THE MACHO PROJECT 9 MILLION STAR COLOR-MAGNITUDE DIAGRAM OF THE LARGE MAGELLANIC CLOUD

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ABSTRACT

We present a 9 million star color-magnitude diagram (9M CMD) of the Large Magellanic Cloud (LMC) bar. The 9M CMD reveals a complex superposition of different-age and -metallicity stellar populations, with important stellar evolutionary phases occurring over 3 orders of magnitude in number density. First, we count the nonvariable red and blue supergiants and the associated Cepheid variables and measure the stellar effective temperatures defining the Cepheid instability strip. Lifetime predictions of stellar evolution theory are tested, with implications for the origin of low-luminosity Cepheids. The highly evolved asymptotic giant branch (AGB) stars in the 9M CMD have a bimodal distribution in brightness, which we interpret as discrete old populations (≥1 Gyr). The faint AGB sequence may be metal-poor and very old. Comparing the mean properties of giant branch and horizontal-branch (HB) stars in the 9M CMD with those of clusters, we identify NGC 411 and M3 as templates for the admixture of old stellar populations in the bar. However, there are several indications that the old and metal-poor field population has a red HB morphology: the RR Lyrae variables lie preferentially on the red edge of the instability strip, the AGB bump is very red, and the ratio of AGB bump stars to RR Lyrae variables is quite large. If the HB second parameter is age, the old and metal-poor field population in the bar likely formed after the oldest LMC clusters. Lifetime predictions of stellar evolution theory lead us to associate a significant fraction of the ~1 million red HB clump giants in the 9M CMD with the same old and metal-poor population producing the RR Lyrae stars and the AGB bump. In this case, compared with the age-dependent luminosity predictions of stellar evolution theory, the red HB clump is too bright relative to the RR Lyrae stars and AGB bump. Last, we show that the surface density profile of RR Lyrae variables is fitted by an exponential, favoring a disk-like rather than a spheroidal distribution. We conclude that the age of the LMC disk is probably similar to the age of the Galactic disk.

Key words: Cepheids — color-magnitude diagrams — galaxies: stellar content — Magellanic Clouds — RR Lyrae variable — stars: evolution — stars: horizontal-branch — stars: variables: other — supergiants

1. INTRODUCTION

The Large Magellanic Cloud (LMC) is a nearby galaxy with one spiral arm and a bar (de Vaucouleurs 1955). The LMC exhibits a disk-like exponential surface brightness profile. The surface brightness profile of the LMC bar is also exponential, which is unlike other bars (Bothun & Thompson 1988). The study of the resolved stellar populations in the LMC bar is challenging because the surface density of stars is quite high. However, the proximity of the LMC otherwise favors detailed observations. It is important to study the stellar populations of nearby galaxies such as the LMC in order to understand the processes of galaxy evolution. In particular, the formation of exponential disks is an outstanding problem in cosmogony (e.g., Freeman 1970; Fall & Efstathiou 1980; Dalcanton, Spergel, & Summers 1997).

Butcher’s (1977) seminal study of the main-sequence luminosity function in the LMC showed that the star for-

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formation histories of the LMC disk and the solar neighborhood Galactic disk are different. Butcher (1977) concluded that the bulk of LMC field stars formed \(~3–5\) Gyr ago rather than \(~10\) Gyr ago, when the Galactic disk appeared to have formed (Salpeter 1955). Numerous subsequent studies of LMC field stars have supported this initial claim (Bertelli et al. 1992; Westerlund 1997; van den Bergh 1999). For example, Geha et al. (1999) found that roughly half of the stars in outer disk fields of the LMC formed before, and roughly half after, 4 Gyr ago. Recent stellar populations studies, such as those made with the Hubble Space Telescope (e.g., Geha et al. 1998; Olsen 1999; Holtzman et al. 1999), are now beginning to probe the spatial variations of the LMC’s star formation history in detail. Holtzman et al. (1999) argue that the LMC bar has a larger relative component of older stars than the outer disk fields.

The first color-magnitude diagram (CMD) study of the LMC bar was made by Tifft & Snell (1971). Their CMD contained \(~1000\) stars to a limiting magnitude of \(V \approx 18\). Tifft & Snell first observed the tip of the red giant branch (RGB) in the LMC bar, thus identifying an old stellar population. Hardy et al. (1984) obtained a CMD of the LMC bar with \(~18000\) stars to a limiting magnitude of \(V \approx 21\). They argued that the dominant stellar population in the bar formed \(~1–3\) Gyr ago and concluded that an older population in their CMD was only a weak component. Elson, Gilmore, & Santiago (1998) reached a similar conclusion. They analyzed a Hubble Space Telescope CMD of an “inner disk” field (close to the bar) and argued that the bar formed \(~1\) Gyr ago and the disk formed \(~3\) Gyr ago. Olsen (1999) and Holtzman et al. (1999) have contested the relatively young disk and bar advocated by Elson et al. (1997).

In this paper, we present a 9 million star color-magnitude diagram (9M CMD) of the LMC bar. Our fields cover almost the entire LMC bar (10 deg\(^2\)) to a limiting magnitude of \(V \approx 22\). These are the same fields extensively analyzed for microlensing by Alcock et al. (1997b). The 9M CMD is assembled from MACHO project two-color instrumental photometry calibrated to the standard Kron-Cousins \(V\) and \(R\) system (Alcock et al. 1999b). For these 9 million stars, the precision of the photometric calibration is \(\sigma_V = \sigma_R = 0.02\) mag. In addition to the sheer number of stars, near-total spatial coverage of the bar, and high-precision calibration, each star in the 9M CMD is represented by a 6 year light curve consisting of \(~1000\) two-color photometric measurements. Variable stars are easily identified with these time-sampled data. The 9M CMD is the product of wide-field imaging array detector technology and a dedicated, ground-based, 1 m-class survey telescope.

In order to discuss the taxonomy of the 9M CMD, we begin with a “tour.” The tour is intended to give the reader an overall impression and introduce key features, which are the subject of more detailed discussions that follow. After the tour, we turn our attention to the young LMC stellar populations. The core helium burning red and blue supergiants and Cepheid variable stars are particularly interesting examples of the late stages of stellar evolution of intermediate-mass stars. Supergiants in the LMC have a long history as testing grounds for the theory of stellar evolution, although past attempts to study these rare stars have sometimes proved difficult for the small samples available (e.g., Maeder & Meynet 1989; Langer & Maeder 1995). The 9M CMD represents the largest homogeneous sample of nonvariable supergiants and Cepheids ever assembled, thus allowing for new and precise comparisons with theory.

Next we examine the old LMC stellar populations. The metallicities and ages of these stars are not well known, which is an obstacle to the sort of detailed comparisons with theory we make with the young stellar populations. Therefore, a model for the old LMC stellar populations is first constructed. In order to minimize the dependence of this analysis on purely theoretical results, we rely primarily on the comparison of major features in the 9M CMD and the properties of variable stars with their counterparts in clusters. Clusters are useful because they serve as “template” populations, or building blocks for the composite 9M CMD. Our simple model for the old LMC populations is intended to serve as a check of more sophisticated but isochrone-dependent analyses of the LMC’s star formation history. In many respects, we repeat our analysis of the intermediate-mass supergiants and Cepheids, but for the low-mass helium-burning giants. By studying the low-mass RR Lyrae variables, we make inferences to the nature of the old and metal-poor LMC field population. This elusive LMC population probes the formation epoch of the LMC, with general implications for cosmogony.

2. TOUR OF THE 9 MILLION STAR COLOR-MAGNITUDE DIAGRAM

2.1. Construction

The MACHO photometry data and transformation of these data to the Kron-Cousins \(V\) and \(R\) standard system are discussed extensively by Alcock et al. (1999b), to which the reader is referred for further details. These calibrated photometry data may be properly compared with other data on the Kron-Cousins standard system. Moreover, we may infer accurate effective temperatures and bolometric luminosities with consideration of stellar atmospheres convolved with the standard \(V\) and \(R\) passbands, thus allowing for direct comparisons of stars in the 9M CMD with theoretical results. Unless otherwise noted, the photometry data analyzed here are derived from single observations; they are not time-averaged magnitudes and colors.

The 9 million stars analyzed in this paper are distributed throughout 22 MACHO project survey fields. A map of these fields overlaid on a wide-field image of the LMC (Bothun & Thompson 1988) is presented in Alcock et al. (1997b; their Fig. 1). Coordinates of the field centers are also provided. For each of the 22 fields, we bin the photometry data into a Hess diagram. A Hess diagram is a CMD that also contains information on the number of stars as a function of color and magnitude. We use a bin size of 0.01 mag in \(V – R\) and 0.02 mag in \(V\), with axes running from \(~0.5\) to 1.5 mag in \(V – R\) and \(~22\) to \(~12\) mag in \(V\). We make the final 9M CMD “image” by summing the 22 individual field CMDs using standard IRAF\(^\text{17}\) (V2.10.2) image processing routines.

2.2. The Tour

We present the 9M CMD in Figure 1. The image is logarithmically scaled and color coded. The logarithm of

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\(^{17}\) The Image Reduction and Analysis Facility is distributed by the National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
the number of stars in each pixel increases following the sequence blue → green → yellow → red. Important stellar evolutionary phases occur over 3 orders of magnitude in stellar number density. The highest pixel value in this image is \( \sim 3.5 \) dex, which is found at the peak of the red horizontal-branch clump (feature C in Fig. 1). This single high pixel therefore represents \( \sim 3000 \) stars with the same \( V - R \) color and \( V \) magnitude to within the resolution of our adopted pixel/bin size. Figure 1 is designed to give an overall impression of the 9M CMD data. A small number of stars brighter than \( V = 12 \) are not shown; this is above the saturation limit of the MACHO image data for the LMC in any case. Incompleteness is clearly evident for \( V > 21 \). For example, the number density of main-sequence stars would still be increasing at this brightness if not for incompleteness in the data (Alcock et al. 1999b). We will restrict our analyses to the brighter stars in the 9M CMD. We have labeled nine features with the letters "A" through "I" in Figure 1. These are identified as follows:

(A) The main sequence.—These stars are primarily core hydrogen burners (Maeder & Meynet 1989). The majority of main-sequence stars visible in the 9M CMD have either O, B, or A spectral types. The ridgeline of the main sequence is not exactly vertical but, instead, runs slightly from blue to red with decreasing brightness. There are almost no stars blueward of the upper main sequence. The stars bluer than the main-sequence ridgeline and increasing in number at progressively fainter magnitudes are consistent with our photometric errors and the total numbers of stars found on the main sequence. The range of brightnesses on the main sequence may be interpreted as a range of initial masses. The bright upper main-sequence stars indicate recent star formation in the LMC bar; these stars only live \( \sim 20 \) Myr (Maeder & Meynet 1989).

(B) The giant branch.—The stars on the giant branch are old, but in a mix of different evolutionary phases. Most of these stars are on the first-ascent red giant branch; they have degenerate helium cores and hydrogen-burning shells...
The base of the RGB (i.e., the subgiant branch) is not visible in the 9M CMD (it is too faint). However, the termination, or “tip,” of the RGB is seen at feature E. Stars at the tip of the RGB ignite helium in their cores and evolve very rapidly to the horizontal branch, near feature C. Some of the stars on the giant branch are also on the asymptotic giant branch (AGB). These stars are helium shell burners and are in an evolutionary state more advanced than the horizontal branch. For many stars in the 9M CMD, the AGB begins at D and continues past E into region F. We do not resolve the RGB and AGB in the 9M CMD. Stars located redward of the giant branch ridgeline are affected by differential reddening or photometric errors. In addition, some of these stars are foreground stars (in our Galaxy), and some are galaxies behind the LMC.

The association of the LMC bar giant branch with an “old” population was first made by Tiit & Snell (1971). This is more precisely defined as a population older than ~1 Gyr, a characteristic age also known as the RGB phase transition (Sweigart, Greggio, & Renzini 1990). The initial mass of stars at this transition is likely ~2 $M_\odot$ (Bertelli, Bressan, & Chiosi 1985; Sweigart et al. 1990), which sets a lower limit on the age of a stellar population with a fully developed (extended) giant branch.

(C) The horizontal-branch red clump.—The stars in the horizontal-branch (HB) red clump are primarily core helium burners older than ~1 Gyr (Seidel, Demarque, & Weinberg 1985), although some of these stars may be in different evolutionary phases. The red HB clump is very prominent in the 9M CMD. Note the elongation along the reddening vector due to differential reddening in the LMC (like some of the stars redward of the giant branch ridgeline). There are also brighter and bluer red HB clump stars, visible as a faint extension of the red HB clump running toward A. These are unresolved blends$^{18}$ of red clump and main-sequence stars. Although confused with the giant branch, clump-clump and clump–giant branch blends are likely present in similar numbers in the 9M CMD.

The ages and metallicities of the red HB clump giants in the LMC are surprisingly ill-constrained. Hardy et al. (1984) argued that the red HB clump giants in the LMC bar are most likely ~1–3 Gyr old. However, their upper age limit is based on quite uncertain subgiant branch star counts. In this work, we will constrain the ages and metallicities of the red HB clump giants using other stellar evolutionary features in the 9M CMD, such as the giant branch (B), the AGB bump (D), and the properties of the field RR Lyrae variable stars.

It is useful to compare the red HB clump giants with the RR Lyrae variable stars in the 9M CMD because they are closely related in a stellar evolutionary sense, and the characteristic ages of RR Lyrae stars are known. RR Lyrae variables are believed to be very old, having been found only in very old clusters (≥9 Gyr). In the LMC, RR Lyrae stars are also known to be metal-poor (see Olszewski, Suntzeff, & Mateo 1996 for a review). We find that the red HB clump is $\Delta V = 0.28$ mag brighter than the mean brightness of the RR Lyrae variables in the 9M CMD (the RR Lyrae stars are not distinct in Fig. 1, but see § 4.2). This brightness difference is larger than expected on theoretical grounds for an old, coeval HB (see, e.g., Fusi Pecci et al. 1996). However, this alone is not proof that the RR Lyrae stars and red HB clump giants in the LMC bar have different ages. The luminosity predictions of stellar evolution theory are very difficult to test at this high level of precision (Alves & Sarajedini 1999). If we estimate the mean metallicity of the red HB clump giants in the LMC bar and assume that age is the so-called second parameter influencing HB morphology (Sandage & Wildey 1967; Stetson, Vandenberg, & Bolte 1996), then the color, brightness, and number of red HB clump giants may give an indication of their age (Lee, Demarque, & Zinn 1994; Sarajedini, Lee, & Lee 1995; Hatzidimitriou 1991).

The analogs of red HB clump stars for populations younger than the RGB phase transition are also present here. These stars populate a feature in the 9M CMD that has been called the VRC, for vertically extended red clump (Zaritsky & Lin 1997). The VRC has been observed in other Local Group galaxies, such as Carina (Smecker-Hane et al. 1994) and Fornax (Saviane, Held, & Bertelli 2000). If we define the VRC as a CMD feature populated by stars in the same stellar evolutionary phase, then the VRC in the LMC is composed of ~2–4 $M_\odot$ core helium burning red giants (Corsi et al. 1994). The VRC is the high-mass extension of the red HB clump and the low-mass extension of the red supergiants, feature I. The VRC is visible in the 9M CMD just to the left (blueward) of the label “B” in Figure 1. At this brightness, the giant branch is beginning to “turn over” to redder colors, which makes it easier to distinguish the VRC sequence.

VRC stars with initial masses very close to the RGB phase transition may actually be up to ~0.5 mag fainter than the peak concentration of the red HB clump in the 9M CMD (Corsi et al. 1994; Girardi et al. 1998). Bica et al. (1998) and Piatti et al. (1999) have probably observed this “subclump” in several outer disk fields of the LMC. After reaching a minimum brightness, progressively younger stars in this evolutionary phase will then be brighter.

The density of stars along the VRC sequence will depend on the lifetimes of red giants of different initial masses, and also on the recent star formation history of the LMC. The theoretical lifetimes of VRC stars are very sensitive to the parameterization of convective overshoot, which may depend on initial mass and metallicity in a nontrivial manner (Schröder, Pols, & Eggleton 1997). Stochastic star formation throughout the LMC disk may also cause variations in the density of stars along the VRC, complicating comparisons with theory. Bica et al. (1998; but see Piatti et al. 1999) and Zaritsky & Lin (1997) have attributed stellar density variations along the VRC to extragalactic stellar populations. The VRC as defined here is a well-known stellar evolutionary branch in CMDs representing mixed-age populations and should not be confused with the fluctuations in stellar density along this branch that have led to claims of new stellar populations in front of (or behind) the LMC.

(D) The asymptotic giant branch bump.—We find a small concentration of stars on the giant branch approximately 1 mag brighter than the horizontal branch. This feature was first observed by Hardy et al. (1984) in their CMD of the LMC bar. It is the AGB bump, a slight evolutionary pause marking the transition from core to shell helium burning.

\footnote{The chance superposition of two stars on the sky that we are unable to resolve with our ground-based image data. Some of these may be binary systems, also unresolved in our data.}
core helium burning stars. They spend most of their post-Galactic poles.

(E) The tip of the red giant branch.—The tip of the red giant branch is defined by ignition of the degenerate helium core in old (low mass) stars, an event known as the helium flash (Renzini & Fusi Pecci 1988). In the 9M CMD, some stars at the blue edge of the tip of the RGB are likely unresolved blends of two giant branch stars. These blends “puff up” the tip of the RGB.

(F) The asymptotic giant branch.—These bright and very red stars are on the AGB. The AGB consists of two major helioshell burning evolutionary phases: the “early AGB,” during which the outer hydrogen shell is extinguished, and the “thermally pulsing AGB,” marked by the reignition of the hydrogen shell (Iben & Renzini 1983). The transition from the early AGB to the thermally pulsing AGB is theoretically predicted to occur near the tip of the RGB and may be associated with the onset of pulsation in these stars (Alves et al. 1998; Wood et al. 1999). The AGB stars brighter or redder than the tip of the RGB are all likely experiencing thermal pulses. The label “F” in Figure 1 marks the upper envelope of where most of the AGB stars are found. The AGB stars populate the region between the label and arrow “E” up to the label “F.” At the red edge of the AGB region (where the most highly evolved AGB stars reside), the 9M CMD reveals a bimodal structure, which we will examine in detail.

(G) The blue supergiants.—These are $4 M_\odot \lesssim M \lesssim 9 M_\odot$ core helium burning stars. They spend most of their post-main-sequence lifetimes as either blue or red supergiants (Maeder & Meynet 1989). While “looping” between the red and blue phases, these supergiants cross the instability strip and become Cepheid variable stars. The blue supergiants therefore define the “tips” of the blue loops. This is the lowest density stellar evolution feature we identify in the 9M CMD. The sequence runs from red to blue with increasing brightness and is visible between the main sequence and feature H, the foreground Galactic disk stars.

(H) Foreground Galactic disk stars.—The wide-field coverage of the 9M CMD results in significant “contamination” by Galactic foreground stars. The foreground Galactic disk stars lie along sequence H. The Galactic spheroid and thick disk make a small contribution at this brightness in the 9M CMD (Yoshii & Rodgers 1989). The moderately low Galactic latitude of the LMC ($b \approx -30^\circ$) increases the number of foreground disk stars relative to halo and thick disk stars over the case of star counts at the Galactic poles.

(I) The red supergiants.—These are $4 M_\odot \lesssim M \lesssim 9 M_\odot$ core helium burning red giant stars associated with the blue supergiants and the Cepheid variables. They are also the high-mass extension of the VRC. Inspection of Figure 1 shows that there are more red than blue supergiants in the LMC bar. We will quantify this observation in the next section.

3. YOUNG STELLAR POPULATIONS: SUPERGIANTS AND CEPHEIDS

The supergiant and VRC sequences in the 9M CMD are collectively known as “intermediate mass” stars. Intermediate-mass stars ignite helium nondegenerately, but they develop a highly electron-degenerate carbon-oxygen core after exhaustion of helium. The exact mass range depends on chemical composition but is likely $\sim 2$ to $9 M_\odot$ (Bertelli et al. 1985). After these stars leave the main sequence and evolve rapidly to become red giants (or supergiants, depending on the initial mass of the star), helium ignites in the core and a hydrogen shell burns outward. This shell eventually approaches a chemical composition discontinuity left by the furthest extent of the convective envelope during core hydrogen burning, which triggers rapid movement of the star back to the blue side of the CMD (Lauterborn,Refsdal, & Roth 1971; Stothers & Chin 1991; but see also Renzini et al. 1992). Subsequently, these stars evolve back to the red side of the CMD, which marks the end of the first “blue loop.” The helium shell ignites (double shell burning), and these stars may make a second blue loop (Becker 1981). Second blue loops are even less well understood than first blue loops (Höppner et al. 1978), but they are theoretically predicted to last $\sim 10\%$ of the lifetime of the first blue loop, if they occur at all.

The first blue loop is sometimes called the Cepheid loop, because it is the longer of the two loops and most Cepheids are believed to be in this phase of evolution (Becker 1981). Even during the first blue loop, these stars evolve very quickly between the tip of the blue loop and the red supergiant sequence. This rapid evolution manifests as a “gap” in CMDs representing young stellar populations, also known as the Hertzsprung gap. Blue loops tend to become shorter in lower mass stars, until no loops occur (Maeder & Meynet 1989). This stellar evolutionary trend is clearly confirmed by the blue supergiant sequence in the 9M CMD, which becomes redder at lower luminosities. We observe the red supergiants making blue loops, but not the VRC stars. The blue supergiant sequence in the 9M CMD represents the outer envelope of intermediate-mass stars on blue loops.

While stellar evolution theory for intermediate-mass stars successfully predicts the major observational characteristics of supergiants and Cepheids, the models fail to match observations in detail (Renzini et al. 1992; Langer & Maeder 1995). Therefore, it is worth examining the supergiants in the 9M CMD and making a comparison with theory for the possibility of advancing the theory. We assume that the intermediate-mass stars in the LMC bar have similar, moderately subsolar metallicities ([Fe/H] = $-0.4$ dex, Westerlund 1997; see also Luck et al. 1998).

In this case, the 9M CMD represents the largest homogeneous sample of nonvariable supergiants and Cepheids ever assembled.

3.1. Isolating the Supergiants

We present two different versions of the 9M CMD in Figure 2. In these diagrams, we adopt a bin size of 0.03 mag in $V - R$ and $V$, with axes running from $-0.3$ to 1.5 mag in $V - R$ and from 17.5 to 14.5 mag in $V$. The scale and bin size are chosen to show the two supergiant sequences clearly. Intensity and contours (1.0 to 2.5 dex in 0.25 steps) indicate the logarithmic number of stars (number per 0.03 mag square color-magnitude bin). Figure 2b is a subset of Figure 2a in which we have removed all variable stars. The variable stars are identified by poor fits to constant-brightness 4 year light curves.

There are only small regions in the 9M CMD where the supergiant sequences are free from contamination by other
Fig. 2.—Log-scaled Hess diagrams representing (a) 261,805 LMC stars with $V-R = -0.3$ to 1.5 and $V = 17.5$–14.5, and (b) the same diagram, but with 35,169 candidate variable stars removed. The variable stars are defined by poor fits to constant-brightness light curves. Intensity and contours (1.0 to 2.5 dex in 0.25 steps) indicate the logarithmic number of stars (number per $10^2$ deg$^2$ and per 0.03 mag square color-magnitude bin). The white rectangular apertures are centered at $(V-R, V) = (0.18, 15.25)$ and $(V-R, V) = (0.66, 15.75)$; they have dimensions $\Delta(V-R, V) = (0.2, 0.5)$. There are clearly more red than blue supergiants in these apertures. We also draw attention to the gradients in number density with increasing brightness within the apertures. While the number density of blue supergiants is nearly constant, the number density of red supergiants is visibly decreasing. In this work, we restrict our analysis to the average properties of supergiants in these two apertures. 

19 We have calculated the ratio of blue and red supergiants in 88 quarter-field regions of the 9M CMD (including variables) and find a mean value $0.504 \pm 0.033$ and a median value of 0.44, excluding one region with an exceptionally high degree of differential reddening. This analysis assures us that the mean ratio of nonvariable blue and red supergiants described in the text is representative of the young LMC bar population.

In Figure 3, we present color-frequency histograms of the bright stars in the 9M CMD (open histograms). These give the number of stars per 0.1 mag color bin and $V \pm 0.25$ mag, where $V$ is labeled in the upper right corner of each panel. The hatched histogram is a model prediction for Galactic disk foreground stars along the line of sight toward the LMC bar. The Galaxy model is briefly summarized in the next paragraph. The agreement between the 9M CMD data and the model is comparable to other well-studied lines of sight (for a recent modeling of star-count data along multiple lines of sight, see Ng et al. 1997). The detailed disagreement between the model and 9M CMD star counts may be due to the normalization of the local disk luminosity function and assumptions regarding the local disk giant branch (see below). This is not critical to our analysis. This model comparison unambiguously identifies feature H in Figure 1 with foreground stars. In addition, the color distribution of foreground Galactic disk stars shows a sharp blue edge, and thus the blue LMC supergiants may be isolated with an appropriate color cut. The fractional contamination of the red LMC supergiants by foreground Galactic disk stars is estimated to be $\sim 10\%$ in the brightness range of interest ($V = 15.75$).

Our Galaxy model consists of two components, a standard double-exponential disk and a spheroid. However, the spheroid is a minor contributor to the star counts at the brightnesses we are concerned with in this work (Bahcall &
Soneira 1980), and this component is not described here. We do not include extinction in our model. Our local disk luminosity function is adopted from Yoshii, Ishida, & Stobie (1987) but is rebinned into (No. stars)(0.5 mag)$^{-1}$ pc$^{-2}$. We predict a local spatial density of $n = 0.036$ stars pc$^{-3}$, which projects to a column density at the solar radius of $47$ pc$^{-2}$. We adopt a CMD for the disk stars consistent with the $z = 0.008$ isochrones of Bertelli et al. (1994). This slightly subsolar metallicity accounts for radial and vertical metallicity gradients in the disk, and dilution from thick disk stars, in an average manner. We have explicitly tested the effect of disk metallicity gradients of the forms given by Yoshii et al. (1987), and we find a negligible effect on the star-count colors for the models relevant to this investigation. We do not include a giant branch in our model. We assume a Galactocentric solar radius $R_\odot = 8$ kpc and a disk radial scale length $R_d = 3.8$ kpc (Yoshii & Rodgers 1989). Our vertical scale heights ($H_z$) are a function of absolute magnitude $M_V$, running from $H_z = 90$ pc for $M_V < 1$ to $H_z = 400$ pc for $M_V > 5$. This function is consistent with the data summarized by Bahcall & Soneira (1980). We have tested our Galaxy model against star-count data along lines of sight toward the north Galactic pole (Yoshii et al. 1987), the south Galactic pole (Reid & Gilmore 1982), and the Galactic anticenter (Ojha et al. 1994), and we find satisfactory agreement in all cases.

In Figure 4, we present a CMD also showing a parallelogram connecting the nonvariable supergiant apertures used to count Cepheids. We plot the time-averaged magnitudes and colors of 1720 Cepheids identified in the 9M CMD as small open circles (not all of these are within the limits of Fig. 4). The smattering of very blue or very red Cepheids may be attributed to photometric blends or differential reddening and do not affect this analysis. We assume that the catalog of Cepheids is complete at this brightness. We also plot fiducial sequences for the nonvariable supergiants as heavy circles. These fiducial marks were calculated by assembling all stars within a $30^\prime$ radius of each Cepheid into color-frequency histograms and adopting the center of the highest bin. The contrast of supergiants relative to the foreground Galactic disk stars is high because many Cepheids and nonvariable supergiants are grouped in clusters and loose associations. As a check, we also performed a statistical subtraction of foreground stars predicted by our Galaxy model and remade the color-frequency histograms. The fiducial marks derived in this manner are consistent. The supergiant fiducial marks are listed in Table 1, along with other marks to be described later.

Also plotted in Figure 4 are two $z = 0.008$, $M = 5 M_\odot$ stellar evolution model tracks. These are projected into the observable plane ($V$, $V-R$) with analytic approximations to the Bertelli et al. (1994) isochrone data. The tracks have
been shifted to “fit” the supergiant fiducial sequences and also the color of the main-sequence turnoff (not shown). The fit was judged by eye. For a fixed metallicity, the color difference between the red and blue supergiants is a function of initial mass. The color difference between the main sequence and red supergiants is also a function of initial mass. The shifts are needed to place the model tracks “in the LMC,” i.e., to account for distance and reddening. We disregard the sloping initial mass function in this analysis because the time \( \sim 5 \, M_\odot \) stars spend as helium-burning supergiants is small compared with their main-sequence lifetimes. Although the model tracks extend outside of the apertures (notably the red aperture), the time spent outside is very small compared with the time spent inside. The model that enters in the lower right of the red aperture is from Schaerer et al. (1993), while the other model is from Fagotto et al. (1994). The Schaerer et al. model crosses the Cepheid aperture at a brighter magnitude than does the Fagotto et al. model. Both models have a metal abundance \( z = 0.008 \) and use the same OPAL opacity tables (Iglesias & Rogers 1996). The Schaerer et al. model has a helium abundance \( y = 0.265 \), while the Fagotto et al. model has \( y = 0.250 \). The treatments of convection (including overshoot) and mass loss are similar but may differ in some details.

### 3.2. Counting Supergiants and Comparison with Theory

The numbers of nonvariable red supergiants, blue supergiants, and Cepheids are \( r = 2064, b = 805, \) and \( c = 280 \), respectively. If we make a 10% correction to \( r \) for foreground stars, the blue-to-red supergiant ratio is \( b/r = 0.43 \) and the ratio of Cepheids to nonvariable supergiants is \( c/(b + r) = 0.105 \). We estimate an uncertainty of 10\%, allowing primarily for the uncertainty in our foreground-star correction. The blue edge of the Cepheid instability strip in our aperture is at \( V = 0.30 \pm 0.02 \) and the red edge is at \( V = 0.47 \pm 0.02 \). Shifting the theoretical models to match the fiducial supergiant sequences in the 9M CMD provides a self-consistent color-temperature calibration for these stars. Using this calibration, we find the blue and red edges are \( T = 3.77 \pm 0.01 \) and \( 3.70 \pm 0.01 \) dax, respectively. We adopt \( T = 3.68 \) dax as the blue edge of the red aperture.

Adopting the red edge of the blue aperture and the blue edge of the red aperture to demark the red and blue supergiant phases, the Schaerer et al. (1993) model predicts \( b/r = 0.31 \) while the Fagotto et al. (1994) model predicts \( b/r = 1.02 \). We use the same segments of the model tracks as shown in Figure 4. Adopting the instability strip as derived above, we find \( c/(b + r) = 0.096 \) and 0.109 for the Schaerer et al. and Fagotto et al. models, respectively. The agreement between our measurement and the single-mass model predictions for \( c/(b + r) \) is quite good. This consistency is strong support for these models’ accurately representing the physical processes by which these stars evolve. Once evolution across the Hertzsprung gap for the first blue loop is initiated in these models, it may proceed through the instability strip on a timescale that is fairly insensitive to the detailed differences in model input physics.\(^{20}\) In contrast, it would appear that evolution at each end of the blue loop is quite sensitive to differences in the model input physics. The nearly equal number of red and blue supergiants predicted by the Fagotto et al. (1994) model is difficult to reconcile with our measured ratio. We speculate that subtle differences in the parameterized treatments of convection may be the cause of this discrepancy between models.

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**Table 1**

| \( V \) | \( V - R \) | \( V \) | \( V - R \) |
|------|--------|------|--------|
| **Blue supergiants:**\(^a\) | **Red supergiants:**\(^a\) |
| 14.75 | 0.09 | 14.75 | 0.76 |
| 15.25 | 0.18 | 15.25 | 0.71 |
| 15.75 | 0.30 | 15.75 | 0.66 |
| 16.25 | 0.39 | 16.25 | 0.64 |
| Field RRA's.\(^b\) | Red HB clump.\(^b\) |
| 19.45 | 0.31 | 19.17 | 0.51 |
| **Giant branch:**\(^c\) | AGB bump.\(^b\) |
| 16.75 | 0.825 | 18.38 | 0.57 |
| 17.25 | 0.713 | RGB tip: |
| 17.75 | 0.639 | 16.26 | 0.80 |
| 18.25 | 0.576 | 16.76 | 0.95 |
| 19.75 | 0.505 |

\(^a\) Median color for stars with \( V \pm 0.25 \) mag. Estimated uncertainty in \( V - R \) is 0.01 mag. See text for data selection.

\(^b\) Estimated uncertainty in \( V - R \) and \( V \) is 0.01 mag.

\(^c\) Average from 22 fields (median color per field) for stars with \( V \pm 0.25 \) mag. The standard deviation \( \sigma_{\text{V} - R} \approx 0.04 \) mag for each mark gives the width of the giant branch. See text for data selection.

\(^{20}\) This would make sense for the first, or the fourth and fifth, crossings (Becker 1981) because these proceed on the thermal (Kelvin-Helmholtz) timescale of the envelope. However, the first blue loop proceeds on a nuclear timescale of the core (Kippenhahn & Weigert 1990), which might be just as sensitive to model input physics as evolution at the each end of the blue loop.
The agreement between our measured ratio \( c/(b + r) \) for \( \sim 5 \, M_\odot \) Supergiants and the model predictions has several interesting implications. If the instability-strip crossing time is nearly independent of model input physics, we infer that the models accurately predict the total time these stars spend as helium-burning supergiants. Since the ratio of hydrogen- to helium-burning lifetimes for intermediate-mass stars is sensitive to the treatment of convective overshoot (Lattanzio et al. 1991), our result lends support to the overall amount of parameterized convective overshoot in the two models examined, despite the detailed differences found.

There are additional implications for the Cepheids. A theoretical Cepheid period-frequency histogram calculated by assuming a constant star formation rate and a Salpeter (1955) initial mass function predicts fewer \( \sim 5 \, M_\odot \) Cepheids than observed in the LMC bar, which has been interpreted as indicating a short-duration “burst” of star formation \( \sim 100 \) Myr ago (Alcock et al. 1999a). The inference of a burst is likely a model-independent result, because the time spent in the instability strip is very nearly the same for the two \( 5 \, M_\odot \) models examined here. However, we caution that results pertaining to the peak of the Cepheid period-frequency histogram in Alcock et al. (1999a) are strongly model dependent, since the peak number of Cepheids in a period-frequency histogram corresponds to the time spent at the tips of those blue loops that enter the instability strip \( (M < 5 \, M_\odot \) in the LMC). Finally, we note that neither of the two \( 5 \, M_\odot \) models examined here has second blue loops. However, the uncertainty of our measured \( c/(b + r) \) is too large to rule out or confirm the existence of a small number of Cepheids on second blue loops.

An additional interesting implication of the ratio \( c/(b + r) \) in the 9M CMD pertains to the discovery of \( \sim 600 \) Cepheids with \( V \gtrsim 17 \) and periods \( \lesssim 25 \) days (Alcock et al. 1999a; see also Alves et al. 1998). These Cepheids clearly lie below the observed blue supergiant sequence in the 9M CMD, implying evolution via a “nonstandard” channel. Alcock et al. (1999a) propose that the faint Cepheids are merged binaries, formerly two \( \sim 1.5 \, M_\odot \) stars. Indeed, these stars may be ubiquitous if a major burst of star formation occurred \( \sim 3 \) Gyr ago. The number of merged \( \sim 2.5 \, M_\odot \) stars that produce \( \sim 5 \, M_\odot \) Cepheids is calculated by scaling from the faint Cepheids, as follows: We assume a Salpeter (1955) initial mass function, viz., \( dN/dM = M^{-2.35} \), and a constant star formation rate over the period of time during which 1.5 to 2.5 \( M_\odot \) Cepheids are born in the LMC. In this case, the number of \( \sim 5 \, M_\odot \) Cepheids produced by binary mergers would be \( n \approx 600(1.5/2.5)^{2.35} \approx 180 \). Adding this to the number of Cepheids predicted from the number of red and blue supergiants yields \( c = 460 \), which compares with \( c = 280 \) observed.

It may be difficult to reconcile the binary merger hypothesis for the origin of the low-luminosity Cepheids with the value of \( c/(b + r) \) for \( \sim 5 \, M_\odot \) Cepheids. First, it is unlikely that merged binaries will follow single-star evolutionary paths through the red and blue supergiant phases if the Cepheid loop is triggered by the discontinuity in the chemical profile of the envelope, as suggested by theory. There is no obvious mechanism by which the necessary envelope discontinuity would form during, or after, a binary merger. Therefore, merged binaries would not produce the correct numbers of Cepheids and nonvariable red and blue supergiants. Second, while it is possible that the star formation history of the LMC conspired to produce very few \( 2.5 \, M_\odot \) stars (thus avoiding the problem of too many \( \sim 5 \, M_\odot \) merged-binary Cepheids), this requires very fine tuning of the star formation history. If the \( 5 \, M_\odot \) models are to be trusted, we conclude that either (1) the probability of binary mergers is much lower for higher mass LMC stars, and thus only low-luminosity Cepheids are produced from binary mergers, or (2) binary mergers are not responsible for the curious low-luminosity Cepheids.

### 4. OLD STELLAR POPULATIONS: THE DATA

#### 4.1. 9M CMD Fiducial Marks

Fiducial marks on the giant branch are defined as the peak of color-frequency histograms in \( \Delta V = 0.5 \) mag bins centered on the values listed in Table 1 \( (V = 16.75, 17.25, 17.75, 18.25, \) and 19.75). The fiducial marks were measured separately for each of 22 MACHO survey fields\(^{21} \) included in the 9M CMD (see Alcock et al. 1997b). In some cases, no clear peak was evident at \( V = 19.75 \) (fields 11, 15, and 81), and these fields were excluded when calculating this average mark. The average marks should accurately represent the shape (i.e., curvature) of the giant branch in the 9M CMD; they are listed in Table 1. We find a standard deviation for each of the mean RGB fiducial marks of \( \sigma_{V-R} = 0.04 \) mag, which gives an indication of the natural width of the giant branch (due possibly to superposed RGBs and AGBs, but also differential reddening throughout the bar).

In the top panel of Figure 5, we plot a random \( \sim 10,000 \) stars from the 9M CMD located near the tip of the RGB. In the middle panel, we show a different sample of \( \sim 10,000 \) stars, where we have now excluded all candidate variable stars. The horizontal lines in these two panels are the giant branch fiducial marks (these show \( \pm 0.04 \) mag in color). The angled mark corresponds to \( W_{3.3} = V - 3.3(V - R) = 13.62 \) mag for \( 0.80 < V-R < 0.95 \). The derivation of this fiducial mark is illustrated in the bottom panel. Here we plot histograms of all stars in this region of the 9M CMD (not just the subsets shown in the top two panels) projected along the \( W_{3.3} = V - 3.3(V - R) \) vector. The bin size is 0.02 mag. The solid line shows all stars, while the dotted line shows all nonvariable stars. The luminosity functions fall off at large \( W_{3.3} \) because we only count stars within the limits of \( (V, V-R) \) shown in the upper two panels. The slope of the \( W_{3.3} \) vector was chosen by eye (trials with different slopes did not change the result). We calculate the difference in height between consecutive bins, divided by the square root of the mean number of stars in the two bins, as a measure of the “step” that occurs at the tip of the RGB. Both histograms yield \( W_{3.3} = 13.62 \) mag as the most significant step, which is marked with an arrow in the bottom panel of Figure 5. However, the lack of a well-defined RGB tip is the most notable feature of these \( W_{3.3} \) luminosity functions. This may be due to photometric blends, differential reddening, mixed-

\( ^{21} \) Although it is beyond the scope of this work to provide a detailed comparative analysis of these 22 \( \sim 0.4 \) million star CMDs, we remark on a few outstanding field giant branches (see Alcock et al. 1997b, their Fig. 1): Fields 11 and 82 appear to suffer from notably large amounts of differential reddening. Fields 3, 77, and 80 are quite red (these are adjacent, running north from near the center of the bar). We speculate that there is a higher degree of foreground reddening for these fields (i.e., possibly a foreground dust cloud). Field 7 had the bluest giant branch (it is adjacent and south of field 77), and we suspect a particularly small degree of foreground reddening.
The angled mark corresponds to stars. The horizontal marks in these two panels are two of the RGB fiducial middle stars.

We deﬁne two subsamples of the RRab catalog in order to calculate different mean properties. The ﬁrst subsample we deﬁne is for consideration of the period-amplitude diagram, which we will refer to as the Bailey diagram sample. We begin with the ∼35% least crowded,24 or about 1280 RRab’s. Next, we make strict cuts in magnitude, 19.7 < V < 19.2, eliminating highly reddened stars (whose amplitudes may be underestimated because of Malmquist bias at minimum light), the numerous blended stars (whose amplitudes will certainly be underestimated because of the contaminating Ñux), and foreground RR Lyrae stars (Alcock et al. 1997c). This cut is similar to a “sigma clip” and leaves 935 RRab’s.

Next, we deﬁne a CMD RRab sample. We remove the sigma clip to guard against a possible bias in our estimate of the median color and brightness of the RRab’s. However, we tighten the crowding cut to exclude all but the ∼20% least crowded, or about 680 RRab’s. Without the sigma clip, this sample contains a few bright RRab’s blended with blue (main sequence) and red (giant branch or clump) stars in the

23 Excluded ﬁelds are 1, 7, 9, 77, 78, and 79 (see Alcock et al. 1997b; their Fig. 1). These are “round 1” ﬁelds, with a diﬀerent naming convention in the year 1 catalog and the 4 year light-curve database.

24 For each photometric measurement in the full MACHO database, there is a “crowding parameter” that gives the percentage ñux inside the point-spread function ﬁt box contributed by neighboring stars. It is useful to think of the least crowded stars as living in “empty” patches of sky scattered throughout the otherwise crowded LMC bar.
CMD. Some of the brighter stars may also be evolving off of the "zero age" horizontal branch. There are also fainter and redder RRab's, which are most likely affected by differential reddening in the LMC. The median color and magnitude of this RRab subsample are \( V = 19.45 \) and \( V - R = 0.31 \), which are listed in Table 1.

The ancient LMC clusters NGC 1835 and NGC 1898 each reside in one of the six fields excluded from the RRab catalog described above. Therefore, we have identified a few RRab stars in these clusters by culling through the MACHO database "by hand." No effort was made to identify complete samples. Variables lying within \( \sim 1' \) of each cluster center are assumed to be members. We identify eight RRab's in NGC 1835 and five in NGC 1898. This is the first report of RR Lyrae variables in NGC 1898. Walker (1993) and Graham & Ruiz (1974) have also discovered RR Lyrae stars in NGC 1835. The properties of the RRab's in these two LMC bar clusters are summarized in Tables 2 and 3. We assume that the mean colors and magnitudes are representative of each cluster.

**TABLE 2**

**NGC 1898 RRab Stars**

| MACHO ID     | R.A. (J2000.0) | Decl. (J2000.0) | Period (days) | \( V \) (mag) | \( V - R \) (mag) | \( A_V \) (mag) |
|--------------|----------------|----------------|---------------|--------------|-----------------|----------------|
| 78.5857.2941 | 5 16 46.7      | -69 39 07      | 0.475227      | 19.336       | 0.287           | 1.16           |
| 78.5857.2419 | 5 16 46.6      | -69 39 24      | 0.492045      | 19.274       | 0.300           | 1.25           |
| 78.5857.2749 | 5 16 29.0      | -69 39 27      | 0.532596      | 19.718       | 0.334           | 1.21           |
| 78.5857.2984 | 5 16 38.5      | -69 40 11      | 0.554789      | 19.215       | 0.248           | 1.00           |
| 78.5857.2200 | 5 16 33.2      | -69 38 23      | 0.647280      | 19.212       | 0.414           | 0.55           |
| Mean         |                |                | 0.540         | 19.351       | 0.315           | 1.04           |
| s.d.         |                |                | 0.029         | 0.095        | 0.029           | 0.13           |

**Note:** Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
these RR variables' used in Alcock et al. (1997a). The mean properties of these variables in Alcock et al. (1999b) supersede the calibration used in Alcock et al. (1997a). The mean properties of these RR variables are now $\langle V \rangle = 19.327 \pm 0.021$ and $\langle V-R \rangle = 0.259 \pm 0.006$.

4.3. AGB Sample Selection

In order to study the asymptotic giant branch in the 9M CMD, we begin with the ~88,000 candidates in the 4 year LMC variable star catalog. Each light curve is calibrated to $V$ and $R$, and time-averaged, flux-weighted mean magnitudes and colors are calculated. The statistical cuts used to identify candidate variable stars are looser in this 4 year catalog than those used to generate the 1 year catalog (the latter was used to select the RRab's). We remind the reader that the MACHO variable star catalogs are a by-product of the microlensing searches (Alcock et al. 1997b) and subject to the designs of those analyses, not the present one. In order to "clean up" the relatively loose-cut 4 year variable star catalog, we calculate a Welch-Stetson variability index (Welch & Stetson 1993) and several light-curve quality statistics. Applying cuts with these statistics, we reduce the catalog to a sample of ~19,000 of the most significantly variable stars, including only those with the highest quality light-curve data. The AGB variables in this "clean" sample are analyzed in the next section.

5. OLD STELLAR POPULATIONS: ANALYSIS

Simple theories of galactic chemical evolution predict that progressively younger stellar populations will be more metal-rich. Analyses of planetary nebulae confirm that the young stellar populations in the LMC are more metal-rich than the old stellar populations (Dopita et al. 1997). Aget-metallicity data for LMC clusters show the same trend (Da Costa 1999), although comparing the field and cluster histories may not be strictly appropriate (van den Bergh 1999). If two old populations are required to account for features in the 9M CMD, we assume that the younger population is relatively more metal-rich.

5.1. The AGB

In Figure 7, we plot the clean sample of AGB variables with small circles. We show the RGB tip as the steeply angled short mark with 0.80 to 0.95 mag in $V-R$. The thinner solid line corresponds to $W_{2,0} = V - 2.0(V-R) = 13.5$ mag, which runs approximately parallel to the extended sequences of AGB stars. AGB variables from the LMC clusters NGC 1898 (heavy filled circles) and NGC 1783 (heavy open circles) are also shown. The data for these cluster AGB variables are summarized in Table 4 (see Alves et al. 1998 for light curves).

NGC 1783 is a ~2 Gyr-old cluster located well outside of the LMC bar (Mould et al. 1989). The MACHO photometry data for this outer disk LMC field are transformed to Kron-Cousins $V$ and $R$ by comparison with the standard stars of Alvarado et al. (1995). Finding charts and original AGB star identifications are found in Lloyd Evans (1980), near-infrared photometry and $m_{bol}$ were assembled from

![Fig. 7.—CMD showing a sample of the most statistically significant variable stars from the 9M CMD in the region of the AGB. Several thousand stars are plotted as small open circles. We show the tip of the RGB as the steeply angled short mark ($W_{2,0}$) with $0.80 < V - R < 0.95$. The thicker solid line corresponds to $W_{2,0} = V - 2.0(V-R) = 13.5$ mag, which runs nearly parallel to the extended sequences of AGB stars. We use a projection perpendicular to $W_{2,0}$ to study the "thickness" of the AGB. The length of this line along the color axis (0.8 < $V-R$ < 2.0) corresponds to the full range of colors in Fig. 8. The heavy filled circles are three AGB variables from the LMC cluster NGC 1783. The heavy open circles are AGB variables from the LMC cluster NGC 1783.](image-url)
Frogel, Mould, & Blanco (1990), and spectral types are from Mould et al. (1989). The spectroscopic metallicity of NGC 1783 is $[\text{Fe/H}] = -0.5$ dex (Cohen 1982). NGC 1898 is an ancient LMC cluster located in the bar (Olsen et al. 1998). The spectroscopic metallicity is $[\text{Fe/H}] = -1.4$ dex (Olszewski et al. 1991). Finding charts, near-infrared photometry, and $m_{\text{bol}}$ for these AGB stars are given by Aaronson & Mould (1985).

The AGB in Figure 7 shows a rich morphology. We draw attention to the concentration of AGB variables lying near the tip of the RGB. Offset from this concentration are two extended sequences, both running approximately parallel to the $W_{2.0} = 13.5$ mag line. The fainter sequence is the most prominent. The variables from NGC 1783 lie along the brighter sequence, showing that the variables on the brighter AGB sequence are consistent with an “intermediate age” LMC bar population (like NGC 1783). The variables from NGC 1898 lie in the concentration near the tip of the RGB, and not along either of the extended sequences. We conclude that the concentration of AGB variables near the RGB tip is consistent with an old and metal-poor LMC bar population (like NGC 1898).

Figure 8 shows four $W_{2.0} = V - 2.0(V-R)$ luminosity functions. Three of these histograms represent different color cuts through the AGB variables shown in Figure 7. The dotted line represents $0.8 < V-R < 1.1$, the solid line with open circles shows $1.1 < V-R < 1.4$, and the solid line with filled circles shows $1.4 < V-R < 2.0$. These $W_{2.0}$ luminosity functions have bin sizes of 0.1 mag; the left axis gives the number of stars in each bin. The $W_{2.0}$ luminosity function for 266 known carbon stars (Blanco, McCarthy, & Blanco 1980) is indicated with the hatched histogram (the bin size is also 0.1 mag). The number of carbon stars is given on the right axis. We mark $W_{2.0} = 13.5$ mag with an arrow, which corresponds to the thin solid line in Figure 7.

First, consider the 9M CMD stars in the two histograms with the reddest colors (open circles and solid circles in Fig. 8). These clearly show the bimodality of the AGB. We note that the ratio of the number of stars on the faint AGB sequence to those on the bright AGB sequence is higher in the intermediate color-cut histogram (open circles) than in the reddest color-cut histogram (filled circles), an effect primarily due to the relatively more rapid decrease in the number of stars along the faint sequence. The distribution of carbon stars rises sharply at $W_{2.0} \approx 13.5$ mag, coincident with the rise in the number of AGB variables. We do not know the completeness of this sample of carbon stars identified in the 9M CMD. However, if the true carbon star luminosity function does not rise dramatically (i.e., a second peak in $W_{2.0}$), we conclude that the majority of stars on the faint AGB sequence and those concentrated near the tip of the RGB (dotted line) are likely

### Table 4

**LMC Cluster AGB Variables**

| MACHO ID    | ID | $\langle P \rangle$ | $\langle R \rangle$ | $\langle V \rangle$ | $K$ | $J-K$ | $m_{\text{bol}}$ | Spectral Type |
|-------------|----|---------------------|---------------------|---------------------|-----|-------|-----------------|---------------|
| **NGC 1783** |    |                     |                     |                     |     |       |                 |               |
| 55.3008.13... | LE 1 | 410                | 15.77               | 17.55               | 10.26 | 1.93   | 13.47           | C             |
| 55.3008.12... | LE 2 | 46.3               | 15.06               | 16.22               | 11.27 | 1.13   | 14.19           | S4/2          |
| 55.3129.16... | LE 3 | 307                | 15.07               | 16.41               | 10.37 | 1.60   | 13.41           | C             |
| 55.3129.12... | LE 4 | 128                | 15.06               | 16.22               | 11.10 | 1.09   | 13.98           | S5/2          |
| 55.3129.14... | LE 5 | 120                | 15.03               | 16.09               | 11.23 | 1.09   | 14.11           | M3            |
| 55.3008.14... | LE 6 | 62.4               | 15.07               | 16.11               | 11.34 | 1.08   | 14.20           | M3            |
| 55.3129.13... | LE 9 | 270                | 15.25               | 16.56               | 10.93 | 1.11   | 13.83           | S5/3          |
| 55.3129.15... | LE 15 | 63                 | 14.94               | 15.88               | 11.78 | 1.00   | 14.49           | M1            |
| **NGC 1898** |    |                     |                     |                     |     |       |                 |               |
| 78.5857.27... | AM 6 | 51.5               | 15.30               | 16.06               | 12.38 | 0.94   | 15.03           | M?            |
| 78.5857.25... | AM 4 | 46.1               | 15.32               | 16.20               | 11.71 | 1.08   | 14.62           | M?            |
| 78.5857.38... | AM 1 | 35.8               | 15.50               | 16.24               | 12.58 | 0.98   | 15.32           | M?            |

* Identifications from Lloyd Evans 1980 and Aaronson & Mould 1985.
oxygen-rich, not carbon-rich. Note that the AGB variables in the clusters are mostly located along one or the other AGB sequence. This suggests how AGB stars from different-age populations evolve through the 9M CMD. Intermediate-age populations produce both carbon- and oxygen-rich AGB stars, but very old populations produce only oxygen-rich AGB stars. Surveys for carbon stars in clusters tell us that the characteristic transition age for a stellar population to begin producing carbon stars increases with decreasing metallicity. This transition age may be ~3 Gyr for solar metallicity, but it is much older for low metallicities, i.e., ~10 Gyr at [Fe/H] ~ 1.5 dex (Bessell, Wood, & Lloyd Evans 1983). No ancient LMC clusters have carbon stars (frogel et al. 1990). Therefore, if we assume that the two extended AGB sequences arise from distinct populations and assume that the population responsible for the faint AGB sequence does not produce carbon stars, then if the AGB variables on the faint sequence are metal-poor, they are likely quite old.

In summary, most of the highly evolved AGB stars in the 9M CMD are variable. Some of the AGB variables concentrate near the tip of the RGB. These stars are consistent with being old and metal-poor, like AGB variables in the cluster NGC 1898. Offset from this concentration are two extended AGB sequences, both running approximately parallel to the vector $W_{3V} = V - 2.0(V - R)$. The AGB variables on the bright sequence are consistent with being ~2 Gyr old and having a metallicity [Fe/H] ~ −0.5 dex, like AGB variables in NGC 1783. The majority of AGB variables on the faint sequence and in the concentration near the tip of the RGB are likely oxygen-rich, not carbon-rich. This may imply that they are quite old, if they are fairly metal-poor. We caution that the latter inference depends on the completeness of the Blanco et al. (1980) carbon star survey data in the MACHO fields analyzed here.

Stellar evolution theory relies heavily on observations of AGB stars in the LMC to tune various free parameters in AGB star models. For example, the models are tuned to reproduce the carbon star luminosity function in the LMC and SMC (Marigo, Girardi, & Chiosi 1996). Therefore, logical inferences from these models regarding the detailed makeup of the LMC stellar populations would be disconcerting circular. However, we note that our discussion about which stellar populations produce carbon stars, and what path of AGB evolution is followed through the 9M CMD, is consistent with extant theory. It would be particularly interesting to use the numbers of AGB stars along the extended sequences to derive stellar evolutionary lifetimes and test the AGB models. In addition, analysis of the pulsation properties of these many AGB variables will be very important to the accurate interpretation of their ages and metallicities.

### 5.2. The RR Lyrae Stars

Figure 9 is the Bailey period-amplitude diagram, which shows the RRab's from the 9M CMD (small open circles), those from NGC 1898 (heavy circles), and those from NGC 1835 (heavy triangles). In the inset, we plot RRab's from the Galactic globular cluster M3 (Kaluzny et al. 1998). The axes of the inset are the same as those in the main panel. We define a reduced period,

$$\log \text{PA} = \log P + 0.15A_V\;,$$

(1)

and calculate the median value for M3, log $\text{PA}_{M3} = -0.1116$. This line is plotted in the inset, and again in the main panel. The median reduced period of the RRab's in the 9M CMD is log $\text{PA}_{9M} = -0.1110$. Although the 9M CMD RRab's define a prominent ridgeline, their distribution is asymmetric. They form a "cloud" to the right of the ridgeline, with larger amplitudes and longer periods.

The reduced period correlates with metallicity. We derive the following calibration using high-quality $V$-band light curves of RRab's in the Galactic globular clusters M3, M5, and M15. Data for M5 are assembled from Reid (1996), M3 from Carretta et al. (1998), and M15 from Silbermann & Smith (1995), from which we calculate median reduced periods: log $\text{PA}_{M5} = -0.1352$, log $\text{PA}_{M3} = -0.1117$, log $\text{PA}_{M15} = -0.0646$. We adopt metallicities of [Fe/H] = −1.4, −1.6, and −2.1 dex taken from Sandquist et al. (1996), Carretta et al. (1998), and Silbermann & Smith (1995) for M5, M3, and M15, respectively. These yield a calibration,

$$[\text{Fe/H}] = -8.85 \log \text{PA} - 2.60\;.$$

(2)

As a check of this calibration, we assemble $A_V$, log $P$, and spectroscopic [Fe/H] data for 86 nearby Galactic field RRab's from Jurcsik & Kovács (1996). We shift the Jurcsik & Kovács metallicity scale by −0.2 dex to place it on the scale of our clusters. Our calibration predicts the metallicity of these RRab's with an accuracy of $\sigma_{[\text{Fe/H}]} = 0.31$ per star.

The median metallicity of RRab's in the 9M CMD is [Fe/H] = −1.6 dex, which agrees with the mean spectroscopic metallicity of 15 field RRab's presented by Alcock et al. (1996), $[\text{Fe/H}] = -1.7 \pm 0.2$ dex on the scale of Zinn & West (1984). For the NGC 1898 and NGC 1835 cluster RRab's, we find $[\text{Fe/H}] = -1.58 \pm 0.10$ and −1.95 ± 0.09 dex, respectively (errors are statistical only). Our metallicity for NGC 1835 agrees with the spectroscopic value.
follows: The median color and brightness of the RR branch — fiducial marks with CMD data for one of three M1986; Sarajedini 1994). Each panel in Figure 10 the dereddened colors of their giant branches yield accurate which we have neglected here.

The RRab's in the LMC bar define a prominent ridgeline in the Bailey diagram similar to the ridgeline defined by RRab's in M3, which we interpret as indicating similar mean metallicities. The 9M CMD RRab's with higher amplitudes and longer periods are consistent with a tail in the metallicity distribution to lower values. Observational evidence strongly suggests that some RR Lyrae stars in the LMC have metallicities as low as —2.3 dex (Walker 1992; Alcock et al. 1996). However, we caution that the distribution of RRab's in the Bailey diagram is subject to evolutionary effects, and perhaps also population effects (i.e., age), which we have neglected here.

5.3. The Giant Branch and AGB Bump

When cluster ages are the same to within a few gigayears, the dereddened colors of their giant branches yield accurate relative metallicities (Sandage & Smith 1966; Da Costa & Mould 1986; Sarajedini 1994). Each panel in Figure 10 compares the 9M CMD horizontal branch and the giant branch fiducial marks with CMD data for one of three different clusters. The 9M CMD fiducial marks are as follows: The median color and brightness of the RRab's are indicated with an open triangle, the red HB clump with a large open circle, and the AGB bump with a smaller open circle. Dash marks show the giant branch and the tip of the RGB.

In the top panel of Figure 10, we plot the CMD of M5 (Sandquist et al. 1996). In the middle panel, we plot the CMD data for M3 (Ferraro et al. 1997). In these two cases, we have transformed their photometry using $V - R = 0.557(B - V) + 0.019$, which follows from Alcock et al. (1997a; see also Bessell 1990). Next we calculate shifts to match the mean magnitudes and colors of the cluster RRab's with the 9M CMD fiducial mark. For M5, we assembled $B - V$ data for 11 RRab's from Storm, Carney, & Beck (1991; see also Sandquist et al. 1996) and calculate $\langle B - V \rangle_{M5} = 0.292$ and $\langle V \rangle_{M5} = 15.057$, yielding shifts of $\Delta V_{M5} = 0.13$ and $\Delta V_{M5} = 4.39$ to place this cluster “in the LMC.” Using the sample of M3 RRab's from Carretta et al. (1998), we find $\langle B - V \rangle_{M3} = 0.376$ and $\langle V \rangle_{M3} = 15.688$ and shifts of $\Delta V_{M3} = 0.08$ and $\Delta V_{M3} = 3.76$. In the bottom panel of Figure 10, we show the SMC cluster NGC 411, which is 1.5 Gyr old and has a metallicity of [Fe/H] = —0.7 dex (Alves & Sarajedini 1999). With the NGC 411 data transformed to $V - R$ as above, they are shifted $\Delta V_{N411} = 0.06$ and $\Delta V_{N411} = 0.22$ to match the location of the 9M CMD red HB clump (the fit is by eye).

Figure 10 shows that the color of the giant branch in the 9M CMD is well matched by the giant branch of M3. If the difference in color between the RRab's and the giant branch, $\delta(V - R)_{RRab}$, depends only on metallicity, this may imply that the metallicity of the old field population in the bar is similar to that of M3. However, this interpretation ignores the influence of the second parameter (Sandage & Wildey 1967; Stetson et al. 1996) and the finite width of the fundamental-mode instability strip (Bono, Caputo, & Santolamazza 1997). Although we avoided making numerous assumptions about the distance and reddening to the LMC and these clusters by registering the RRab's metallicity and the second parameter are degenerate in this comparison.

Consider $\delta(V - R)_{RRab}$ for the classical second-parameter pair of Galactic globular clusters, M3 and M13. We assembled the photometry of Guarnieri, Bragaglia, & Fusi Pecci (1993) for M13 and the photometry of Pike & Meston (1977) for the one RRab in this cluster. We find $\delta(V - R)_{RRab} = 0.36$ for M13, which compares with $\delta(V - R)_{RRab} = 0.233$ for M3. Using the HB morphology index 25 of Lee et al. (1994), these clusters have $(b - r)/(b + v + r) = +0.08$ and $+0.97$, respectively (Catelan & de Freitas Pacheco 1995). The cluster with the redder HB morphology has redder RRab's (although M13 has only one RRab). For comparison, a spline fit to the giant branch fiducial marks yields $\delta(V - R)_{RRab} = 0.207$ mag for the 9M CMD, which is close to the value for M3.

Figure 10 also shows that the giant branch and red HB clump in the 9M CMD are consistent with an NGC 411—like population. An “intermediate age” population in the LMC bar older than ~1.5 Gyr and more metal-rich than [Fe/H] = —0.7 dex is unlikely to contribute significantly to the 9M CMD giant branch. This is somewhat more metal-

\[25\] This index is defined as the number difference between blue (b) and red (r) HB stars, divided by the total number of HB stars, including the number of RR Lyrae variables (c). We use lowercase to distinguish from magnitudes, i.e., $B/V/R$. The index runs from —1 to 1 for completely red and blue HBs, respectively.
poor (and younger) than often suggested for the intermediate-age population in the LMC but is consistent with other recent analyses (e.g., Bica et al. 1998). It is unlikely that an NGC 411–like population accounts for all of the red HB clump stars in the 9M CMD unless the main-sequence luminosity function analysis of Hardy et al. (1984) is seriously in error. Finally, we note that an M3-like HB is not responsible for the bright red HB clump in the 9M CMD.

We have drawn arrows in Figure 10 indicating the AGB bumps in M3 and M5. The cluster AGB bumps have similar brightnesses to the AGB bump in the 9M CMD, which supports our identification of this feature (see also Gallart 1998) and our association of the AGB bump with an old and metal-poor population. However, the AGB bump in M3 is distinctly bluer than the AGB bump in the 9M CMD. At a constant metallicity, the AGB bump will appear redder for progressively more massive HB progenitor stars, until the AGB bump lies near the Hayashi line. At this point, even more massive HB stars will populate similar-color AGB bumps, but with higher luminosities (Castellani, Chieffi, & Pulone 1991). The AGB bump for a population as young as NGC 411 would be ~0.7 mag brighter than the AGB bump in the 9M CMD (Alves & Sarajedini 1999). In summary, the brightness of the AGB bump in the 9M CMD associates this feature with an old population, while the color of the AGB bump strongly suggests a red HB morphology.

5.4. The Horizontal Branch and AGB Bump

In Figure 11, the 9M CMD fiducial marks for the RRab's, red HB clump, the AGB bump, and giant branch are plotted with the same symbols used in Figure 10 (except that the red HB clump and AGB bump are now filled

![Fig. 11. Fiducial marks for the horizontal branch (RRab's and red HB clump), giant branch, and AGB bump (horizontal lines) compared with a sample of field RRab (small open circles) and BL Herculis variables (large open circles) in the 9M CMD. Two HB model sequences are shown as solid lines. Theoretical edges of the instability strip are shown as dashed lines. See text for details.](image)

We also plot the $M = 0.70$ and $0.75 M_\odot$, $z = 0.0004$, scaled-solar HB models of Castellani et al. (1991) in Figure 11 with solid lines. The lower mass model begins on the zero-age HB near the center of the instability strip (dashed lines). Both of the HB model tracks are truncated at their mean AGB bump luminosity. The color-temperature calibration is the same analytic approximation to the Bertelli et al. (1994) isochrone data used throughout this paper. In this analysis, we shift the endpoints of these two HB model tracks to match the location of the AGB bump in the 9M CMD, which recalibrates color and temperature to account for the LMC's distance and reddening. We show the prediction of Bono et al. (1997) for the fundamental blue and red edges of the instability strip (IS), for a mass $M = 0.725 M_\odot$. The good agreement between the theoretical IS and the distribution of these 9M CMD variables over several magnitudes in brightness strongly supports our color-temperature calibration, as well as the theoretically predicted IS for the fundamental-mode pulsators (Bono et al. 1997).

Figure 11 shows that the 9M CMD field RRab's lie very close to the red edge of the IS. The tail of RRab's fainter and redder than the theoretical IS is likely due to differential reddening in the LMC bar. The median brightness and color of the 9M CMD field RRab's are consistent with the mean color and brightness of RRab's in NGC 1898, and significantly redder than the mean color and brightness of RRab's in NGC 1835. The HB morphology indexes for NGC 1835 and NGC 1898 are $(b - r)/(b + v + r) = +0.48 \pm 0.05$ and $-0.08 \pm 0.10$, respectively (Olsen et al. 1998). As for the case of M3 and M13, these relative mean RRab colors correlate with the overall HB morphology.\(^{25}\) Thus, we infer an HB morphology for the old and metal-poor field population in the 9M CMD that is at least “as red” as the HB in NGC 1898. Specifically, this comparison suggests an HB morphology index of $(b - r)/(b + v + r) \leq 0$.

Next we consider the HB morphology index for the two HB models shown in Figure 11. For the $M = 0.70 M_\odot$ model, the time spent in the IS is ~90 Myr, while the time spent in the AGB bump is ~4 Myr. This model predicts a ratio of AGB bump to HB stars $a/(b + v + r) \approx 0.05$. This model would correspond to the case of $(b - r)/(b + v + r) \approx 0$ because the model track begins near the middle of the IS. The $M = 0.75 M_\odot$ model predicts ~22 Myr in the IS, ~65 Myr redward of the IS, and ~4 Myr in

\(^{25}\) BL Herculis stars are related to the W Virginis (type II Cepheid) and RV Tauri variables (Alcock et al. 1998).

\(^{26}\) The LMC clusters NGC 1898 and NGC 1835 have different metallicities, which is not the case for M3 and M13. Thus, the LMC clusters are not necessarily showing second-parameter effects.
the AGB bump. This model also predicts $a/(b + v + r) \approx 0.05$. If we assume $b < v + r$, the $M = 0.75$ model predicts $r/v \approx 3$, $a/v \approx 0.2$, and $(b - r)/(b + v + r) \approx -0.75$. This is a plausible HB morphology for this model given the red color of the zero-age HB and assuming a small HB mass dispersion, as used for model HB constructions (e.g., Lee et al. 1994). In summary, the $M = 0.70$ model should have $(b - r)/(b + v + r) \approx 0$ while the $M = 0.75$ model should have $(b - r)/(b + v + r) \approx -0.75$.

Assuming that our RRab catalog is 50% complete, correcting for the six excluded fields (22/16), and accounting for type “c” variables with a ratio of RRab/RRc = 3/2 (Kinman et al. 1991), we estimate the total number of RR Lyrae stars in the 9M CMD to be $v \approx 15,000$. We count the number of AGB bump stars as follows: First, we fit a power law to a differential luminosity function of the giant branch (the number of stars with $V - R > 0.4$ per 0.02 mag bin, and with $V \sim 17$). We extrapolate the fit to fainter magnitudes and subtract it from the data. This reveals a clear “excess” of stars on the giant branch totaling $a \approx 22,000$ stars. The observed ratio of AGB bump to RR Lyrae stars in the 9M CMD is $a/v \sim 1.5$, which is nearly 8 times the $M = 0.75$ model prediction.

Adopting the ratio of AGB bump to HB stars $a/(b + v + r) \approx 0.05$ from the models and assuming $b < v + r$, the ratio $a/v \sim 1.5$ yields $r/v \approx 30$, or $(b - r)/(b + v + r) \approx -0.97$. We compare this HB morphology index with those of ancient LMC clusters in the next subsection. Scaled by the number of RR Lyrae variables, this HB morphology predicts $r \approx 455,000$ red HB clump giants, which is probably uncertain by a factor of 2. In any case, $r$ is a very large number. Finally, we estimate the total number of red HB clump stars in the 9M CMD to be $r \sim 900,000$ (the measurement procedure was similar to that described for the AGB bump). By inspection of Figure 6, we conclude that $\sim 455,000$ red HB clump giants associated with the old and metal-poor field population could only lie under the main peak of the observed red HB clump, which therefore likely indicates their mean brightness.

5.5. Summary and Discussion of Old Populations

The field of the LMC bar is composed, in part, of an old population that produces RR Lyrae variable stars. This population appears to have a metallicity of $[\text{Fe/H}] = -1.6$ dex, as evidenced by spectroscopy of RRab stars (Alcock et al. 1996), the distribution of RRab’s in the Bailey diagram, and the color of the giant branch in the 9M CMD. In some respects, the Galactic globular cluster M3 is a satisfactory template for this old and metal-poor population. However, M3 does not have enough bright red HB clump stars, and its AGB bump is bluer than the AGB bump in the 9M CMD. It is likely that some of the bright red HB clump stars in the LMC bar represent an intermediate-age population. We suggest that the 1.5 Gyr-old, $[\text{Fe/H}] = -0.7$ dex cluster NGC 411 is a suitable template for this population. The AGB bump for an NGC 411-like population would be redder than the AGB bump in M3, but much brighter than the AGB bump in the 9M CMD. Thus, while a simple model for old populations in the 9M CMD might consist of two components similar to the clusters M3 and NGC 411, we find some discrepancies in detail.

The highly evolved AGB in the 9M CMD shows three prominent features: (1) a concentration of stars near the tip of the RGB consistent with an old and metal-poor population like NGC 1898, (2) an extended faint sequence that lacks carbon stars, and (3) an extended bright sequence that runs parallel in the 9M CMD to the more prominent faint sequence. The bright sequence is consistent with an intermediate-age population like NGC 1783 (or NGC 411). The population associated with this bright AGB sequence may account for the majority of LMC carbon stars. We suggest that the multiple AGB sequences in the 9M CMD represent discrete old populations in the LMC bar. The concentration of stars near the tip of the RGB and those on the faint sequence may be old and metal-poor, while those on the bright AGB sequence may be significantly younger, and relatively more metal-rich. However, inferring the nature of stellar populations from the AGB is difficult because the predictions of stellar evolution theory are uncertain for these highly evolved stars, and few AGB stars are observed in suitable template clusters.

There are several indications the old and metal-poor field population in the 9M CMD has a red HB morphology: the AGB bump is quite red, the field RRab’s lie close to the red edge of the instability strip, and the number ratio of AGB bump to RR Lyrae stars is quite large. For an HB morphology of $(b - r)/(b + v + r) \approx -0.97$, the ratio $a/v \approx 1.5$ associates $\sim 50\%$ of the red HB clump stars in the 9M CMD with an old and metal-poor population (the same population responsible for the RR Lyrae variables).

The red HB clump giants in the 9M CMD are distinctly brighter than the red HB stars in M3 relative to the RR Lyrae stars, which may suggest the relative youth of the former. If we adopt a canonical brightness difference between RRab’s and a red HB of $-0.1$ mag, as found for globular clusters (Fusi Pecci et al. 1996), then the red HB clump in the 9M CMD is about $-0.2$ mag brighter than a typical, ancient red HB. If ancient clusters are $\sim 13$ Gyr old, theoretical calibrations of the age-dependent red HB clump luminosity predict that the old and metal-poor field population in the bar is $\sim 5$ Gyr old (Alves & Sarajedini 1999; Sarajedini et al. 1995). A systematic uncertainty in this estimate may arise from the possible coupling of age and metallicity effects on the theoretical red HB clump luminosity-age calibration, the nature of which is poorly constrained by observation.

In addition to the brightness of the red HB clump, the inferred HB morphology index of $(b - r)/(b + v + r) \lesssim -0.97$ may also indicate the relative youth of the metal-poor field population. For $[\text{Fe/H}] = -1.6$ dex, the Lee et al. (1994) models predict that the field population is at least $\sim 2$ Gyr younger than the oldest LMC clusters (Olsen et al. 1998). It is worth noting the magnitude of the age difference inferred from the Lee et al. models depends sensitively on a variety of theoretical assumptions (Catelan & de Freitas Pacheco 1993). Nevertheless, the weight of evidence supports a scenario whereby the majority of old and metal-poor field stars in the bar formed after the oldest LMC clusters.

The brightness difference between the red HB clump and AGB bump in the 9M CMD, $AV_{\text{clump}} \approx -0.8$ mag, does not agree well with observations of old and metal-poor
clusters (e.g., Ferraro et al. 1999) or with theoretical predictions. If the old and metal-poor field population is as young as ~5 Gyr, the disagreement with theory is even worse (Alves & Sarajedini 1999). However, we find that the brightness difference between the AGB bump and RRab's in the 9M CMD is in good agreement with observations of globular clusters and with theory. Therefore, while the brightnesses of the RRab's and AGB bump conform to expectations, the red HB clump appears too bright.

To review, we find that the brightness difference between the AGB bump and RR Lyrae stars is consistent with the luminosity predictions of stellar evolution theory for an old and metal-poor population. The observed ratio of AGB bump stars to RR Lyrae variables and the lifetime predictions of stellar evolution theory lead us to associate a significant fraction of the observed red HB clump giants with this old and metal-poor population, which in turn allows us to infer their mean brightness. However, these red HB clump giants appear to be brighter relative to the AGB bump and RR Lyrae stars than predicted by stellar evolution theory. We have argued that the old and metal-poor field population is probably younger on average than the truly ancient LMC clusters. However, this only worsens the disagreement with theory.

Have we incorrectly associated a large fraction of the bright red HB clump giants in the 9M CMD with an old and metal-poor population? One possibility is that an RGB bump of an intermediate-age population may also populate the region of the giant branch near the AGB bump in the 9M CMD. A young RGB bump like this may have been observed in NGC 411, and it is predicted by theory (Alves & Sarajedini 1999). If we have overestimated the number of AGB bump stars, we would expect a smaller number of old, faint red HB clump giants in the 9M CMD (these old, faint red HB clump giants may be overwhelmed by a much larger number of young red HB clump giants). However, this scenario probably requires far too many ~1.5 Gyr–old stars populating a very bright RGB bump (Hardy et al. 1984). In addition, we do not observe a bright AGB bump, which would be expected if a ~1.5 Gyr population dominated the 9M CMD giant branch.

Are the HB models missing a parameter other than age that would produce bright red HB clumps in old and metal-poor populations? In this case, the hypothesized parameter would not appear to affect the luminosities of the AGB bump or RR Lyrae stars. A second possibility is that the luminosity of the red HB clump has a very strong dependence on age in metal-poor populations (i.e., a strong coupling of the age and metallicity dependencies of the red HB clump luminosity). This trend is seen in the HB models of Sarajedini et al. (1995), but the effect is probably too small to account for the ~0.2 mag found here. In either of these scenarios, the old and metal-poor field population in the LMC bar may still be younger than the oldest clusters, but the currently available HB models would not yield accurate estimates of the age difference. Finally, we note that the inferred brightness of these old and metal-poor red HB clump giants follows directly from the lifetime and luminosity predictions of stellar evolution theory for the AGB bump. The possibility that these predictions are flawed seems unlikely given the good agreement between the observed and theoretically predicted values of $\Delta T_{\text{bump}}^{\text{RRab}}$. New theoretical models and further observational detections of AGB bumps in clusters might help clarify this situation.

6. THE OLD LMC DISK

We conclude this work with a brief examination of the spatial density profile of RRab stars. In Figure 12, we plot the logarithm of the number of RRab's per square degree as a function of true LMC radius. We assume the LMC disk is inclined ($i = 35^\circ$), with a line of nodes running north-south and a center near the optical center (Westerlund 1997). MACHO data for 16 fields are shown as filled circles (no corrections for completeness). We plot data for six additional fields from Kinman et al. (1991) as open circles (error bars are $\sigma = 25^{1/2}$). A fit to all of the data (dotted line) and a fit excluding the Kinman et al. (1991) data (solid line) are also shown. We report a radial scale length of $\Lambda = 1.6 \pm 0.1$ kpc (statistical error only), which is the same as derived from surface brightness data (Bothun & Thompson 1988).

For the purposes of this work, we need only illustrate the good fit of the exponential profile. Fits with analytic King (1962) models (not shown) are worse than the exponentials. The King models tend toward vanishingly small core radii and are poor representations of the Kinman et al. (1991) data points. Future work might include a more thorough exploration of the model parameter space (i.e., accounting for uncertainties in the LMC center, inclination, and line of nodes), and corrections for RR Lyrae completeness as estimated from artificial-star tests (Alcock et al. 2000). In any case, the data shown here strongly suggest that the majority of the old and metal-poor LMC field stars lie in a disk, not in a spheroid.

A lower limit for the age of the LMC disk is set by the age of the youngest RR Lyrae variables, which may be ~9 Gyr, following the discussion of Olszewski et al. (1996). An upper limit is set by the old and metal-poor LMC field population forming after the oldest LMC clusters (as we have argued.
here) and the absolute ages of those clusters. We suggest a plausible range of \(9 \text{ Gyr} \leq \tau_{\text{disk}} \leq 12 \text{ Gyr} \) for the formation epoch of the LMC disk. The Milky Way disk is estimated to be \(\sim 9 \text{ Gyr} \) old (Leggett, Ruiz, & Bergeron 1998; Salaris & Weiss 1998) from white dwarf cooling times and the ages of disk clusters. Therefore, we conclude that the LMC disk is quite old and may have formed contemporaneously with the Milky Way disk.

7. CONCLUSION

We have presented a 9 million star color-magnitude diagram of the LMC bar. By assembling a variety of theoretical results, carefully selected samples of MACHO-discovered variable stars, and extant observational data for clusters (Galactic, LMC, and SMC), we have investigated the stellar populations of the LMC bar. After an examination of the young LMC stellar populations, we turned our attention to the less well understood old stellar populations. Regarding the old and metal-poor LMC field population, we find a typical metallicity of \([\text{Fe}/\text{H}] = -1.6 \text{ dex}\) and argue that this population likely formed a few gigayears after the oldest LMC clusters. We showed that this population lies in a disk. Our results are consistent with isochrone-dependent parametric studies of stellar populations in the LMC disk (Geha et al. 1998), which do not rule out a substantial \(\sim 10 \text{ Gyr} \) old and metal-poor population. We are also consistent with recent suggestions that the LMC bar harbors a relatively larger component of old stars than the outer regions of the LMC disk (Holtzman et al. 1999).

As emphasized by others (Butcher 1977; Hardy et al. 1984), the LMC disk appears to have a different star formation history from the solar neighborhood Milky Way disk. The key difference hinges on a major “event” of star formation, which apparently took place a few gigayears ago in the LMC. The details of this event and the prior evolutionary history of the LMC are the subject of some debate (Bertelli et al. 1992; Olszewski et al. 1996; Elson, Gilmore, & Santiago 1997; Geha et al. 1998; Holtzman et al. 1999). We have suggested that the bimodal AGB in the 9M CMD arises from discrete old populations, which is consistent with the occurrence of a major star formation event in the LMC. These discrete populations may be due to either a distinguishing “dip” in the star formation rate prior to the event or a “burst” coincident with the event. In addition, we showed that the red HB clump giants, giant branch, and AGB in the 9M CMD are consistent with the so-called burst population’s having a metallicity and age similar to the clusters NGC 411 and NGC 1783, which is somewhat younger and more metal-poor than others have suggested.

Although our results are consistent with the occurrence of a star formation event a few gigayears ago in the LMC, we do not constrain the intensity of the event. Consider the following simple calculation: If \(\sim 50\%\) of the red HB clump giants are old and metal-poor, we assume that the remaining \(\sim 50\%\) are born in the event/burst. Adopting equal red HB clump lifetimes (Vassiliadis & Wood 1993), a Salpeter (1955) initial mass function, and representative initial masses of 0.8 and 1.6 \(M_\odot\) for the old and intermediate-age populations, respectively, the roughly equal numbers of red HB clump giants from the two populations imply relative star formation rates of \(\text{SFR}_{1.6}/\text{SFR}_{0.8} \propto (0.8/1.6)^{-2.55} \sim 5\). If the number of old and metal-poor clump giants is uncertain by a factor of \(\sim 2\), and the total number of red HB giants is fixed, the ratio of star formation rates may range from 1 to 10.

Finally, we have shown that the old and metal-poor field population in the LMC bar lies in a disk. This contradicts suggestions that the LMC disk formed only a few gigayears ago, during the star formation event (Hardy et al. 1984; Elson et al. 1997). Instead, we find that the LMC disk is at least as old as the Milky Way disk, \(\tau_{\text{disk}} \sim 9 \text{ Gyr}\). The Milky Way and the LMC have absolute visual magnitudes of \(M_V \approx -20.4\) and \(-18.4\), and masses of \(M \approx 6 \times 10^{10}\) and \(3 \times 10^{10} M_\odot\), respectively (Bahcall & Soneira 1980; de Vaucouleurs 1955; Bothun & Thompson 1988; Kim et al. 1998). Thus, we conclude that very different mass galactic disks may form at similar and quite early cosmological epochs, a new clue that may help constrain the physical processes governing their formation. It is interesting to note that the kinematics of the ancient LMC clusters do not reveal a halo, but rather a disk (Freeman, Illingworth, & Oemler 1983). The existence of a bona fide spheroidal or halo stellar population in the LMC is not ruled out by our analyses. The metal-poor RR Lyrae stars in the tail of the metallicity distribution are likely good candidates for this LMC population. Identifying this population will be important for probing the pre-disk/collapse era of galaxy evolution in the LMC (Eggen, Lynden-Bell, & Sandage 1962).

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