 7.9	0	1,2
NGC 2210	– 2.0	– 8.1	12	1,2
NGC 2257	– 1.8	– 6.9	37	1
Reticulum	– 1.7	– 6.0	32	1
ESO 121-SC03	– 0.9	– 5.2	0	3
		SMC		
NGC 121	– 1.3	– 7.8	4	4
Lindsay 1	– 1.3	– 5.7	0	5
Kron 3	– 1.3	– 7.0	0	6

[a]Possible old clusters in the LMC: Hodge 7 (Bica et al 1991), SL244, NGC 1865, NGC 1928, NGC 1939 (Bica et al 1992). Walker (1989b) found no variables in the SMC clusters Kron 7, Kron 44, Lindsay 113, NGC 339, and NGC 416. Graham & Nemec (1984) found no variable in NGC 2121 and NGC 2155.
[b]1. Basic data given in Suntzeff et al (1992). 2. Confirmed to be metal poor by Dubath et al (1993). 3. Basic data in Mateo et al (1986). Cluster is 9 Gyr old and significantly younger than the other LMC clusters listed. 4. Spectral metallicity from Suntzeff et al (1989b). More variables may be in cluster center (Walker 1989b). Cluster is 12 Gyr old (Stryker et al 1985). 5. Younger than NGC 121. No variables (Walker 1989b). Age and metallicity given by Olszewski et al (1987, 1991). 6. Younger than NGC 121. No variables (Walker 1989b). Age and metallicity given by Rich et al (1984).

which can be measured from ground-based data for the clusters in uncrowded regions of the MCs. The expected main-sequence turnoff of the old population in the LMC will be at $V \sim 22.5$. The CMDs for the LMC clusters NGC 1466, NGC 1841, and Reticulum listed above, and for NGC 2257 (Testa et al 1995), all show main-sequence turnoffs roughly consistent with the ages of Galactic globular clusters, but the quality of the published color-magnitude diagrams is inadequate to say with certainty whether the LMC clusters are truly ancient or are a few Gyr younger. Two major programs have been undertaken in Cycle 5 of *HST* to observe the oldest LMC clusters listed in Table 1 to improve the age determinations.

Because all the LMC clusters known to be old based on CMD dating are also very metal poor, we have assumed all metal-poor LMC clusters to be old. The list of LMC clusters in Table 1 is therefore a compliation of all clusters with known old ages or low metallicities. In some cases, the old age is verified by the existence of RR Lyrae variables. A number of LMC clusters that could be considered old based on their red colors are excluded from Table 1 because their metallicity was found to be similar to the intermediate-age clusters (Olszewski et al 1991). No new metal-poor clusters have been found in recent spectroscopic surveys of MC clusters (Olszewski et al 1991).

In the SMC, NGC 121 (Stryker et al 1985) is the oldest cluster, but all three clusters listed in Table 1 are younger than the ancient Galactic globular clusters (Olszewski et al 1987, Rich et al 1984) based on ages from CMDs (see also Sarajedini et al 1995).

Some of the oldest MC clusters may no longer be in the Magellanic Clouds. Lin & Richer (1992) have argued, on the basis of cluster positions and velocities, that the Galactic globulars Pal 12 and Rup 106 have been captured from the LMC. This idea is actually not radical, for we know that the Sagittarius dwarf spheroidal is contributing four globular clusters to our Galaxy (see Da Costa & Armandroff 1995). van den Bergh (1994) has pointed out a possible problem with the Lin & Richer scenario. Pal 12 has a rather high metallicity to be an LMC cluster of its age, unless it is somehow an analogue to the unique LMC cluster ESO121-SC03. The possibility that Pal 12 came from the SMC should be examined.

It is probably true that no luminous old clusters ($M_V \lesssim -7$) remain to be found in the Clouds. The large clusters have had well-determined integrated *UBV* photometry for many years (van den Bergh 1981). Most have been or will be searched for RR Lyraes and observed with *HST* in the next few years. There may be old clusters among the generally less-luminous clusters cataloged by Olszewski et al (1988), Kontizas et al (1990), and Bica et al (1991, 1992). To find them efficiently, we will have to resort to indirect indicators of age such as low metallicity, integrated colors, and the presence of RR Lyrae variables.

2.2.1 RR LYRAES It is generally accepted that the existence of RR Lyrae variables or a blue horizontal branch (BHB) is prima facie evidence of the existence of an old population. Exactly how old is not well determined observationally or theoretically. RR Lyraes are low-mass helium core-burning stars. The thickness of the envelope determines whether such a star is redward of, blueward of, or in the instability strip. The envelope mass is a complicated function of age, metallicity, helium abundance, rotation, and mass loss; the latter is poorly understood (Lee et al 1994).

There is evidence that RR Lyraes are not all extremely old. Taam et al (1976) and Kraft (1977) have argued that the metal-rich RR Lyraes with thick-disk kinematics in the Milky Way may be younger than the ancient clusters, but the age difference is not known. How young can an RR Lyrae be? Clusters of known ages containing RR Lyraes provide a most direct way of estimating the youngest age for an RR Lyrae. We note, however, that it is difficult to age-date the metal-rich field RR Lyraes in either the Milky Way or the Magellanic Clouds. Although one can envision mechanisms that would make these stars very young, new data from HST (J Liebert, 1996, private communication) show that some metal-rich globular clusters do contain substantial blue horizontal-branch populations, thus allowing the possibility that metal-rich field RR Lyraes are old. Da Costa & Armandroff (1995) give the most recent list of Milky Way "young halo" globulars; many of these 21 objects have long been known (Sawyer Hogg 1973) to contain RR Lyraes. Ruprecht 106 is thought to be more than 3 Gyr younger than the typical globular (Buonanno et al 1993), yet it contains 12 RR Lyraes (Kaluzny et al 1995).

From Table 1, we see that the 12-Gyr old SMC cluster NGC 121 has four RR Lyraes whereas the 9-Gyr old cluster Lindsay 1 has none. This comparison is often cited as evidence that the youngest RR Lyraes are older than 10 Gyr (Olszewski et al 1987). However, L1 is 7 times fainter than NGC 121 (van den Bergh 1981). Scaling NGC 121's RR Lyrae population to L1, we expect less than one RR Lyrae. While the number of known RR Lyraes in the concentrated cluster NGC 121 is likely an underestimate, the expected number ot RR Lyraes in L1 will still be subject to small number statistics, and will not provide a good constraint on the age of the youngest-possible RR Lyraes. None of the other relatively luminous, older SMC clusters have RR Lyraes (Walker 1989b). For LMC clusters, it is unlikely that any of the luminous clusters in Table 1 are young enough to constrain the minimum age of the RR Lyraes. There are no known luminous LMC clusters in the age range 4–12 Gyr (see Section 3.4 below). It may be possible to constrain the age of the youngest RR Lyraes by seaching Milky Way old open clusters, the globulars in the Fornax dwarf spheroidal, and the luminous intermediate-color star clusters in M33.

In summary, the existence of RR Lyraes probably means that the population is old, but there is no strong observational evidence that can rule out their presence in a substantially younger population. The gravitational lens experiments such as MACHO should be very effective in searching for RR Lyraes in the less-luminous clusters in the MCs, which may overcome the low a priori chance of finding RR Lyraes in any individual low-luminosity cluster.

2.2.2 LOW METAL ABUNDANCES The metallicity of a cluster is often used to indicate old age (cf Andersen et al 1984) in analogy to our Galaxy where the metal-poor globular clusters are all old. For the Galaxy and the LMC, low metallicity is apparently a sufficient condition to indicate that a population is old. In the SMC, however, low abundance does not imply old age. The field giants near NGC 121 have ages of about 8 Gyr, with a mean metallicity [Fe/H] = −1.6 (Suntzeff et al 1986), and the 8-Gyr SMC cluster Kron 3 has a metallicity of [Fe/H] = −1.3 (Rich et al 1984).

The mean metal abundance of the LMC old clusters is [Fe/H] = −1.84, whereas that of the Galactic globulars outside of the solar circle is −1.70 (Suntzeff et al 1992). These similarities imply that fragments of long-destroyed galaxies not very different from the LMC could have assembled the halo (e.g. Searle & Zinn 1978). Van den Bergh (1993, 1994) has argued that objects like the current LMC could not have donated many clusters, but the differences between LMC clusters and Galactic halo clusters are subtle. The entire Galactic halo cannot simply be the debris from LMC-like protogalaxies, since inside the solar circle the Galaxy shows a metallicity gradient (Zinn 1985, Suntzeff et al 1991), implying (in part) a dissipational evolution involving chemical feedback from earlier generations of stars. Of course, a mechanism in which the largest density fluctuations in a protogalaxy were themselves sites of star and cluster formation would also be an explanation (Sandage 1990).

2.2.3 INTEGRATED COLORS A third indication of an old population can be found in the integrated colors or spectra. The broad-band integrated color of a star cluster changes continuously with age, although the color separation between very disparate ages is sometimes small (Searle et al 1980; Elson & Fall 1985, 1988; Bica et al 1991, 1992; Girardi et al 1995). Nevertheless, broad-band colors remain a useful indicator of clusters with potentially interesting properties. Bica and collaborators have obtained integrated *UBV* photometry for 624 LMC clusters and a number of SMC clusters (Bica et al 1986); this sample can be searched for possible old clusters. The LMC clusters Hodge 7 (Bica et al 1992) and NGC 2155 (Searle et al 1980) were both claimed to be ancient clusters. Our CMDs show that these clusters are not old, illustrating the potential problems of age classifications of lower luminosity clusters in crowded fields using broad-band photometry (see also Girardi & Bica 1993, Girardi et al 1995).

2.3 *Age of the Oldest Clusters*

Walker (1992b, Figure 9) and Da Costa (1993, Figure 2) have shown that LMC clusters have a redder HB morphology than expected for their metallicities. Zinn (1993) and van den Bergh (1993) have similarly shown the division of Galactic halo clusters into two major families in this metallicity–HB distribution plane. This division appears to be another manifestation of the "second parameter" effect in Galactic clusters and dSph galaxies. It is now common to associate this effect with an age difference of 2–3 Gyr (Lee et al 1994) between the two families of halo clusters. In our Galaxy, this effect is also accompanied by a kinematical signature (Rodgers & Paltoglou 1984, Chaboyer et al 1992, van den Bergh 1993, Zinn 1993, Da Costa & Armandroff 1995). If age is truly the second parameter determining the HB morphology, after metallicity, then we expect that the ancient LMC clusters will prove to be some 2 Gyr younger in the mean than old halo Milky Way clusters.

Suntzeff et al (1992) have used the data in Table 1 to argue that the old LMC cluster population is very similar to the Galactic cluster population outside the solar circle in terms of metallicity, cluster luminosity, number of RR Lyraes per unit cluster luminosity, and the ratio of luminous cluster mass to field star mass. The number of clusters in the LMC also is consistent with the luminosity difference between the LMC and the Galaxy. This similarity is somewhat surprising given that the dynamical mass of the Milky Way is 10 times that of the LMC, although the dynamical mass of the LMC is likely to be an underestimate (Suntzeff et al 1992).

If we scale the LMC to the SMC luminosity, we would expect the SMC to have about two old clusters: In Table 1, we find one old cluster with RR Lyrae and two substantially younger clusters. Little can be said of the general properties of the old clusters in the SMC due to small number statistics.

It is tempting to try to use the data in Table 1 (and the HB magnitudes given in Suntzeff et al 1992) to determine a M_V–[Fe/H] relationship for RR Lyraes. This relationship is an important and controversial one. We discuss it further in Section 2.5. The published cluster metallicities, however, have more scatter than can be tolerated for this problem—they are typically based on only one or two spectra or on the color of giant branches in the CMD. Even with better metallicities the relationship cannot be determined due to the small range in metallicities in these particular clusters and the unknown position of any cluster in front or behind the galaxy. It had been thought that the HB magnitude as a function of age was constant for stars older than a few Gyr (e.g. Olszewski et al 1987), allowing the metallicity effects to be derived by studying all LMC and SMC clusters older than a few Gyr. Recent results on the Carina dwarf galaxy (Smecker-Hane et al 1994; PB Stetson 1996, private communication) show, however, that 7- and 14-Gyr populations at [Fe/H] $= -2$ produce HB luminosities that differ by 0.25 mag, implying that age effects are as important as metallicity effects.

A more promising approach would be to search the large number of LMC RR Lyraes discovered by the MACHO project for large-amplitude, short-period RRab variables, which will tend to be metal rich. A few such stars are known in the MCs (Hazen & Nemec 1992), though they are clearly quite rare. Such a metal-rich sample, coupled with the much more numerous metal-poor RR Lyraes, should yield a definitive M_V–[Fe/H] relationship.

2.4 *Kinematics of the Oldest Clusters*

If the LMC contained a dynamically hot halo surrounding an inner disk, the velocity dispersion of this halo would be between $v_{\rm circ}/\sqrt{2} = 56$ km s^{-1} and $v_{\rm circ}/\sqrt{3} = 46$ km/s, where $v_{\rm circ} = 79$ km s^{-1} is the circular velocity of the H I disk (Freeman et al 1983; see the derivation of equation 4-55 in Binney & Tremaine 1987). Unexpectedly, Freeman et al (1983) found that the oldest LMC clusters had a much smaller velocity dispersion than expected from these arguments. This very important result implies that the oldest clusters do not populate a kinematically hot halo supported by its velocity dispersion. In fact, the oldest LMC clusters form a rotating disk system. The velocities available to Freeman et al (1983) implied that the oldest LMC population, although in a disk, was not in the same disk as the H I gas.

Olszewski et al (1991) and Schommer et al (1992) have enlarged the sample of clusters and improved the observed cluster velocities. They confirmed that the oldest clusters were in a disk, and they eliminated the perceived difference between the old and young disks. They were able to derive a more precise kinematic solution, albeit with substantial errors due to the small number of old clusters. They found that the oldest clusters have a disk model solution in good agreement with the model fit to the H I gas, when velocities are corrected for the transverse motion of the LMC (Jones et al 1994) and when the oldest clusters superposed on the bar of the LMC are removed. This disk has $v/\sigma = 2$. This old-disk model has a significantly smaller circular velocity than does the H I disk (50 vs 79 km s^{-1}) and larger velocity dispersion (23 vs 10 km s^{-1}). In an adiabatic sense, the lower rotation speed and higher velocity dispersion are consistent in that the circular velocity of the old component lags the disk, and that some of that energy is now in the z component.

There are several interesting aspects to this set of "disk clusters" in the LMC defined by the oldest clusters. First, we return to the question discussed in Section 2.3: What is the age of this set of oldest clusters? If the oldest LMC clusters are indeed a few Gyr younger than an ancient population, then their disk kinematics could be explained merely by the fact that the clusters were created during disk formation, well after the initial population finished forming. In this case, where is this putative ancient population? The only other obvious old population is the population of RR Lyrae variables. But as shown by Suntzeff et al (1992), the number of field RR Lyraes in the LMC is consistent with the luminous mass in the old clusters, if we scale from the same populations in the outer Galactic halo. It therefore seems reasonable to associate the RR Lyraes and the oldest disk clusters with the same population. We feel the most natural explanation is that given by Freeman et al: The LMC does not have a prominent hot (supported by its velocity dispersion) halo. An obvious test would be to measure the velocity dispersion of the RR Lyraes or of the most metal-poor field stars.

A second aspect of the old cluster disk is that the disk is relatively large. The average distance from the bar of the LMC is 3.9 kpc for the total sample of old clusters and 6.1 kpc for those clusters away from the bar. This radius is two to four times the LMC disk scale length (Bothun & Thompson 1988).

Third, there are few clusters beyond 8 kpc from the bar of the LMC. Even though the velocities of these clusters formally give the same disk solution as that of the H I gas, it would be good to find other tracers to derive the rotation and the mass of the LMC out to the distances of the Reticulum cluster (11 kpc) or NGC 1841 (14 kpc). The best stellar tracer would presumably be young, because such objects could have a small velocity dispersion about a rotation solution, if no major recent perturbations of the LMC by interactions with the Milky Way or SMC exist. As pointed out above, the disk solutions for all major LMC components are similar to those of the H I gas. One can assume that the older components of the LMC continue to follow the same disk as the younger components, as the clusters imply, and use carbon stars (Demers et al 1993) or Cepheids or as-yet-uncataloged red giants to derive the rotation curve. As it stands, Figure 8 of Schommer et al (1992) is a good summary of current knowledge: The rotation curve is relatively flat from 2–8 degrees, with minimal information beyond 8 degrees (1 degree $=$ 0.94 kpc). The mass implied by this rotation curve is $\sim 10^{10}\ M_{\odot}$. If the LMC were simply an exponential disk, the rotation curve should peak at 2.2 disk scale lengths, or 3.5 kpc. There is no evidence for a Keplerian falloff at this point, whose position would change outwardly slightly if a low-mass halo were added. If the rotation curve is flat out to the distance of NGC 1841, then substantial dark matter is needed.

Fourth, the cluster systems of the Magellanic Clouds, the Milky Way, M31, and M33 have been compared by Schommer et al (1992) and Schommer (1993) in terms of their spatial and kinematic distributions. The Milky Way and M31 both have disk globular cluster systems (Mayall 1946, Morgan 1958, Kinman 1959, Zinn 1985, Huchra et al 1991) that are metal rich and spatially concentrated to the inner parts of the cluster system. M33, with a wide range of cluster colors similar to the LMC and distinct from the Milky Way or M31, shows a trend of kinematics with color. The set of reddest M33 clusters (Schommer et al 1991) has no global rotation, a velocity dispersion of approximately the expected isothermal value of $\sim$ 70 km s^{-1}, and $v/\sigma = 0.6$. As we examine bluer M33 clusters (color presumably being related to age), rotation increases and line-of-sight velocity dispersion decreases. It is important to remember here that M33 is about twice as luminous as the LMC; it is hard to say if this mass difference is critical or incidental. It will be important to understand why some old cluster systems rotate and why some disk systems are inner-cluster system phenomena while others are outer-cluster system phenomena.

No global statements can be made about the kinematics of SMC clusters; no systematic survey of cluster abundances and velocities has been made. The dominant reason seems to be the small number of SMC clusters, coupled with the fact that most of the SMC clusters are in fairly crowded fields. A second reason is that it has always been tacitly assumed that the SMC kinematics will be quite complicated. It would be fascinating to know if the SMC has a halo that is even remotely spherical, or if it is unrecognizable because of its interactions.

2.5 *The Field RR Lyraes*

Although the Magellanic Clouds are known to be rich in variable stars, the published literature on field RR Lyraes is remarkably sparse. The Harvard Surveys were not deep enough to measure stars as faint as 19$^{\mathrm{th}}$ magnitude. While there are 17 bright foreground RR Lyraes in the Hodge & Wright (1967) LMC, and 46 stars with periods less than 1^{d} in the Hodge & Wright (1977) SMC Atlas, most of these are foreground variables or possible bright members of the anomalous Cepheid population in the SMC.

The first major survey for RR Lyrae variables was done by Thackeray and collaborators (see Thackeray & Wesselink 1953), who found cluster variables in NGC 121 in the SMC and in NGC 1466 in the LMC and near NGC 1978 in the LMC. Graham (1975, 1977) initiated the first modern survey in the regions surrounding NGC 1783 in the LMC and NGC 121 in the SMC. Kinman et al (1991) summarize the major studies of field RR Lyraes in the LMC. As of 1991, there were 122 field RR Lyraes known, almost all in the two fields surrounding NGC 1783 and NGC 2210 in the inner regions of the LMC. In total, 4.3 square degrees have been thoroughly searched in the LMC, with most of this area in regions more than 5 kpc from the center of the LMC where the variable density is low. Kinman et al (1991) have fit a King model to the density distribution in the six LMC fields, and they estimate that the total number of LMC field RR Lyraes is $\sim 10{,}000$.

The MACHO group (Alcock et al 1993) is monitoring 41 square degrees of the LMC and 15 square degrees of the SMC for microlensing by objects in the halo of the Milky Way. A by-product of this survey is an extensive catalog of RR Lyrae variables in the areas surveyed. This catalog is probably complete except near the cores of the larger clusters. Alcock et al (1996) have published an initial review of their LMC RR Lyrae catalog, where they announce the discovery of 7902 LMC RR Lyraes in the innermost, densest regions (11 square degrees), based on light curve data with 250 individual observations per star over a 400-day observing cycle. Some basic properties of the LMC RR Lyrae population from this first reconnaissance of the data are: 1. The surface density of RR Lyraes in the central LMC regions is a factor of two higher than the Kinman et al (1991) estimate; 2. the mean period of the RRab variables is 0.583 days; 3. the mean metallicity based on the period-amplitude relationship and spectral observations is [Fe/H] = −1.7; 4. the period-amplitude relation for 500 randomly chosen LMC RR Lyraes is skewed to amplitudes lower than 1 magnitude, unlike the case for Milky Way RR Lyraes; and 5. about 1% of the variables may be second-overtone pulsators with $\langle P \rangle = 0.281^d$.

The Alcock et al results on the mean metallicities of the RR Lyraes are similar to previous metallicity measurments for field variables. Using image tube spectra, Butler et al (1982) derived [Fe/H] = −1.4. Hazen & Nemec (1992) and Walker (1989a), from the period-amplitude relation for the RR Lyraes in the clusters NGC 1783, NGC 2210, and NGC 2257 and their surrounding fields, measured mean abundances of [Fe/H] = −1.3, −1.8, and −1.8, respectively. The mean cluster RR Lyrae abundance from Table 1 (weighted by number of variables) is [Fe/H] = −1.8.

Both the Butler et al and Alcock et al metallicity studies are based on spectral data of rather poor quality by modern standards. With so many RR Lyraes with accurate periods and phases cataloged from the MACHO study, now is the time to consider a major new effort to study the abundance (and velocity) distribution of the RR Lyraes in the LMC, before the phase predictions are compromised by intrinsic period changes and period errors in the catalog.

Alcock et al (1996) provide some interpretation for the mean characteristics of the field RR Lyrae population. They argue that the excess of small-amplitude fundamental pulsators (RRb-type variables), the mean period of the RRab variables, and the "transition period" between the fundamental (RRab) and first overtone (RRc) pulsators imply that the HB stars are evolving from the red of the instability strip blueward. An underlying red horizontal branch in such a metal-poor population of variables may indicate that this population is not ancient but somewhat younger, something we have already seen in the HB characteristics of the LMC clusters. We note, however, that trends seen in mean properties of RR Lyraes in Galactic globular clusters are based on stars in a given cluster where all objects have the same age and metallicity. Interpreting the same mean properties in a population that almost certainly has a wide range in metallicity and possibly in age is problematical.

In the SMC, there have been two major surveys. Graham (1975) discovered 75 RR Lyrae stars in 1.3 square degrees surrounding NGC 121, and Smith et al (1992) surveyed 1.3 square degrees surrounding NGC 361, finding 22 definite and 20 probable RR Lyraes. The metallicity of the RR Lyraes is [Fe/H] = −1.6 from the period-amplitude relationship given by Smith et al and −1.8 from the spectra of three field stars (Butler et al 1982). Both estimates are quite uncertain.

Little work has been done on the kinematics of the RR Lyrae populations. The only quoted attempt to measure the velocity dispersion of the LMC RR Lyraes was made by Freeman a decade ago (Freeman 1996), who derived a dispersion of ~ 50 km s^{-1}. This result, if confirmed by modern data, is quite remarkable because, although it corresponds to the expected dispersion of a kinematical halo, it also disagrees with the LMC old cluster kinematics as discussed above. It should be noted that because RR Lyraes can have velocity amplitudes well in excess of 50 km s^{-1}, it is very important to have good phases in order to determine accurate corrections to the gamma velocities.

With accurate photometry, the mean magnitudes of the RR Lyraes can be used to derive the distance, tilt, and reddening of the LMC; to measure the relative distances between the Clouds; and to check the consistency of the RR Lyrae and the Cepheid distance scales. To date, however, there are only a few fields with relatively high-quality (error in magnitude < 0.05 mag) photometric zero points. In the LMC, three fields have adequate photometry: the NGC 2210 field (Hazen & Nemec 1992), the NGC 1466 field (Kinman et al 1991), and the NGC 2257 field (Walker 1989a). The mean B magnitudes, corrected for the presumed reddening, are 19.56, 19.55, and 19.29, respectively. In the SMC, the mean B magnitude for the NGC 121 field is 19.95, and for NGC 361 it is 19.91. Evidently the difference in mean RR Lyrae magnitude between the Clouds is ~ 0.45 (if we ignore the small difference in mean reddening to the Clouds), but accurate photometry in more fields across both Clouds are needed to reduce the uncertainty in this result to below 0.1 magnitudes. A final complication is that parts of the SMC are very extended along the line of sight (Mathewson et al 1986). Some of the fields discussed in Kinman et al (1991) have reasonably accurate relative photometry but need modern zero points.

In principle, the spread in magnitudes in a given field can be used to derive the line-of-sight depth in the galaxy, but two effects limit the usefulness of this statistic. The first effect is that Galactic globular clusters apparently have a natural dispersion in RR Lyrae luminosities, presumably due to evolution from the zero-age HB. For instance, 33 variables in M15 (Bingham et al 1984) give a dispersion of 0.15 mag, and 35 variables in M3 (Sandage 1981) give 0.07 mag, implying a natural dispersion in magnitude of about 0.1. The second effect is that, in a population with a range in abundances, there should be a natural range in luminosities due to the variation of M_V as a function of [Fe/H]. Although the precise level of this variation is controversial, it is roughly 0.2–0.3 mag per dex in [Fe/H] (Sandage & Cacciari 1990).

Do we resolve the depth in either of the Clouds? In the SMC, 34 RR Lyraes near NGC 121 (Graham 1975) have a dispersion of 0.12 mag in B, whereas near NGC 361, the data in Smith et al (1992) imply a dispersion of 0.19 mag for

17 stars with periods greater than 0.4 days. We may be marginally resolving a real depth in the SMC near NGC 361, but it is surprising that the dispersion is not much larger since NGC 361 lies close to the central body of the SMC where the Cepheid studies imply a line-of-sight depth of 15 to 20 kpc (Mathewson et al 1986, Caldwell & Coulson 1986). In the LMC we find the following dispersions: 0.16 mag for 55 stars in the NGC 1783 field (Graham 1977), 0.16 mag for 28 stars with periods longer than 0.4^d in the NGC 2210 field (Hazen & Nemec 1992), and 0.17 mag for 13 RRab variables near NGC 2257 (Nemec et al 1985, new zero points in Walker 1989a). Little can be said about the LMC depth with these data.

The distances to the Magellanic Clouds, the absolute magnitudes of the Population I Cepheid variables and the Population II RR Lyrae stars, the [Fe/H]-absolute magnitude relation for RR Lyrae stars, the ages of globular clusters, and the value of the Hubble Constant are all interrelated. It is beyond the scope of this review for us to try to provide best values for each of these parameters. We can, however, recapitulate the problems that occur when certain values are adopted. These problems will show that substantial fundamental work is still needed before local distance calibrators are on a firm footing.

If we assume that the LMC distance modulus $(\text{m-M})_0 = 18.55$, based on the Cepheid distance scale (Feast and Walker 1987, Walker 1992c), the absolute magnitude of LMC and of SMC RR Lyraes follows. For the LMC field variables near NGC 2210, NGC 2257, and NGC 1866, we calculate the dereddened mean V to be $\langle V \rangle = 19.0$ (Walker 1989a, 1995; Hazen & Nemec 1992 with a transformation from B to V). The resultant absolute magnitude of $M_V = 0.45$ is identical to that found for the LMC cluster RR Lyraes (see Walker 1992c, 1993a).

The results for the SMC seem to be in mild discord with the LMC result. If we use the mean B magnitudes for the NGC 121 and NGC 361 fields given above, along with the mean B magnitude of 19.91 for the four variables in NGC 121 (Walker & Mack 1988), and deredden the NGC 361 field by E(B–V) = 0.06 (Smith et al 1992), and the NGC 121 field by 0.04, we find $\langle B \rangle = 19.75$. With an SMC Cepheid distance modulus of 18.8 (Feast and Walker 1987) and a B–V of 0.3 for the typical RR Lyrae, we derive an absolute V magnitude of ~ 0.65 for the SMC RR Lyraes. The NGC 121 field, at least, is in the portion of the SMC that has a small line-of-sight depth. Although no evidence for the depth of the SMC is seen in these small RR Lyrae samples, it is clear that the sample should be enlarged.

An interesting test of the relative photometry of the Cepheids and the RR Lyraes is to measure relative magnitudes of these types of stars in the same fields. One possible field is near the young, Cepheid-rich cluster NGC 1866, where Welch and Stetson (1993) and Walker (1995) have discovered a total of four field RR Lyraes.

Are the absolute V magnitudes of 0.45 or of 0.65 the expected values for metal-poor RR Lyraes? A number of authors have attempted to derive the metallicity-absolute magnitude relation for RR Lyraes. If we use the average relation given in Sandage and Cacciari (1990), and the relations of Carney et al (1992), and Layden et al (1996), we find $M_V = 0.7$ at $[Fe/H] = -1.7$. The LMC RR Lyraes would be brighter than this relation by 0.25 magnitudes, while the SMC RR Lyraes would be consistent with this Galactic calibration. Sandage (1993) has argued for a steeper slope in the relation, which makes the LMC RR Lyraes consistent with his calibration, and the SMC RR Lyraes inconsistent. Careful calibration of extant large samples of RR Lyraes in both Clouds is clearly of paramount importance, as is the discovery and photometry of metal-rich Magellanic Cloud RR Lyraes discussed above. We do note that an absolute magnitude of 0.45 for Galactic RR Lyraes does affect the calibration of globular cluster ages (Walker 1992c), and the value of the Hubble constant (van den Bergh 1996).

2.6 *The Old Long-Period Variables*

More than 1000 Long-Period Variables (LPVs) are known in the field of the LMC. A representative set of articles, with references to the other literature, are found in Bessell et al (1986), Hughes (1989, 1993), Hughes et al (1990, 1991), and Reid et al (1995). Most LPVs are luminous asymptotic giant branch (AGB) stars with $-7 < M_{\rm bol} < -4$ and come from a population younger than the ancient populations being considered here (Wood et al 1983). The small number of LPVs in Galactic globular clusters tend to have periods between $\sim 190^d$ and $\sim 230^d$, which places them at the lower end of the range of LPV periods. They are generally found in clusters with $[Fe/H] > -1$ (Frogel & Elias 1988). The globular cluster LPVs are generally up to a magnitude brighter than the core helium flash termination point of the first ascent red giant branch (RGB) $M_{\rm bol} \sim -3.5$, and therefore they are AGB stars close to the point of nuclear fuel exhaustion.

The Milky Way field short-period LPVs have halo kinematics, whereas the longer-period LPVs have disk kinematics (see the introduction to Bessell et al 1986). Under the assumption that the LMC LPVs would have similar properties, Bessell et al (1986) and Hughes et al (1990, 1991) define a class of old long-period variables (OLPVs) in the LMC. The theoretical pulsational masses for the OLPVs derived by Wood et al (1983) also support this assumption.

Hughes (1989) gives a large catalog of LPVs from which a sample of OLPVs were drawn. Hughes & Wood (1990) showed that these OLPV stars (defined as LPVs with periods of 150–225 days) in the LMC had absolute magnitudes consistent with those found in Galactic globulars, and Hughes et al (1991) measured velocities and the velocity distribution of the group. They find a trend of velocity dispersion with period (Figure 7 and Table 8 in Hughes et al 1991) that seems to vindicate their assumption that the LPV period is closely associated with the stellar age. The OLPVs have a dispersion of 35 km s^{-1}, which is significantly larger than that for any other population except the preliminary RR Lyrae result discussed above. This velocity dispersion is not corrected for the problem of observing these LPVs at random phase, but Hughes et al (1991) argue that the random-phase velocity errors are approximately the same as the measurement errors. This velocity dispersion implies that the OLPVs belong to a flattened spheroid and that the mean age derived from the pulsational masses is about 10 Gyr.

How certain are we that the OLPVs are truly an old population? The association with Galactic globulars and the halo-like kinematics of the field OLPVs certainly are consistent with these facts. Yet the OLPVs have some other curious properties. The association of the OLPVs with metal-rich clusters in the Galaxy would imply the Galactic OLPV population should have a kinematical signature that is more like a thick disk than a halo. In addition, almost all LPVs are either carbon (C) stars or M stars. Most of the OPLVs in the lists of Hughes et al (1991) are also C and M stars; many are late M stars. C stars are nonexistent in the Galactic globulars and are found in intermediate-age populations in the Clouds. M stars are found only in the metal-rich clusters ([Fe/H] $\gtrsim -1$). The OLPV population, therefore, seems signficantly more metal rich than the old clusters listed in Table 1, and if we are interpreting the presence of the C stars correctly, they are also signficantly younger. Finally, there is the disturbing fact that the Galactic globular cluster LPVs do not have the same period-luminosity relationship as the OPLVs of the LMC (Menzies & Whitelock 1991). These authors point out that unless both the Cepheid and RR Lyrae distances scales are in error, this difference implies that the OLPVs in the LMC are more massive than the variables in the Galactic clusters. Whether or not the OLPVs are as old as claimed by Hughes et al (1991), the fact that the velocity dispersion is *higher* than the old cluster population is provocative.

It would be very interesting to discover and study LPVs in Magellanic Cloud clusters to allow a direct age dating to verify the period-age assumptions and the pulsational masses. Frogel et al (1990) note that a few of their C and M stars found in a grism survey of clusters are clearly dusty LPVs. Periods are not known for these stars.

2.7 *The Old and Metal-Poor Field Stars*

There are two ways to find the ancient population of normal stars. The first is to derive abundances and velocities of red giants in a well-defined field to identify the most metal-poor stars. Simple photometry is inadequate because of Galactic foreground contamination. The second is to look for old and metal-poor main-sequence turnoffs and subgiant branches in the color-magnitude diagrams of the field.

There are two studies of complete samples of field giants in the Magellanic Clouds: Suntzeff et al (1986) for the field surrounding NGC 121 in the SMC and Olszewski (1993) for the NGC 2257 field in the LMC. The two RGB abundance distributions are quite different.

The NGC 2257 field is the same field used by Jones et al (1994) to derive the proper motion of the LMC as a whole. Many, but not all, foreground stars are therefore removed from the sample because they have large proper motions. This field is 8 kpc north of the LMC bar and would normally therefore be called a "pure halo" field. Its surface brightness is very low, ~ 27 mag arcsec^{-2}, according to the surface brightness model of Bothun & Thompson (1988). The present-day neutral hydrogen density is less than 1.6×10^{20} cm^{-2}. Potential giants were picked from the CMD by superposing ridge lines of metal-poor and metal-rich Milky Way clusters, with care to ensure that no potentially metal-poor stars would be missed. Spectra were obtained for all such stars brighter than the red giant branch clump. Only 8 or 9 of the 36 resultant member giants are more metal poor than [Fe/H] ~ -1.3. The vast majority of the stars in this "halo" field have abundances centered on [Fe/H] $= -0.5$ (see Figure 3 in Olszewski 1993). This abundance distribution is not expected for a "Population II halo." It is not yet understood how such a field can be dominated by stars more metal rich than 47 Tuc. The velocity dispersion of the stars more metal poor than [Fe/H] $= -1.3$ is 29 km s^{-1} (23 km s^{-1} with one extreme-velocity star removed). The velocity dispersion for the more metal-rich stars is 16 km s^{-1}. These velocity dispersions are not obviously different from those of the clusters or OLPVs. Very large areas on the sky will need to be observed to derive the velocity dispersion of subsamples of the metal-poor population.

The NGC 121 field in the SMC is much more normal for a distant "halo" field. Astrometry was again used to cull foreground stars. Spectra were then obtained for 13 stars. The spectroscopy and photometry were then used to derive abundances for 31 stars in the field. The distribution of metallicities peaks at [Fe/H] $= -1.6$ (Suntzeff et al 1986, Figure 9) and is very similar to the abundance histogram of Galactic halo RR Lyraes and of Galactic halo globular clusters. There is no component similar to the dominant metal-rich component in the NGC 2257 field. The velocity dispersion is 24 km s^{-1}.

Old and metal-poor main-sequence turnoffs are an indication of the progenitors of the giants discussed above. Elson et al (1994) attempted to find this population with pre-Costar *HST* images of the young and crowded 30 Dor region. If their assumptions about the errors in the photometry are correct, they see a small excess of stars blueward of the dominant main-sequence population. They attribute these stars to a metal-poor population. We believe that this result is inconclusive. Elson et al (1994, Figure 6) show a color cut across the main sequence at $22 < V < 22.5$ in two 30 Dor fields approximately 30 arcmin apart. The color of the dominant population does not change, while the color of the putative metal-poor population changes by 0.08 mag. Fields known to contain BHB stars or strong subgiant branch populations will show the old metal-poor main sequence most clearly. This population is easily hidden. The clusters and RR Lyrae results suggest that the ancient population is no more than 10% of the luminous mass of these galaxies. Simple Monte Carlo simulations of synthetic color-magnitude diagrams show that the ancient population will be difficult to find because the lower main sequences of younger populations are superposed on the old turnoff.

The horizontal branch and red clump (RC) can be populated by populations with a wide range of ages (see Section 3.2). Gardiner & Hatzidimitriou (see references in Section 3.2) have made extensive studies of the color-magnitude diagrams of large areas of the SMC field using scans of SRC sky survey plates. A similar study is not currently published for the LMC, but surveys such as the MACHO project have already collected the appropriate photometry. Gardiner & Hatzidimitriou (1992) have argued that the majority of clump stars come from intermediate-age populations, though the bulk of the field populations near NGC 121 and L113 are claimed to be older than 10 Gyr. The RC stars closest to the instability strip can come from a population older than 10–12 Gyr (Hatzidimitriou 1991). Color cuts through the RC region of the CMD show this slightly bluer, fainter red HB population. More recent ages and abundances for the calibrating clusters (Armandroff et al 1992, Armandroff & Da Costa 1991, Buonanno et al 1990) lead to the conclusion that this population of red HB stars near the instability strip may be as much as several billion years younger than the oldest globulars. This subset of older clump stars is approximately 7% of the total number of clump stars. About 7% of the stars older than 2 Gyr are thus older than 10–12 Gyr. More importantly, there is little evidence for blue horizontal branch stars. Gardiner & Hatzidimitriou (1992) estimate that the number of BHB stars is an order of magnitude smaller than the number of old RHB stars. Given the low metal abundance of the SMC clusters and field it is more likely that BHB stars do not exist because ancient SMC stars do not exist. NGC 121 and its RR Lyraes are demonstrably younger than the oldest globulars. Therefore the SMC clusters do not contradict this reasoning. Important observational tests are needed to derive the metal abundance of the SMC RR Lyraes, to see if there exists significant populations with abundances more metal poor than $[Fe/H] = -1.6$. It is also important to derive the abundance distribution of the clump giants.

If one isolates a set of old clusters or field stars, then with the next generation of telescopes we can expect to make detailed analyses of elemental and isotopic ratios. The ratio most commonly discussed is [O/Fe], because oxygen is made in Type II supernovae, whose progenitors are very short lived, and iron is made in Type I supernovae, whose progenitors are very long lived. [Mg/Fe], [Ca/Fe], and [Si/Fe] should change in the same way as [O/Fe] and are easier to measure. As Gilmore & Wyse (1991) summarized, the ancient objects described in this review should be overabundant in oxygen if the initial star-formation burst were short, but could have a Solar ratio of [O/Fe] if these objects were formed near the end of a lengthy episode of star formation. If the clusters are not self polluted, we may be able to tell if the ancient clusters were formed before or after the ancient field.

2.8 *The CH Stars*

Another stellar type often associated with old populations are CH stars. They comprise a rather ill-defined class of carbon stars that are seen in dSph galaxies, the Galactic globular cluster ω Cen, and in the Galactic halo. Although CH stars do have a number of spectral peculiarities (strong CH bands, s-process enhancements, low metallicities, and bluer colors than N-type carbon stars), there is presently no spectroscopic way to identify a carbon star as a CH star unambiguosly. The existence of “CH-like” stars (Yamshita 1975), which have disk-like motions in the Galaxy but otherwise appear the same as CH stars, compounds the problem. The classification of a star as a CH star is therefore associated with its kinematics. While the kinematics coupled with spectral characteristics may allow the identification of a star as a CH star in our Galaxy, the unambigous identification of a star as a CH star in another galaxy cannot be made without other information, such as velocities or bolometric luminosities.

Hartwick & Cowley (1988) and Cowley & Hartwick (1991) have identified blue carbon stars with enhanced s-process features in the LMC. Infrared photometry of these stars by Suntzeff et al (1993) and Feast & Whitelock (1992) have shown these stars to be very luminous [$M_{\rm bol} = -5.3$ in the mean]. They are probably carbon stars that are younger ($t < 1$ Gyr) than the dominant C-star population (Section 3.2 below) discovered with infrared plates (Blanco et al 1980). A deeper survey in the peripheries of the Clouds should reveal a number of true CH stars near the tip of the old RGB tip at $M_V = -3$, but no convincing population of these old carbon stars have been made to date.

3. THE INTERMEDIATE-AGE POPULATIONS OF THE MAGELLANIC CLOUDS

3.1 *Definitions*

In this section, we consider field stars and clusters with ages between approximately 1 Gyr and 10–12 Gyr (using the age scale adopted in Section 2.1) to represent the “intermediate-age” populations of the Clouds. For comparison, Westerlund (1990) adopted the age range 0.2–7 Gyr for this purpose. Our definition of intermediate-age has the advantage of being empirically easy to apply. The upper age limit corresponds to the epoch of RR Lyr formation that was discussed in Section 2.2, while the younger age limit corresponds to the earliest appearance of the red giant branch. The precise ages of these limits remain uncertain because different treatments of convective overshoot significantly affect the ages of clusters younger than 1–2 Gyr (e.g. Mateo & Hodge 1987, Seggewiss & Richtler 1989, Bomans et al 1995). Moreover, the RGB-turnon age seems to exhibit an intrinsic spread of 250–500 Myr (Ferraro et al 1995).

3.2 *Evolved Field Stars*

3.2.1 ASYMPTOTIC GIANT BRANCH STARS For many years, "intermediate-age" in the Magellanic Clouds was taken to be nearly synonymous with the presence of luminous asymptotic giant branch stars. Numerous workers have identified and studied AGB stars in field and clusters of the MCs (e.g. Aaronson & Mould 1985, Frogel et al 1990, Mould 1992). Because the peak AGB luminosity increases steadily with decreasing age (due to the increase in core mass with increasing ZAMS mass), and because AGB stars are relatively easy to identify, the brightest AGB stars are useful as beacons for the intermediate-age populations throughout the Clouds and their environs. Infrared observations are required to determine AGB luminosities because these stars have low surface temperatures and correspondingly large optical bolometric corrections (e.g. Frogel et al 1990).

Magellanic Cloud clusters have played an important role in calibrating the luminosities of AGB stars in terms of age. Frogel et al (1990) provide the most recent calibration of AGB luminosities as a function of cluster age, but, as has been known for some time (Aaronson & Mould 1985, Hodge 1983), this correlation between AGB properties and age is very broad: For clusters of a given age, the observed peak AGB luminosities vary significantly in different objects. In practice, it becomes impossible to use the AGB to attain age resolution of better than a factor of two for populations older than about 1–2 Gyr. One important reason for this is that the AGB is a short-lived evolutionary phase (Iben & Renzini 1983). Thus, defining an AGB sequence or determining the peak AGB luminosity depends sensitively on the sample size. Metallicity differences between clusters at a given age and star-to-star variations in core mass and mass-loss rates also affect their AGB luminosities and lifetimes and contribute to the intrinsic scatter of AGB properties with age. The AGB is a blunt tool with which to constrain ages, but for many galaxies with only partially resolved stellar populations, it is often the only tool available.

While acknowledging these limitations, we can still use AGB stars to study intermediate-age populations in the MCs. Frogel & Blanco (1983, 1990) used the detailed features of AGB stars to estimate ages of the progenitor field populations in the Bar-West field of the LMC. They conclude that the luminosity and IR-color distribution of the AGB can be understood as two sequences. The bluer, more luminous AGB stars appear to be associated with stars as young as 10^8 yrs, while the redder, lower-luminosity AGB stars trace 1–5 Gyr populations (Frogel et al 1990, Feast & Whitelock 1994). Frogel & Blanco (1990) show that the young and intermediate-age populations are present in the ratio 1:4 in this inner LMC field. The results imply an episodic star-formation rate in the inner LMC coupled with a slow overall decline in star formation during the past few Gyr. These studies also illustrate the value of IR photometry as a way to identify AGB stars easily without the need for confirming optical spectroscopy.

Studies of carbon AGB stars—luminous, cool AGB stars with dredged-up carbon in their atmospheres—have recently been used to map the extent of intermediate-age populations in both MCs. Feast & Whitelock (1994) have analyzed the C stars identified by Demers et al (1993) to trace intermediate-age populations in the outer parts of the LMC, in the inter-cloud "bridge" connecting the two Clouds, and in the outer halo of the SMC. In all three cases, the mere presence of the C stars indicates the presence of a significant intermediate-age population in these regions.

The utility of AGB stars as intermediate-age population tracers is well illustrated by the Magellanic bridge. Demers and collaborators (Grondin et al 1990, 1992; Demers & Irwin 1991; Battinelli & Demers 1992; Demers et al 1991) have demonstrated the existence of young ($\lesssim$ 200 Myr) stars and loose clusters or associations in a stellar inter-cloud bridge connecting the two galaxies. This stellar bridge is closely associated with the H I bridge between the Clouds (Mathewson & Ford 1984, Westerlund 1990). The presence of luminous AGB stars in the bridge (Demers et al 1993) suggests that the young population—which may well have been born when the bridge itself formed (Demers et al 1991, Gardiner & Hatzidimitrou 1992)—may be accompanied by older stars that possibly predate the bridge. Whatever mechanism formed the bridge and its youngest stars was also probably responsible for stripping some intermediate-mass stars from one or both of the Magellanic Clouds (see Section 3.5).

3.2.2 ANOMALOUS CEPHEIDS Anomalous Cepheids (ACs) are believed to form during the late evolution of intermediate-mass metal-poor stars (Hirshfeld 1980). ACs have periods of 0.25–1.5^d and obey a period-luminosity relation (Nemec et al 1994). These stars have luminosities considerably higher than RR Lyrae stars, making ACs relatively easy to identify in external galaxies. The field of our Galaxy is not known to contain any ACs, but, even if present, they would be very difficult to identify due to confusion with RR Lyraes of similar periods (see

Mateo 1996a), and with type II Cepheids and evolved HB stars (Sandage et al 1994). Because the standard model for ACs requires them to be more massive than the turnoff masses of ancient clusters such as NGC 5466 (Hirshfeld 1980), it is generally believed that NEC 5466-V19 formed as the result of mass transfer in a now-merged binary progenitor (Zinn & King 1982, Nemec & Harris 1987).

In contrast, dwarf spheroidal galaxies (Mateo et al 1995, Nemec et al 1994) and the SMC (Smith & Stryker 1986, Smith et al 1992) appear to be rich in ACs. In the case of the SMC, this conclusion rests on observations of only four bona fide candidates. In dwarf galaxies—where complex star-formation histories appear to be the norm rather than the exception (e.g. Da Costa 1992, Smecker-Hane et al 1994, Mateo 1996a)—ACs are generally believed to result from the evolution of single, relatively massive metal-poor stars as described by Hirshfeld (1980; see also Smith et al 1992). Anomalous Cepheids therefore represent another potential tracer of the intermediate-age populations in the Clouds. One candidate AC has been reported for the LMC (Sebo & Wood 1995); however, these authors also note that the light curve of this star could be understood as that of a normal 0.51-day RR Lyrae star with a nonvariable but unresolved companion of comparable brightness. Thus it remains uncertain whether the LMC contains any ACs at all. Ongoing and planned large-scale MACHO and OGLE photometric surveys should soon provide comprehensive censuses of the ACs in both Clouds.

It is tempting to attribute the higher frequency of ACs in the SMC as evidence that this galaxy contains intermediate-age progenitors while the LMC does not. The details of how anomalous Cepheids relate to their progenitor population appear to be quite complex, with metallicity and age probably playing nearly equal roles (Smith & Stryker 1986, Mateo et al 1995). One can also confuse ACs with other types of pulsating, short-period variables found above the HB but which are generally evolved from old–not intermediate-age–progenitors (Sandage et al 1994). In dwarf spheroidal galaxies the frequency of ACs does *not* appear to correlate strongly with the age of the predominant field population (Mateo et al 1995). The LMC's deficiency of ACs may simply reflect the absence of suitably metal-poor intermediate-age progenitors rather than the complete absence of that population. New theoretical models of ACs applicable to Cloud metallicities and age ranges are badly needed to address this issue.

3.2.3 INTERMEDIATE-AGE LONG-PERIOD VARIABLES As described in Section 2.6, LPVs with periods less than about 250 days are generally classified as "old." Hughes et al (1991) have identified such stars with an old spheroidal-like population of the LMC. For LPVs with periods in the range 225^d–425^d, which are found in abundance in the LMC, the putative progenitors have main-sequence lifetimes of about 1–3 Gyr (Wood et al 1983, 1985; Hughes & Wood 1990).

This conclusion is consistent with their kinematics, which are disk-like and intermediate between the kinematical properties of young LMC components (e.g. H I clouds, very young clusters) and of older components (the ancient clusters, old LPVs). Hughes & Wood (1990) note that the relative frequency of old and intermediate-age LPVs suggests that the older population is considerably more abundant, by up to a highly uncertain factor of five.

We see below that very few field stars or clusters seemed to have formed 4–12 Gyr ago. The period distribution of LPVs shows no sign of a break corresponding to this hiatus in star formation, suggesting to us that the scatter in the mass-period relation for LPVs is comparable to the full mass range corresponding to intermediate-age stars. Alternatively, the progenitors of LPVs may have continued to form during an epoch when star-formation activity was otherwise very low in the LMC.

3.2.4 PLANETARY NEBULAE Planetary nebulae (PNe) are associated with the late stages of evolution in intermediate-mass stars. About 150 and 50 PNe are cataloged in the LMC and SMC, respectively (Meatheringham 1991, Vassiliadis et al 1992). In the late 1980s, Meatheringham and collaborators studied the spatial, kinematic, and physical properties of PNe in the LMC; Westerlund's (1990) review describes this work in detail.

How old are the PNe in the Magellanic Clouds? Using a simple orbital diffusion model based on heating by massive molecular clouds in the LMC, Meatheringham et al (1988) concluded that the mean age of the PNe sample is about 2–4 Gyr. This value is also consistent with stellar evolutionary models for PNe formation. It should be stressed that these models only very weakly constrain the PNe progenitor masses and therefore their ages. More recently, Vassiliadis et al (1992) confirmed the earlier kinematic solution and mean age for LMC PNe after adding to their sample radial velocities of 11 new nebulae located in the outskirts of the galaxy. Both the kinematic and stellar evolutionary ages of LMC PNe suggest that these objects belong to the galaxy's intermediate-age population. Given the large uncertainties in how the ages of PNe are determined in the Clouds, we cannot currently rule out that some of the PNe come from the ancient population.

In the SMC, Dopita et al (1985) measured a large velocity dispersion and found no clear evidence for rotation in a sample of 44 PNe. Interestingly, Hardy et al (1989) likewise found a kinematic solution very similar to that of a true spheroid or halo for C stars in the SMC. Unlike in the LMC, these two tracers of intermediate-age populations seem to be kinematically ancient. Whatever caused the complex structure and chaotic kinematics of the SMC as a whole are undoubtedly behind this unusual kinematic signature as well (e.g. Hatzidimitriou et al 1993); see section 3.5. If, as in the LMC, the PNe and C stars correspond to 2–6 Gyr populations, then we can conclude that whatever event induced the spheroidal-like kinematics in these objects probably did so within the past few Gyr. A lower limit of about 0.5–1 Gyr for the time when this event occurred is imposed by the fact that the H I in the SMC has approximately disk-like kinematics.

3.2.5 RED GIANT CLUMP STARS Virtually all intermediate-age stars experience a stable He core-burning phase. Among the oldest stars, this evolutionary phase corresponds to the horizontal branch seen in ancient star clusters (Sections 2.2 and 2.5). Stars in intermediate-age populations evolve into an analogous region located just blueward of the base of the red giant branch in the HR diagram. This evolutionary phase was first systematically studied in Galactic open clusters by Cannon (1970), and its location in the HR diagram is referred to as the red clump (RC). Data presented by Sarajedini et al (1995) nicely illustrate that the distinction between the RC and HB is fuzzy: As a population ages, the RC evolves smoothly into a red HB such as observed in 47 Tuc.

Unlike globular cluster horizontal branches (e.g. Lee & Demarque 1990), the structure and locations of red clumps do not change drastically over a very large range of age. Using photometry from MC and Galactic clusters with well-known ages, Hatzidimitrou (1991) noted that the (B-R) color separation of the RC and the RGB at the same luminosity varies systematically as a function of cluster age. This separation, $d_{B\text{-}R}$, varies systematically by about 0.15 mag as a population ages from 1 to 10 Gyr. This behavior is, to first order, independent of metallicity since RC and similar-luminosity RGB have similar surface temperatures and thus vary in color by similar amounts as line blanketing varies (though see Smecker-Hane et al 1994 for a counter-example of this simple evolutionary scenario observed in the Carina dwarf galaxy). For composite stellar populations it is nearly impossible to separate stars with different ages within this age range because the color spread of the RC itself is comparable to the full range of $d_{B\text{-}R}$. However, one can determine the mean age by measuring the color of the RC centroid.

Gardiner & Hatzidimitriou (1992) applied this technique to seven SMC fields, deriving mean ages for each. The individual age determinations scatter between 3 and11 Gyr, with a mean age of 7.6 ± 1.2 Gyr. We see below that the LMC seems to have formed very few stars at this time. These authors also claim the existence of an ancient population in their SMC fields on the basis of the color distribution of RC stars (see Section 2.7). Hatzidimitrou et al (1989, 1993), Gardiner & Hawkins (1991), and Gardiner & Hatzidimitrou (1992) have also used RC stars to determine the distribution of intermediate-age populations in the outer SMC, to study the line-of-sight depth of the SMC, and to measure the SMC kinematics as a function of depth.

Numerous photometric studies have identified a prominent RC population throughout the LMC (e.g. Hodge 1987, Brocato et al 1989, Bencivenni et al 1991, Bertelli et al 1992, Vallenari et al 1994a,c, Walker 1993b, Elson et al 1994, Reid & Freedman 1994, Gilmozzi et al 1994, Bhatia & Piotto 1994, Westerlund et al 1995) and the SMC (Brück 1980, Bolte 1987, Hilker et al 1995). In some cases, detailed photometric studies have subsequently revealed the intermediate-age main-sequence progenitors of these RC stars. The fact that the RC is visible in all fields suggests that the intermediate-age populations of the MCs are ubiquitous. With the possible exception of the inter-cloud bridge (Grondin et al 1992) and some fields located quite far from the MCs (e.g. near NGC 1841; Walker 1990), we know of no MC fields with adequate photometry that do not reveal RC stars. Such stars are even seen as a pervasive background in regions located close to active sites of present-day star formation (e.g. Elson et al 1994).

3.3 *Main-Sequence Stars*

Butcher (1977) identified a break in the slope of the main-sequence luminosity function of field stars in the LMC. This change in slope occurs about 1 mag brighter than the turnoff in globular clusters, leading him to conclude that the field was predominately composed of stars with ages 3–4 Gyr or younger. Later studies by Stryker (1983) and Hardy et al (1984) reached nearly identical conclusions for other fields in the LMC. In the SMC, Brück and collaborators (e.g. Brück 1980) and others (Hardy & Durand 1984, Bolte 1987) have also identified the presence of an intermediate-age population, but in this case with a mean age that seems to be significantly older than in the LMC.

More recently, studies using CCDs have begun to map out the detailed composition of the intermediate-age populations in the MCs. In order to adequately sample the old and intermediate-age stars, such data must reach to $V \sim 24$ to obtain good photometric precision at the level of the ancient turnoff, at $V \sim 22.5$ in the LMC and ~ 22.9 in the SMC. They should also cover a large area on the sky to adequately sample the rarest population present in a given field. Table 2 lists all MC fields for which deep photometry has been obtained that can constrain the frequency of populations as old as 10–15 Gyr using main-sequence stars. Linde et al (1995) provide a chart showing the locations of some of these fields in the LMC.

Bertelli et al (1992) analyzed deep CCD data in three LMC fields with the aim of deriving the star-formation histories at each location. They calculated a number of well-defined parameters—such as the ratio of red subgiants to main-sequence stars in a specified magnitude interval—and compared these with predictions from synthesized color-magnitude diagrams generated from the Padova stellar evolutionary models (e.g. Bertelli et al 1994). The indices were designed to be easy and robust to measure, to be relatively insensitive to photometric incompleteness, and yet to remain sensitive to various important physical parameters, such as the slope of the mass function (assumed to be constant with time), the mean metallicity, and the relative numbers of stars formed at different epochs. Remarkably, only a limited range of star-formation histories and metallicities could simultaneously account for the observed values of these parameters. Bertelli et al (1992) suggest that all three fields underwent a significant enhancement in the star-formation rate—by at least a factor of 10—some 3–5 Gyr ago. Though the precise age of this "burst" epoch depends on the models, the conclusion that the bulk of star formation commenced contemporaneously in all three fields is practically model independent.

Subsequent studies have broadly confirmed the Bertelli et al (1992) results, with some interesting differences. Westerlund et al (1995; see Linde et al 1995 for the input data) have studied two LMC fields, one each in the NW and SW regions of the galaxy. They find in both fields that the oldest major population corresponds to stars with ages of 1–3 Gyr. The ages of the youngest stars in the

Table 2 Deep main-sequence field-star studies in the Magellanic Clouds[†]

Field	α_{2000}	δ_{2000}	Galaxy	V^{a}_{max}	Area (arcmin^2)	N^{b}_{f}	N^{c}_{*}	Age range (Gyr)
B77	05 14	– 65 46	LMC	23.0	0.6 (2.5)[d]	1	120	$<$3–5
H84	05 09	– 68 53	LMC	21.3	72	1	18000	$<$3
DH84	01 08	– 72 34	SMC	21.4	33	3	$\sim$2000	0.1$\rightarrow$3
S84	06 30	– 64 04	LMC	22.8	540	11	3700	1–6
A85	05 19	– 70 57	LMC	23.0	3.2	2	1150	0.1$\rightarrow$1
B87	01 03	– 70 51	SMC	23.8	15	1	$\sim$800	0.2–8
H87	04 33	– 72 14	LMC	22.0	400	1	350	2–3
B92-N1783	04 58	– 65 58	LMC	23.5	15	1	2030	0.5–4.5
B92-N1866	05 13	– 65 26	LMC	23.5	15	1	2370	0.5–3.8
B92-N2115	05 58	– 65 28	LMC	23.8	15	1	1780	1.3–4
E94-F1	05 39	– 68 54	LMC	24.1	7.3	1	3000	0.7–5 + anc?[e]
E94-F2	05 35	– 69 10	LMC	24.1	7.3	1	4200	0.7–5 + anc?
W95-NW	05 03	– 65 52	LMC	22.9	15.5	4	2190	0.2–3
W95-SW	05 48	– 73 32	LMC	23.0	11.6	3	940	1–3

[a] V_{max} is the limiting V-band magnitude of the survey.
[b] N_f is the number of fields studied; in some cases different fields come from the same imaging data, but were measured and analyzed separately (e.g. S84, A85).
[c] N_* is the approximate number of stars observed; this could only be very roughly estimated in the case of HD84.
[d] Two field sizes are listed for B77; the smaller value refers to the field size in which stars as faint as $V \sim 23$ were measured.
[e] E94 claim detection of a possibly ancient field-star population, denoted "anc."
[†] This table lists only studies aimed principally to study intermediate-age MC field-star populations. Other field-star results can be found in the references listed in Section 3.3 of the text. Projects in progress are not listed here. Stryker (1984b) gives a summary of additional MC field-star studies. References: B77 = Butcher 1977; H84 = Hardy et al 1984; HD84 = Hardy & Durand 1984; S84 = Stryker 1984a; A85 = Ardeberg et al 1985; B87 = Bolte 1987; H87 = Hodge 1987; B92 = Bertelli et al 1992; E94 = Elson et al 1994; W95 = Westerlund et al 1995 (data for this study are described in Linde et al 1995).

two fields appear to differ significantly. In the NW field, stars as young as 0.3–0.8 Gyr are present, whereas the youngest population in the SW field appears to be slightly older than 1 Gyr. This is surprising because both are located beyond 5° from the LMC center, far from the well-known active star-forming sites in the LMC. Westerlund et al (1995) claim also to see evidence for a 7–10 Gyr population in their SW field, but the depth of their photometry and their sample size is probably only marginally adequate to constrain the presence of stars this old. This interesting result demands confirmation with deeper photometry. Vallenari et al (1994a,b) report preliminary results of a study patterned after that of Bertelli et al (1992) for several fields scattered throughout the LMC. They report that the age of the oldest significant population in one of the fields is 7–8 Gyr. Some of their data also seem to show evidence of distinct intermediate-age bursts in one of their fields, not seen in other fields.

No comparably deep photometric studies have been carried out in the SMC. The most comprehensive effort (Gardiner & Hatzidimitrou 1992) only probes main-sequence stars younger than about 2 Gyr. Gardiner & Hatzidimitrou conclude from these data that the SMC star-formation rate seems to be globally declining over the past 2 Gyr, with the obvious exceptions of active star-forming regions in the inner SMC and in the SMC "wing," which contain stars as young as 200 Myr. Deep CCD studies of the distribution of ages of field stars in the SMC are badly needed. Some care should be taken in selecting SMC fields. The very large line-of-sight depth of the galaxy (particularly on its eastern side; Hatzidimitrou et al 1989, Gardiner & Hawkins 1991) is troublesome. It would be very difficult to disentangle depth and age effects without independent kinematic data (Hatzidimitrou et al 1993). To avoid this problem, deep population studies should focus on the western portions of the SMC at present.

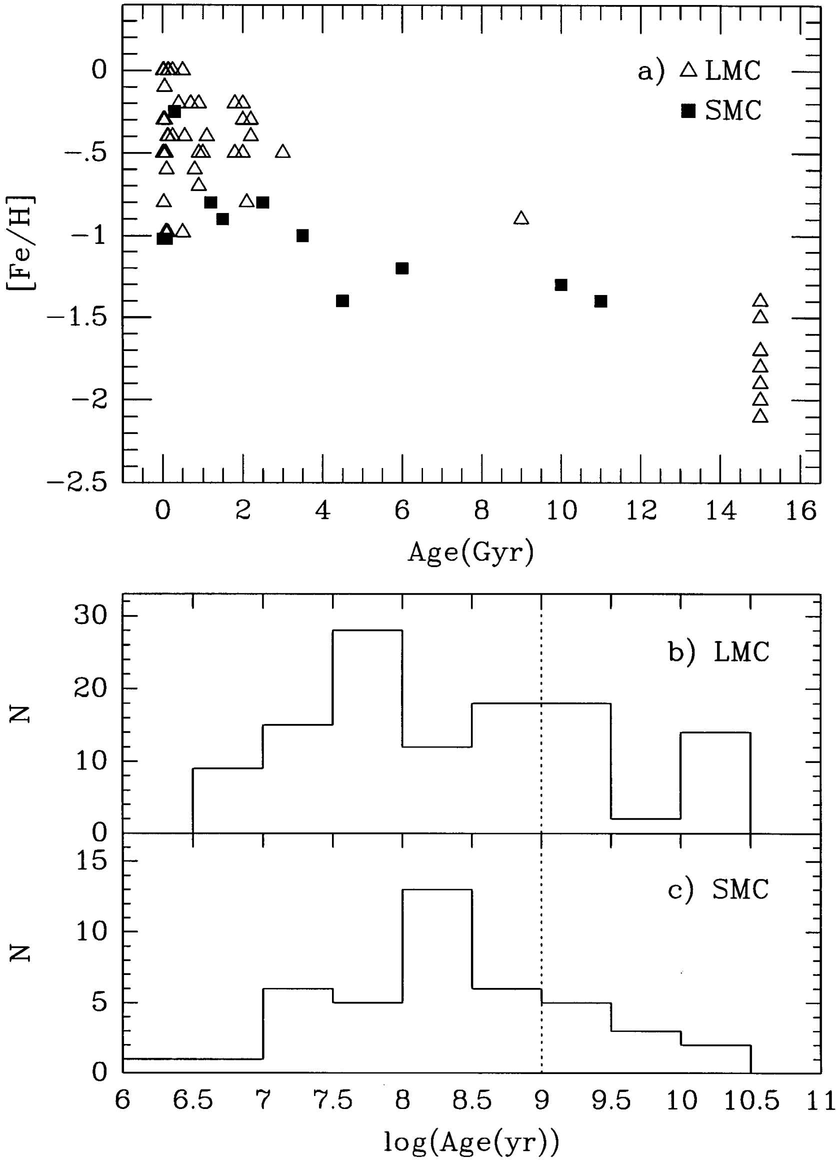
3.4 *Intermediate-Age Clusters*

3.4.1 THE AGE DISTRIBUTION It is now widely accepted that the distributions of cluster ages differ dramatically between the two Clouds (e.g. Olszewski 1993, Da Costa 1993, Feast 1995; see Figure 1). For example, we know of (almost) no LMC star clusters with precise age estimates obtained from deep, main-sequence photometry in the age range 4–12 Gyr. The one exception—ESO121SC-03—has an age of approximately 6–9 Gyr (Mateo et al 1986, Sarajedini et al 1995). In contrast, the SMC contains many clusters with ages between 4 and 12 Gyr: L 113 (age 4 Gyr; Mould et al 1984), K 3 (age 7 Gyr; Rich et al 1984), L 1 (age 9 Gyr; Olszewski et al 1987), NGC 121 (age 12 Gyr; Stryker et al 1985) all have ages that are either within or close to the LMC age gap. This suggests that ESO121SC-03 may have originally formed in the SMC and was swapped to the LMC (see also Lin & Richer 1992).

This dichotomy in cluster ages is not due to evolutionary fading of clusters. Hodge (1988a) has shown that the typical cluster destruction timescale is about 5–10 times longer in the LMC than in the Galaxy. In the LMC, there are numerous examples of 1–4 Gyr clusters that will remain prominent objects when they are older than 10 Gyr (Mateo 1993), including NGC 1978 (current age 2 Gyr; Bomans et al 1995), NGC 2155 (current age 3.5 Gyr; Mateo 1996b), and NGC 1831 (current age 1 Gyr; Vallenari et al 1992). There is also little doubt that the LMC age gap is real and not merely some statistitical fluke. Da Costa (1991) reported the preliminary results of a deep CCD survey designed to target clusters in the age gap exhibited by the LMC, selecting the clusters on the basis of their integrated colors. Of all the candidate clusters, none had ages in the 4–12 Gyr gap. Likewise, Mateo (1996b) reports the results of a study of clusters over a wide luminosity range in a small northern region of the LMC (see also Mateo 1988); none of these clusters are older than 4 Gyr. NGC 2155, noted in Section 2.2, is in fact one of the oldest intermediate-age clusters known. Olszewski et al (1991) note that the age gap is also a metallicity gap: The old clusters are metal poor; the younger ones are metal rich. This also strongly suggests a physical origin for the gap.

Girardi et al (1995) and Girardi & Bica (1993) have recently analyzed the integrated *UBV* photometric properties of a sample of over 624 newly observed LMC clusters (Bica et al 1992). Even though they span a range of over 10 Gyr in age, the intermediate-age and old clusters in this sample span a range of only 0.25 mag in $(B\text{-}V)$ and $(U\text{-}B)$ centered at approximately $(B\text{-}V) = 0.80$, $(U\text{-}B) = 0.90$. Clusters younger than 1 Gyr span a range of 0.8 and 1.1 mag in $(B\text{-}V)$ and $(U\text{-}B)$, respectively. The color degeneracy of intermediate-age and old MC clusters is also apparent in broad-band UV and IR colors (Cassatella et al 1987, Meurer et al 1990, Testa 1994). Broad-band photometry can lead to a distorted picture of the distribution of cluster ages (e.g. Elson & Fall 1988). This is not due to any sort of intrinsic error in the photometry or because of shortcomings in the evolutionary models used to interpret the photometry. Rather, the age resolution of broad-band colors is poorest precisely in the age range of greatest interest for intermediate-age and old MC populations (Girardi et al 1995). The only way to study the detailed differences in the distribution of ages of intermediate-age and old MC clusters is to obtain precise main-sequence stellar photometry.

Existing data clearly suggest that the LMC has formed clusters in at least two distinct bursts (4 Gyr and younger plus the ancient clusters), whereas the SMC has formed clusters more uniformly over the past 12 Gyr. Nevertheless, some additional work is desirable to strengthen and extend these conclusions. First, clusters are rarely selected for age determination on the basis of any clear


a) △ LMC
■ SMC
[Fe/H]
0
−.5
−1
−1.5
−2
−2.5
0 2 4 6 8 10 12 14 16
Age(Gyr)
b) LMC
N
30
20
10
0
c) SMC
N
15
10
5
0
6 6.5 7 7.5 8 8.5 9 9.5 10 10.5 11
log(Age(yr))

selection rules [one exception is the study of Da Costa (1992) mentioned above]. Before we can confidently rule out the existence of any 4–12 Gyr clusters in the LMC, reliable ages should be determined for a complete sample of clusters. The brute force approach to this problem—measuring main-sequence ages for all MC clusters—is still impractical at this time: The LMC contains about 4200 clusters and the SMC about 2000 (Hodge 1986, 1988b). Nonetheless, fewer than 2% of all MC clusters currently have reliable age determinations—a figure that can certainly be significantly improved upon. Some recent attempts at complete studies (e.g. Kubiak 1990a,b; Westerlund et al 1995; Mateo 1988, 1996b) have sampled only very small numbers of clusters and have been limited, so far, to the LMC. Such complete studies would also help to constrain the destruction rate of MC clusters and to obtain a better estimate of the absolute rate of cluster formation (cf Hodge 1988a).

A second difficulty in interpreting the age distribution of clusters is that in many cases one must combine age determinations based on very different assumptions about the relevant physical parameters (e.g. distance, reddening, metallicity) or based on comparisons with fundamentally different evolutionary models. For clusters younger than about 1–2 Gyr, modern models yield ages that can differ by a factor of up to two depending simply on how they treat convection at the core/envelope interface of intermediate-mass main-sequence stars (Mateo & Hodge 1987, Seggewiss & Richtler 1989). For the intermediate-age clusters discussed here, this effect is not too serious. But other effects are. Bomans et al (1995) have reanalyzed a number of CCD color-magnitude diagrams using a consistent set of evolutionary models and adopted astrophysical parameters. Although their new age determinations do not alter the basic conclusion above (no clusters are known older than about 2.5 Gyr in their reanalyzed LMC cluster sample) the ages of some of the clusters did change significantly from

←

Figure 1 (*a*) A plot of [Fe/H] vs age (in Gyr) for Magellanic Cloud clusters with precise metallicity and age determinations. The open triangles denote LMC clusters, while the filled squares denote SMC clusters. Results for 60 LMC and 11 SMC clusters are plotted. Following Da Costa (1992), we have plotted the age scale in *linear* units to emphasize the duration of the age gap in the LMC; no clusters seemed to have formed in that galaxy over $< 50\%$ of its lifetime. Note that the present-day metallicity of LMC clusters is considerably larger in the mean than for SMC clusters, whereas the metallicites were more similar 15 Gyr ago. (*b*) The age distribution histogram for LMC star clusters, now plotted as a function of log (Age). More clusters are represented in this panel than in panel (*a*) because of the considerable numbers of clusters with reasonable age estimates but only very crude metallicity determinations. (*c*) The same as panel (*b*), except for the SMC. In comparing panels (*b*) and (*c*), note that the intermediate-age and old populations reside to the right of the dotted lines. It is in this age range that the cluster age distributions show strikingly dissimilar behavior.

previously published values. Again, this does not reflect any sort of "error" in the initial studies, but rather the change in the age scale as one adopts different evolutionary models or astrophysical parameters. Until such time as all isochrones yield identical ages for a given cluster, it might be wise to establish a standard age scale based on a single set of models and parameters so that the relative ages of MC clusters can be compared with ease and confidence.

3.4.2 THE AGE-METALLICITY RELATION FOR STAR CLUSTERS Olszewski et al (1991) obtained abundances of approximately 80 LMC star clusters. This study represents by far the most extensive set of metallicities for intermediate-age clusters on a common scale, enlarging greatly the number of spectroscopic abundance determinations for these clusters (e.g. Cohen 1982, Cowley & Harwick 1982). Very few SMC clusters have spectroscopically determined abundances; their metallicities are generally derived from isochrone fits to the clusters' color-magnitude diagrams or from applications of empirical relations between the metallicity and the color of the RGB (e.g. Zinn & West 1984). Figure 1 illustrates the age-metallicity relations for clusters in both Magellanic Clouds. The data come from the compilations of Sagar & Panday (1989) and Seggewiss & Richtler (1989), supplemented by more recent results. We wish to highlight two important differences between the Clouds that are apparent from this Figure.

First, the mean LMC cluster metallicity jumps by a factor of about 40 during a time when virtually no clusters or—as we saw above—field stars were forming. Gilmore & Wyse (1991) and Köppen (1993) have shown that the chemical evolution of a galaxy characterized by a star-formation history punctuated by bursts can be very complex. In the case of the LMC, Gilmore & Wyse (1991) would argue that type I supernovae from the initial population steadily polluted the interstellar medium (ISM) during the long hiatus in star formation. When stars finally did begin to form again some 4 Gyr ago, the ISM was greatly enriched. One important implication of this idea—that O and other α elements should be enriched relative to Fe compared to their present day abundances—has already been described in Section 2.7.

But can this idea account for the very large observed increase in metallicity (Figure 1) during the age gap? A simple model in which only 2% of the LMC's dynamical mass formed in a burst more than 10 Gyr ago cannot account for this huge increase in metallicity. Supernova (type I and II) yields from Weaver & Woosley (1993) and Thielemann et al (1986) imply that the ancient LMC population could have only raised the mean iron abundance of the entire galaxy to [Fe/H] $= -1$ or less, far short of the value ~ -0.4 seen in 2–3 Gyr clusters. We do not seem to see sufficient numbers of field stars and clusters with ages between 4–12 Gyr to explain this discrepancy, unless the SN rates was much higher in the old MC populations than predicted by these models.

The second noteworthy feature of Figure 1 is that the two Magellanic Clouds have experienced quite distinct chemical enrichment histories (Da Costa 1992, Olszewski 1993, Feast 1995). This is clearly apparent in the shape of the age-metallicity relations, but also in the starting and ending values. Today the LMC is more metal rich than the SMC; 12 Gyr ago, these two galaxies may have had very similar abundances; it is not clear what the SMC abundance was 15 Gyr ago. In the case of the SMC, heavy-element enrichment (presumably from Type I SNe) may have lagged the star formation by a few Gyr. Currently, we see the metallicity rising as heavy elements are injected into the ISM. The lower mean abundance in the SMC simply reflects the fact that it has converted a smaller fraction of its gas to stars in accordance with a simple closed-box model of chemical evolution, and consistent with the present-day gas fractions of the two galaxies $(M_{\mathrm{HI}}/M_{\mathrm{total}}) \sim 0.35$ and 0.03 for the SMC and LMC, respectively.

Of course, all the arguments above assume that the MC clusters reliably track the chemical evolution of the LMC and SMC as a whole. Richtler (1993) summarizes the empirical and theoretical evidence for why this may not be the case.

3.4.3 KINEMATICS OF INTERMEDIATE-AGE CLUSTERS Freeman et al (1983) and Schommer et al (1992) obtained velocities for large numbers of intermediate-age clusters along with the results for ancient clusters described in Section 1. The intermediate-age clusters exhibit kinematics that are quite similar to those of young clusters and intermediate-age LPVs. Unlike the ancient clusters for which a disk rotation solution and small velocity dispersion was unexpected, the intermediate-age clusters appear to have kinematics that are “normal” for their ages. The orientation of the intermediate-age disk and the disk defined by the ancient clusters are statistically indistinguishable.

Feast (1995) has suggested that the commencement of the active star-formation epoch in the LMC some 4 Gyr ago may have coincided with the final collapse of the disk component of the LMC. The smooth transition of cluster kinematical properties is hard to understand in this scenario. Moreover, this idea does not offer any explanation why the old clusters also show disk kinematics: The LMC disk seems to have already been present when the oldest clusters formed.

3.5 *What Triggers Star Formation in the Magellanic Clouds?*

The Magellanic Clouds show extensive evidence of mutual interaction. The extreme depth of the SMC (Caldwell & Coulson 1986, Mathewson et al 1986, 1988, Gardiner & Hawkins 1991), the inter-cloud bridge, and the Magellanic Stream all testify that the Clouds have had a tumultuous recent interaction history. Lin & Richer (1992) and Muzzio (1988) argue that some MC clusters may have been lost to the Galactic halo on longer time scales. We have noted above (Section 3.4) that the unusual LMC cluster ESO121SC-03 may have formed originally in the SMC.

There is growing confidence that many of these global properties can be understood as originating in the tidal interactions of the Clouds with each other and with the Milky Way. Numerous workers (Murai & Fujimoto 1980, Lin & Lynden-Bell 1982, Shuter 1992, Gardiner et al 1994, Moore & Davis 1994, Heller and Rohlfs 1994, Lin et al 1995) have produced increasingly elaborate dynamical models that successfully account for many of the basic properties of the Magellanic Stream and the inter-cloud bridge and also properly account for the space velocity of the LMC (Kroupa et al 1994, Jones et al 1994). We have also seen in this review that the star-formation history of the Clouds are complex and distinct. Could tidal encounters between the MCs have provided the triggering mechanism needed to initiate this complex star-formation history? Interestingly, de Vaucouleurs & Freeman (1973) and Freeman (1984) pointed out that Magellanic systems tend to come in pairs, as if tidal interactions may be *necessary* to form galaxies similar to the Clouds.

All dynamical models of the LMC/SMC system agree that the two galaxies had a particularly close encounter within the past 100–500 Myr (Gardiner et al 1994, Moore & Davis 1994, Heller et al 1994, Lin et al 1995). For example, Gardiner et al (1994) note that the minimum separation of the Clouds was about 5 kpc compared to the 18 kpc separation we see today. Moreover, the best recent models also demand that in order to account for many of the present-day features of the Magellanic system and the space motions of the Clouds, the two galaxies must form a long-lived ($>$ 10 Gyr) binary pair. Thus, a tidal trigger for the complex star-formation histories of the Clouds is plausible since they probably have tidally affected each other all their lives. One particular model of Gardiner et al (1994) shows that the LMC/SMC separation has had two particuarly close encounters during the past 15 Gyr: the recent encounter 200 Myr ago, and a similarly close mutual passage 4 Gyr ago. The latter time corresponds very closely to when the LMC recommenced forming stars and clusters after its long hibernation (see Sections 3.3 and 3.4; Figure 1).

Before we can conclude that the star-formation histories of the Clouds are driven by tidal triggers, we must address at least three basic problems. First, the *preferred* model of Gardiner et al (1994) does not show any close encounters prior to the one 200 Myr ago, and in fact the Clouds have maintained a nearly constant separation prior to that time. Second, we must somehow account for the fact that the LMC and SMC have such different star-formation histories. One possibility is that the tidal effects of the LMC on the SMC have been sufficient to maintain an enhanced star-formation rate in the smaller galaxy, while only very close encounters of the SMC can trigger star formation in the more massive LMC. Finally, we lack a solid physical model that can translate tidal interaction into star-formation activity.

Recent *HST* imaging of actively interacting galaxies has enabled the identification of vigorous star and cluster formation (Holtzman et al 1992, Whitmore & Schweizer 1995). These results show that encounters between massive galaxies can and do induce vigorous star and cluster formation. Can the much milder encounters between small galaxies such as the MCs also trigger activity? The answer is important not only to understand the Clouds, but also to explain the complex star-formation histories of other satellites in the outer halo and the evolution of faint blue galaxies seen in deep surveys.

4. WISH LIST

We conclude this paper by listing observations we hope will be made and papers we hope will be written on the old and intermediate-age populations in the Magellanic Clouds:

1. Deep, wide-field field star photometry in both Clouds.
2. Complete samples of ages and abundances of clusters in well-defined areas of the Clouds.
3. Precise ages of the oldest Cloud clusters.
4. Definitive evidence for or against a blue HB in the Cloud fields.
5. Red Clump magnitude distributions in the central and western portions of the SMC, keeping in mind that the northeast and east regions of the SMC have a large line-of-sight depth.
6. Magnitude and structure of the intermediate-age red clump and of the old red HB in the LMC.
7. Identification and spectroscopy of radially distant mass tracers in the LMC.
8. Detailed abundances, especially [α/Fe] for the ancient population and for the stars and clusters in the LMC burst that began 4 Gyr ago.
9. Metallicity distribution of clump giants.
10. Star-formation rates in both Clouds, based on deep field star photometry.

11. Abundances of a large sample of SMC clusters.
12. Identification of metal-rich RR Lyraes in the LMC and the abundance-luminosity relation for RR Lyraes.
13. An RR Lyrae survey in the SMC.
14. A firm photometric footing for the previous RR Lyrae work.
15. Age of the youngest RR Lyraes.
16. Resolution of the RR Lyrae and Cepheid distance scales in the Clouds.
17. Velocity dispersion of RR Lyrae stars and extremely metal poor giants in the LMC.
18. Catalogs of anomalous Cepheids in the Clouds.
19. Identification of long-period variables in the Cloud clusters.
20. Proper motions of the globular clusters thought to once be Cloud members, but are now Milky Way members.
21. Modeling of dynamical changes in Cloud clusters if they were removed from the Clouds and put into the Milky Way halo.
22. Continued detailed modeling of the Cloud/Galaxy interactions, with an eye to providing times of strongest interactions.
23. Search for tidal signatures in field star components of the Clouds and the Magellanic Stream.
24. Improved proper motions of the Clouds.

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