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AGE, METALLICITY, AND THE DISTANCE TO THE MAGELLANIC CLOUDS FROM RED CLUMP STARS

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ABSTRACT

We show that the luminosity dependence of the red clump stars on age and metallicity can cause a difference of up to $\lesssim$0.6 mag in the mean absolute *I* magnitude of the red clump between different stellar populations. We show that this effect may resolve the apparent $\approx$0.4 mag discrepancy between red clump-derived distance moduli to the Magellanic Clouds and those from, e.g., Cepheid variables. Taking into account the population effects on red clump luminosity, we determine a distance modulus to the LMC of 18.36 $\pm$ 0.17 mag, and to the SMC of 18.82 $\pm$ 0.20 mag. Our alternate red clump LMC distance is consistent with the value $(m-M)_{\rm LMC}$ = 18.50 $\pm$ 0.10 adopted by the *Hubble Space Telescope* Cepheid Key Project. We briefly examine model predictions of red clump luminosity and find that variations in helium abundance and core mass could bring the Clouds closer by some 0.10–0.15 mag, but not by the $\approx$0.4 mag that would result from setting the mean absolute *I* magnitude of the Cloud red clumps equal to the that of the solar neighborhood red clump.

Subject headings: galaxies: distances and redshifts — galaxies: individual (Large Magellanic Cloud, Small Magellanic Cloud) — stars: evolution — stars: late-type

1. INTRODUCTION

The distance to the Magellanic Clouds is a problem of great astrophysical interest because of the Clouds' role in the determination of extragalactic distances (see Madore & Freedman 1998). Despite the large amount of effort that has gone into the determination of these distances, they remain a matter of some controversy (see Westerlund 1990 and 1997 for thorough discussions).

The success of the *Hubble Space Telescope* (*HST*) Cepheid Key Project, whose goal is the determination of H_0 to an accuracy of 10%, depends critically on knowledge of the distance to the Clouds, especially the LMC. Based on the Cepheid variable period–luminosity relation (Madore & Freedman 1998) and the light echoes of SN1987A (Panagia et al. 1997), the Key Project has adopted a distance modulus of $(m-M)_{\rm LMC} = 18.50 \pm 0.10$ (50 $\pm$ 2 kpc) (Rawson et al. 1997). These determinations are in good agreement with recent derivations from RR Lyrae variables, based on both ground-based, statistical parallax methods (Feast 1997) and on the *Hipparcos*-calibrated distance scale (Gratton et al. 1997; Reid 1997).

However, the LMC distance controversy is far from settled. A substantial fraction of recent techniques have yielded smaller values, typically in the range of $(m-M)_{\rm LMC} \approx 18.30 \pm 0.10$. These include further analysis of the SN1987A light echoes (Gould & Uza 1998) and recalibration of the RR Lyrae magnitude–metallicity relation (Layden et al. 1996).

If the distance to the LMC is uncertain, that of the SMC is even more so (Westerlund 1997; Udalski et al. 1998). Because of its smaller Cepheid population and its large line-of-sight depth, distance determinations to the SMC are in generally poorly constrained. We can only say with confidence that it lies some 0.3–0.6 mag beyond the LMC. The best Cepheid distance to the SMC is 18.94 $\pm$ 0.04 (Laney & Stobie 1994).

Recently, the large photometric sample of the OGLE microlensing survey and its resulting high-quality color-magnitude diagrams of the Clouds have permitted the development of the red clump of intermediate-age helium-burning stars as a "standard candle" for single-step distance determinations (Paczyński & Stanek 1998). The key to this method has been the availability of accurate *Hipparcos* parallaxes to calibrate the absolute magnitude of solar neighborhood red clump stars. The *Hipparcos* color-magnitude diagrams (e.g., Jimenez, Flynn, & Kotoneva 1998) show a solar-neighborhood red clump that has a very small dispersion in mean absolute *I*-band magnitude. Because the red clump is the dominant post–main-sequence evolutionary phase for most stars, it makes a tempting target for the application of "standard candle" techniques for distance determinations.

The red clump method was developed very thoroughly and applied to fields in the Galactic bulge (Paczyński & Stanek 1998) and M31 (Stanek & Garnavich 1998). These studies used the mean absolute magnitude of solar-neighborhood red clump stars, $M_I^0 = -0.23 \pm 0.03$, obtained from a volume-limited sample of 228 red clump stars observed with *Hipparcos*. The red clump method is based on a well-populated, well-calibrated phase of stellar evolution; in fact, it is possibly a more reliable distance indicator than many other methods that have been employed.

In a recent paper, Udalski et al. (1998) extended the red clump method to the Magellanic Clouds. After taking careful account of the reddening distributions along Cloud lines of sight, they find mean red clump magnitudes of I_0(LMC) = 17.85 $\pm$ 0.03, and I_0(SMC) = 18.33 $\pm$ 0.03. Using the solar neighborhood value $M_I^0 = -0.23 \pm 0.03$, Udalski et al. (1998) find distance moduli of $(m-M)_{\rm LMC} = 18.08 \pm 0.15$ and $(m-M)_{\rm SMC} = 18.56 \pm 0.09$. These values are $\approx$0.4 mag below the "long" distance scale preferred by the *HST* Cepheid Key Project and only marginally consistent with the "short" scale. Stanek, Zaritsky, & Harris (1998) applied the same technique to an independent large photometric survey of the LMC and obtained the virtually identical result $(m-M)_{\rm LMC}$ = 18.07 $\pm$ 0.12.

2. NONSTANDARD CANDLES

As Udalski et al. (1998) and Stanek et al. (1998) note, the question becomes this: why does such a robust method give results that are plainly inconsistent with other well-developed techniques? We suspect that the effects of stellar evolution are

TABLE 1
SHIFTS IN MEAN RED CLUMP I-BAND ABSOLUTE MAGNITUDE AS A FUNCTION OF MASS AND METALLICITY

Mass	Z	δM_I^0 (mag)
1.70	0.02	−0.17
	0.01	−0.27
	0.004	−0.42
	0.001	−0.65
1.50	0.02	−0.13
	0.01	−0.23
	0.004	−0.35
	0.001	−0.43
1.20	0.02	−0.00
	0.01	−0.10
	0.004	−0.20
	0.001	−0.32
1.00	0.02	+0.05
	0.01	−0.03
	0.004	−0.07
	0.001	−0.10

NOTES.—Table depicts shifts in mean red clump I-band absolute magnitude as a function of mass and metallicity for the models of Seidel et al. 1987a. These shifts must be applied to the *Hipparcos* absolute magnitude calibration of the solar neighborhood red clump [M_I^0(local) $= -0.23 \pm 0.03$] before using the red clump as a standard candle for distance determinations. The values here will be diminished slightly by the increase in BC_I of $\lesssim 0.05$ mag caused by the correlation between metallicity and clump color. These values are computed with constant M_c and Y; see the text for the possible effects of realistic variation of these quantities.

responsible (see, e.g., Caputo, Castellani, & Degl'Innocenti 1995; Aparicio et al. 1996; Jimenez et al. 1998; Da Costa & Hatzidimitriou 1998).

Udalski et al. (1998) very briefly discuss the possibility that population differences between the solar neighborhood and the Clouds may be responsible for the ≈0.4 mag distance discepancy they find. However, they deem these stellar population effects to be negligible for three main reasons (Paczyński & Stanek 1998; Stanek & Garnavich 1998). First, the small observed dispersion in mean clump magnitude for each of the *Hipparcos*, Galactic bulge, M31, and Magellanic Cloud fields; second, the lack of a trend in I_0 with $(V - I)$ color in observed color-magnitude diagrams; and third, the small variation in I_0 between fields with known metallicity differences in M31.

Each of these reasons is open to question. If, for example, the stellar populations differ *from each other* in their ages and metallicities, yet are homogeneous *within each field*, then each red clump may be intrinsically narrow yet differ significantly the solar neighborhood red clump. We found an extreme example of this effect in the very metal-poor, young dwarf irregular galaxy Leo A (Tolstoy et al. 1998), whose red clump must be ≈0.4 mag more luminous than the *Hipparcos* red clump in order to yield a distance that can be reconciled with the color-magnitude diagram of that galaxy. We will address the empirical constancy of M_I^0 and the lack of variation in the M31 fields after considering the theoretical model predictions for red clump properties.

To explore the variation of the mean red clump magnitude M_I^0 with age and metallicity, we examined the theoretical red clump models of Seidel, Demarque, & Weinberg (1987b, hereafter SDW). These models give red clump star evolutionary tracks for masses from 0.74 to 1.70 $M_\odot$ and metallicities $Z = 0.001$, 0.004, 0.01, and 0.02. These models thus span the ranges of red clump formation epochs (1–10 Gyr), and of Galactic, LMC, and SMC metallicities. In their analysis of SMC star clusters, Da Costa & Hatzidimitriou (1998) note that newer models (e.g., Jimenez et al. 1998) yield essentially indistinguishable results.

Seidel, Da Costa, & Demarque (1987a) used these models, compared with star clusters in the Clouds, to constrain the Cloud distances. Interestingly, they also preferred a short distance to the Clouds. However, they do not exclude a long distance modulus because of the problems which, then as now, plague attempts to derive absolute red clump properties from theoretical models. The most vexing of these problems are the issue of mass loss at the tip of the red giant branch, and the effects of convective overshooting from the cores of these stars (see the excellent discussion of mass loss in Jimenez et al. 1998).

In light of these difficulties, we take an empirical approach, in which the *Hipparcos* calibration of M_I^0 is used as our starting point, and deviations from M_I^0(local) are calculated using the relative shifts between the SDW models. We define the mean luminosity of the red clump, L_0, for each track by finding the points at which the model was evolving most slowly, i.e., was most likely to be observed at. For each mass, we made a linear fit to the variation of L_0 with Z and examined the residuals. Where the zero-point offset was larger than the rms residual, we broke the fit into two pieces, one for the high-metallicity end and one for the low. We found the best single line fit to all masses is $\delta M_I^0 = (0.21 \pm 0.07)$ [Fe/H].

We identified the *Hipparcos*-calibrated red clump M_I^0 with the 1.2 $M_\odot$, $Z = 0.02$ model clump. This is appropriate for a solar-metallicity population with roughly constant star formation rate over the past 10 Gyr. We can then calculate the predicted M_I^0 for arbitrary stellar population mixes given the mean ages and metallicities of those populations using the formula $\delta M_I^0 = -2.5\delta \log L_0$. Because the effective temperatures under consideration do not change by much, we ignore the effects of a changing bolometric correction for now. Note that this would be grossly incorrect for populations of still lower metallicity, such as Leo A's, in which the clump is offset to the blue. First we correct each population for its metallicity by adding the $\delta M_I^{0,\,[\mathrm{Fe/H}]}$ determined from our linear fits. Then we add the appropriate $\delta M_I^{0,\,\mathrm{age}}$ found from the luminosity differences between the various masses in the SDW grid of solar-metallicity models. Table 1 gives our adopted values of δM_I^0 for the masses and metallicities we have considered. For stars less massive than ≈1.2 $M_\odot$ (i.e., populations older than ≈4–5 Gyr), the red clump magnitude is nearly independent of stellar mass but can still vary significantly with metal abundance.

To apply these corrections to the *Hipparcos* M_I^0, it is necessary to assume a star formation history (SFH) for the target galaxy. For the LMC, we adopt the SFH of Holtzman et al. (1997), in which 73% of the red clump is produced between 2 and 10 Gyr ago with a mean metallicity $Z = 0.001$, and the remainder derives from a 1–2 Gyr old population with $Z = 0.008$. For this star formation history, we derive $\delta M_I^0 = -0.32 \pm 0.03$, yielding $M_I^0(\mathrm{LMC}) = -0.55 \pm 0.04$. The color shift between a solar-metallicity clump and the LMC clump prompts us to revise M_I^0(LMC) downward by ≈+0.04 mag because of the increasing I-band bolometric correction (BC_I) for these slightly hotter stars, giving $M_I^0(\mathrm{LMC}) = -0.51 \pm 0.04$. To test the sensitivity of this value to adopted SFH, we also examine a much more "burstlike" SFH (Vallenari et al. 1996), in which 44% of the red clump is made between 2 and 10 Gyr in the past with $Z = 0.004$, and 56% of the clump is 1–2 Gyr old at $Z = 0.008$. In this scenario, $M_I^0(\mathrm{LMC}) = -0.46 \pm 0.04$. The brighter red clump produced by a younger population is somewhat offset by the fainter red clump resulting from the higher metallicity in the Vallanari et al. scenario. In light of recent *HST* observations (Geha et al. 1998), we consider the LMC to be more "Holtzman-like" than "Vallenari-like" and adopt $M_I^0(\mathrm{LMC}) = -0.51 \pm 0.04$. This interpretation is reinforced by the relatively small observed spread in red clump magnitude observed by Stanek et al. (1998), who point out that a bursting SFH would lead to a dispersion in clump properties. Stanek et al. (1998) note the relatively blue color of the LMC red clump and conclude that its stars are metal poor but not exceptionally young, in agreement with the Holtzman et al. (1997) and Geha et al. (1998) models.

For the SMC, the SFH is much less constrained. We consider two scenarios, one with a constant star formation rate from 1 to 10 Gyr ago, and one in which all clump stars were produced in a burst 1–3 Gyr in the past (see Pagel & Tautvaišienė 1998). Adopting the age-metallicity relation observed in SMC star clusters (Da Costa & Hatzidimitriou 1998), the mean SMC metallicities we use are, respectively, $[\mathrm{Fe/H}] = -1$ and $[\mathrm{Fe/H}] = -0.8$. The constant SFR scenario yields $\delta M_I^0 = -0.26 \pm 0.04$ and $M_I^0(\mathrm{SMC}) = -0.49 \pm 0.06$. For the burst scenario we obtain $\delta M_I^0 = -0.36 \pm 0.04$ and $M_I^0(\mathrm{SMC}) = -0.59 \pm 0.06$. These low-metallicity models require a change in BC_I of $\approx +0.05$ from the solar-metallicity models. At the present time, either SFH alternative seems plausible, and so we adopt a mean value of $M_I^0(\mathrm{SMC}) = -0.49 \pm 0.06$ (random) $\pm$ 0.05 (systematic).

Combining these new values of M_I^0 with the values of I_0 from Udalski et al. (1998), we find longer distances to the Magellanic Clouds: $(m - M)_{\mathrm{LMC}} = 18.36 \pm 0.05$ (random) $\pm$ 0.12 (systematic); $(m - M)_{\mathrm{SMC}} = 18.82 \pm 0.07$ (random) $\pm$ 0.13 (systematic).

How can we reconcile the variability of red clump properties with the apparent constancy of such stars as observed in the *Hipparcos* and OGLE color-magnitude diagrams? Apart from the homogeneity arguments given above, we can exploit the properties of the theoretical models and the behavior of real stellar populations for some plausible explanations.

It is known from models (e.g., SDW) that metallicity influences the temperature as well as the luminosity of the red clump stars; metal-poor stars are predicted to be bluer as well as brighter than their metal-rich counterparts. The observed lack of variation in I_0 as a function of color has thus been interpreted as empirical proof that I_0 does not vary appreciably with metallicity (A. Udalski 1997, private communication). The differing behavior of bolometric luminosity and I magnitude is presumed to arise from the increasing BC_I which must be applied to bluer stars. However, we find that BC_I changes by only $\approx +0.05$ mag between a solar-metallicity clump and an SMC-metallicity clump. This counteracts some of the age and metallicity variation of M_I^0, especially for stars near 1 $M_\odot$ but cannot negate it completely.

The implicit assumption in the standard candle argument is that a range in metallicity is the major cause of a spread in red clump color. This is almost certainly untrue in a real stellar population, in which star formation has proceeded across a finite range in time. A real red clump contains stars of many masses; each of these begins its helium-burning lifetime at a color determined in part by its individual mass-loss history, and evolves in color during its $\sim 10^7$ yr lifetime. There is no unique mapping from the color-magnitude diagram to initial mass and metallicity.

Another effect that must be considered is the increase in model luminosities with both helium abundance Y and core mass M_c (Sweigart & Gross 1978; SDW; Jimenez et al. 1998). We considered models of constant Y and M_c. However, in real stars, Y increases with Z, and M_c decreases with increasing Y (Sweigart & Gross 1978). Thus, we might expect the mean clump luminosity to depend less strongly on metallicity than we have calculated here.

The exact variations of M_c and Y with Z are subject to much uncertainty, but we estimate using the extensive tabulations of in Sweigart & Gross (1978) that the effect is likely to be $\delta M_I^{0,(M_c,Y)} \lesssim 0.15$ mag in most cases, and $\lesssim 0.10$ mag for the cases considered here. These pieces of stellar physics are of the correct magnitude and sign to erase the trend of M_I^0 with [Fe/H] for populations older than ≈ 6 Gyr and to reduce its effect for younger populations. Because the *Hipparcos* red clump (Jimenez et al. 1998), the Galactic bulge clump (Paczyński & Stanek 1998), and the M31 halo (Stanek & Garnavich 1998) are all older populations, their approximately constant M_I^0 is relatively unsurprising. The younger Magellanic Cloud populations, especially for the "burst" SFH scenarios retain their brighter clumps even assuming a high helium content and weak coupling between M_c and Y, although δM_I^0 is reduced somewhat.

Following the relations from the calculations of Sweigart & Gross (1978) and adopting $dY/dZ = 2.5$ (Jimenez et al. 1998), we estimate that the effects of variation in Y and M_c with Z can dim the LMC's red clump by 0.13 mag for the Holtzman et al. (1997) SFH. The age-metallicity trade-off can be seen strongly in the SMC. For our constant SFR model, its clump will be dimmed by 0.15 mag relative to the values above; for the burst SFH, its clump dims by only 0.04 mag. With these numbers, our revised distances become $(m - M)_{\mathrm{LMC}} = 18.24 \pm 0.17$, and $(m - M)_{\mathrm{SMC}} = 18.73 \pm 0.23$. However, we have taken the variations in Y and M_c from disparate sources, and these values merely serve to illustrate the potential countervailing effects of stellar physics on δM_I^0. More detailed modeling is required.

3. CONCLUSION

Our alternate red clump distance modulus $(m - M)_{\mathrm{LMC}} = 18.36 \pm 0.17$ is ≈ 0.3 mag longer than that obtained under the assumption that the LMC red clump mimics the Galaxy's. This is consistent with the "long" distance modulus of 18.50 ± 0.10 adopted by the Cepheid Key Project and, contrary to Udalski et al. (1998) and Stanek et al. (1998), in agreement with the most recent calibrations of the Cepheid period–luminosity relation, which give $(m - M)_{\mathrm{LMC}} = 18.44 \pm 0.35$ or 18.57 ± 0.11 (Madore & Freedman 1998). Our value of 18.36 ± 0.17 is also in agreement with the shorter distance from RR Lyrae stars of $(m - M)_{\mathrm{LMC}} = 18.28 \pm 0.13$ (Layden et al. 1996).

Taking account of the stellar population of the SMC pushes that galaxy slightly farther away as well, from $(m - M)_{\mathrm{SMC}} = 18.56 \pm 0.09$ derived by Udalski et al. (1998), to $(m - M)_{\mathrm{SMC}} = 18.82 \pm 0.20$. The larger value is in good agreement with that from the Cepheid period–luminosity relation, $(m - M)_{\mathrm{SMC}} = 18.94 \pm 0.04$ (Laney & Stobie 1994).

The detailed stellar physics of mass loss, and the relations between Z, Y, and M_c introduce significant uncertainty into the determination of red clump absolute magnitudes, even in the I band. It is quite likely that these effects may work to bring the Magellanic Clouds to a distance more consistent with the "short" (RR Lyrae) distance scale than the "long" (Cepheid) scale. However, the red clump method does not require Magellanic Cloud distances as much as 15% smaller than commonly accepted. Figure 1 shows the menagerie of recent LMC distance determinations with error bars, and it can be seen that the red clump method gives results consistent with most of the other determinations.

We conclude that the red clump is indeed an extremely useful distance indicator, as described by Paczyński & Stanek (1998), Stanek & Garnavich (1998), and Udalski et al. (1998). However, like most stellar "standard candles," its properties vary with the composition and age of the host galaxy, and the assumption that all red clumps are identical to the *Hipparcos* red clump is probably incorrect. Among populations dominated by stars older than ≈6 Gyr, the standard candle approximation should be valid to a high degree for M_I^0. For younger populations, M_I^0 is probably brighter than M_I^0(local), and the correction may amount to as much as several tenths of a magnitude.

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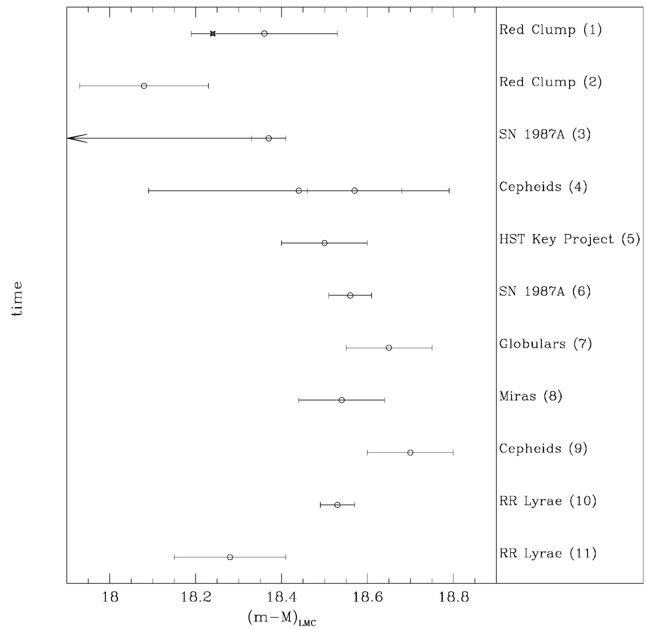

FIG. 1.—Recent distance determinations to the LMC, ordered chronologically from bottom to top. The red clump method yields a range of distances consistent with both Cepheid and RR Lyrae distance scales. The "x" on our Red Clump error bar shows a potential shortening of the distance scale based on the interplay of M_c and Y in theoretical models. References: (1) this Letter; (2) Udalski et al. (1998), Stanek et al. (1998); (3) Gould & Uza (1998); (4) Madore & Freedman (1998); (5) Rawson et al. (1997); (6) Panagia et al. (1997); (7) Reid (1997); (8) van Leeuwen et al. (1997); (9) Feast & Catchpole (1997); (10) Feast (1997); (11) Layden et al. (1996).

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Note added in proof.—J. P. Beaulieu & P. D. Sackett (AJ, in press [astro-ph/9710156] [1998]) carried out a detailed analysis of the morphology of the red clump in the LMC. They found that their color-magnitude diagrams were best fitted by a distance modulus to the LMC of 18.3, suggesting that the LMC's red clump is indeed brighter than the solar neighborhood red clump.