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The MACHO Project LMC Variable Star Inventory: Classical Cepheids, AGB Variables, and the Nine Million Star Color-Magnitude Diagram

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Abstract.
We measure the ratio of $\sim 5M_\odot$ blue and red LMC supergiants (representative of classical Cepheids) using the MACHO Project's 9 million star color-magnitude diagram (9M CMD) of the LMC bar. We find $b/r = 0.39$, which favors the Z=0.008, $5M_\odot$ theoretical model of Schaerer et al. (1993) over that of Fagatto et al. (1994). Next, we examine the low mass (old) and low metallicity LMC field population (Pop. II). Features in the 9M CMD and properties of LMC field RRab variables are consistent with a mean iron abundance of [Fe/H] ≈ -1.5 dex for this population. Newly discovered post-HB/early-AGB Pop. II variables are identified in order to delineate the instability strip (IS). Good agreement with the theoretical IS of Bono et al. (1997) is found. We then compare the field RRab with newly identified RRab variables in the LMC clusters NGC 1898 and NGC 1835. We find the mean colors of these cluster RRab lie near the red and blue edges of the IS, respectively, which is similar to their respective (overall) red and blue HB morphologies. Since the field RRab lie on the red side of the IS, we infer the LMC field Pop. II is likely to have a red HB morphology.

1. Introduction

MACHO Project two-color photometric data have been calibrated to Kron-Cousins V and R with a precision $\sigma_V = \sigma_R = 0.020$ mag for $\sim$9 million stars in and nearby to the LMC bar (Alves 1998; Alcock et al. 1999a). We use the composite "9 million star color-magnitude diagram" (9M CMD) along with our

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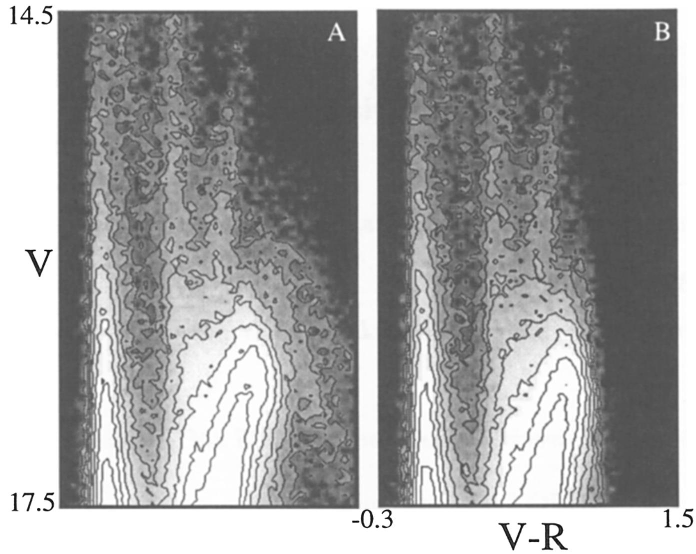

Figure 1. Log-scaled Hess diagrams representing **(A)** 261805 LMC stars with $(V - R) = -0.3$ to 1.5 mag, $V = 17.5$ to 14.5 mag, and **(B)** the same diagram but with 35169 candidate variable stars removed. The variable stars are defined by poor fits to constant brightness lightcurves. Intensity and contours (1.0 to 2.5 dex in 0.25 steps) indicate the logarithmic surface density of stars (no. per ~10 sq. deg. and per 0.03 mag square color-mag bin).

photometric lightcurve data to make new tests of stellar evolution theory and to study LMC stellar populations.

Figure 1 shows the bright end of the 9M CMD. The prominent red giant branch (RGB) and asymptotic giant branch (AGB; see also Alves et al. 1998) extend up to $V \sim 16.5$ mag. The striking difference between panels is on the AGB where virtually all stars appear to be variables. The bright and nearly vertical plumes are (from blue to red): the upper main sequence, Galactic foreground disk stars, and red supergiants (SGs). Careful examination reveals that many stars lying on the red edge of the upper-main sequence are also variables. The blue SGs lie between the upper main sequence and foreground disk star plumes.

2. Classical Cepheids: the LMC Blue/Red Supergiant Ratio

In this section, we summarize our measurement of the blue to red supergiant ratio in the 9M CMD and compare with theory. We report the following ridge line sequences for blue (b) SGs: $(V - R) = 0.09$, 0.18, 0.30, and 0.39, and for red (r) SGs: 0.76, 0.71, 0.66, and 0.64 at $V = 14.75$, 15.25, 15.75, and 16.25 mag, respectively. After consideration of the foreground stars, and shifting $z = 0.008$, $5M_\odot$ model sequences to match these SG ridge lines, we count b/r SGs in $\Delta(V - R, V) = 0.2$, 0.5 mag rectangular "apertures" centered at $(V - R, V)$

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= 0.18, 15.25 and 0.66, 15.75. The average ratio of non-variable $\sim 5M_\odot$ LMC SGs is $b/r = 0.39$, $(b+r) = 2869$. Adopting the Cepheid instability strip at $logT = 3.76$ to 3.70 (cf. Alcock et al. 1999b) to demark the non-variable b and r SG phases, the $z = 0.008$, $5M_\odot$ model of Fagatto et al. (1994) yields $b/r = 0.92$ while the model of Schaerer et al. (1993) yields $b/r = 0.34$. The predicted ratios of Cepheids to non-variable SGs are $c/(b+r) = 0.08$ and 0.06, respectively. A count of MACHO-discovered LMC Cepheids in a parallelogram in the CMD connecting the b & r apertures yields $c = 300$, $c/(b+r) \approx 0.10$. We note that these MACHO-discovered LMC Cepheids show an excess at $\sim 5M_\odot$ (pulsation masses) over model predictions for a constant star formation rate and Salpeter IMF (Alves et al. 1997, 1998; Alcock et al. 1999b).

3. Population II and AGB Variables in the LMC Bar

Next we examine the low mass (old) and low metallicity LMC field population, which we call "Population II." Well known Pop. II variable stars are the RR Lyrae (RRab are the fundamental mode pulsators). Pop. II horizontal branch (HB) stars (like RRab) evolve from the zero-age HB toward the asymptotic giant branch-bump (AGB-bump), i.e., the transition from core helium burning to shell burning. Some of these post-HB/early-AGB stars are also variables.

We find the 9M CMD giant branch is consistent with two superposed populations. Cluster CMDs representative of these dual giant branches are the ~1.5 Gyr-old, [Fe/H] = −0.7 dex SMC cluster NGC 411 (Alves & Sarajedini 1999) and the Galactic globular cluster M3 with [Fe/H] ≈ −1.5 (Ferraro et al. 1997). If the LMC Pop. II is more metal rich than this, it is likely to be younger than M3. We report the color and magnitude of the AGB-bump (Gallart 1998) in the 9M CMD (not shown) at $(V-R, V) = 0.57$, 18.38 mag. We report the median color and magnitude of the LMC field RRab as $(V-R, V) = 0.31, 19.45$ mag (note the considerable scatter due to differential reddening, blends, and HB evolution in Fig. 2). ΔV(AGB-bump − RRab) depends on metallicity. We find the Z=0.0004, scaled-solar, HB models of Castellani, Chieffi, & Pulone (1991) provide a good match, although perhaps a slightly higher metallicity would be preferred. We then shift these model HB tracks in the CMD to match the location of the AGB-bump. This accounts for the uncertain LMC distance and reddening, and also recalibrates the color-temperature relation to the 9M CMD. In the right panel of Figure 2, LMC field RRab ($0.46 < P < 0.71$ day) are shown in the Bailey diagram along with the ridge line for M3 (see inset). This diagram indicates a mean metallicity for these RRab that is similar to M3. The "cloud" of RRab to the right of the prominent sequence in this diagram may indicate some LMC field RRab have lower metallicities. We also refer to the spectroscopic metallicities for a sample of these field RRab in Alcock et al. (1996) which indicate [Fe/H] ~ −1.6, albeit with considerable scatter. Thus, by four methods we arrive at [Fe/H] ≈ −1.5 dex for the LMC field Pop. II.

In the CMD panel of Figure 2, we also plot twenty-four newly identified post-HB variables. These were found in a search of between $17.5 < V < 18.8$, $0.15 < (V-R) < 0.75$, and restricted to variables with periods in the range $0.73 < P < 5$ day. These variables help us define the Pop. II instability strip (IS). The prediction of Bono et al. (1997) for the fundamental blue and red edge shows good agreement. Moreover, it lends support to our color-temperature calibration

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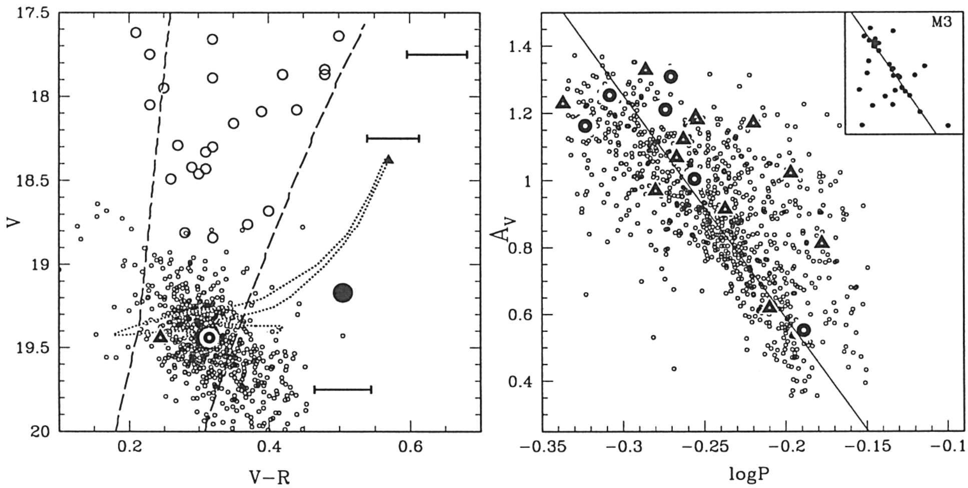

Figure 2. **(Left)** CMD showing LMC field RRab (small open circles) and Pop. II post-HB variables (larger open circles). 9M CMD fiducial sequences are indicated as follows: RGB (errorbar marks), the AGB-bump (solid triangle), and the red HB clump (solid circle). Theoretical data shown are $M = 0.70$ and $0.75\ M_{\odot}$, Z=0.0004 HB evolution tracks from Castellani et al. (1991; dotted lines), and Pop. II variable IS (F mode) from Bono et al. (1996; dashed marks) for $M = 0.60$ $M_{\odot}$. The mean location of NGC 1835 and NGC 1898 RRab are indicated with the bold-faced triangle and circle respectively. **(Right)** Bailey (period-V amplitude) diagram showing LMC field RRab (small circles), RRab from the LMC clusters NGC 1835 (bold triangles) and NGC 1898 (bold circles). The M3 ridge line is also indicated. In the inset (same axes) we plot RRab from Kaluzny et al. (1998) for M3 with ridge line.

derived from the AGB-bump and HB models. We note the discrepancy at the blue edge and high luminosities may imply some of these variables have higher masses.

In the Bailey diagram, we show newly identified RRab found near the LMC bar clusters NGC 1898 and NGC 1835. Spectroscopic metallicities for these clusters are [Fe/H] ~ -1.4 and -1.8 dex, respectively (Olszewski et al. 1991). Recent *HST* CMDs (Olsen et al. 1998) show these clusters have red and blue HB morphologies respectively and also confirm their "old" age. Our selected samples of these cluster RRab are certainly not complete, but we will assume the mean colors and brightnesses are representative. We find mean colors $(V-R) = 0.31$ and 0.25 mag respectively and mean brightnesses of $V \sim 19.45$ mag for both clusters. The RRab mean color for these two clusters distribute in the IS in a manner similar to their overall HB morphologies. Since the LMC field RRab lie in the red portion of the IS, we infer the LMC field Pop. II has a red HB morphology.

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Discussion

Lance Gardiner: I'm interested in a couple of structural paprameters for the LMC. Is it possible to estimate (1) the total mass of the LMC bar and (2) the inclination of the LMC disc, from the data in the 9 million star CMD?

Alves: I have not estimated the structural parameters from all of the stars in the 9M-CMD. However, using the type ab RR Lyrae and the surface density profiles that Kem Cook showed during his talk, I find an inclination of 35°, and a new center very near the optical center.

Assuming the RRab stars trace a luminous halo population in the LCM, I estimate the mass contribution from this halo is a few percent of the total mass of the LMC.

John Dickel: Do you have a handle on how such a small fraction of highly reddened upper main sequence stars might affect your blue supergiant counts?

Alves: Keep in mind that the 9M CMD I showed you is log-scaled in the density. Therefore, the number of upper main sequence stars which might suffer heavy reddening and contaminate my counts of the blue supergiants is really quite small. I would think the effect is negligible.

Jim Hesser: In your CMD for NGC 2065 you said you were able to do a good statistical field star correction because of your excellent field star samples. However, there seemed to be many small black dots to the red of the main sequence.

Alves: That's correct. My field star subtraction was not perfect and I made some cuts in color and magnitude to futher remove field stars. I should be able to revisit the field star subtraction procedure and improve on this preliminary analysis.