A "SHORT" DISTANCE TO THE LARGE MAGELLANIC CLOUD WITH THE HIPPARCOS CALIBRATED RED CLUMP STARS

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ABSTRACT

Following an approach developed by Paczyński & Stanek, we derive a distance to the Large Magellanic Cloud (LMC) by comparing red clump stars from the Hipparcos catalog with the red clump stars observed in two fields in the LMC that were selected from the ongoing photometric survey of the Magellanic Clouds to lie in low-extinction regions. The use of red clump stars allows a single step determination of the distance modulus to the LMC, $\mu_{0,\text{LMC}} = 18.065 \pm 0.031 \pm 0.09$ mag (statistical plus systematic error), and the corresponding distance, $R_{\text{LMC}} = 41.02 \pm 0.59 \pm 1.74$ kpc. This measurement is in excellent agreement with the recent determination by Udalski et al., also based on the red clump stars, but is ~0.4 mag smaller than the generally accepted value of $R_{\text{LMC}} = 45.05 \pm 0.15$ mag. We discuss possible reasons for this discrepancy and how it can be resolved.

Subject headings: galaxies: distances and redshifts — galaxies: individual (Large Magellanic Cloud) — solar neighborhood — stars: horizontal-branch

1. INTRODUCTION

The generally accepted distance modulus to the Large Magellanic Cloud (LMC) is $\mu_{0,\text{LMC}} \approx 18.5 \pm 0.15$ mag (for recent discussion, see Westerlund 1997; Madore & Freedman 1998). However, there is a long standing ~0.3 mag discrepancy between the “long” distance determined using Cepheids (see, e.g., Laney & Stobie 1994) and the “short” distance determined using RR Lyr stars (see, e.g., Walker 1990; Layden et al. 1996). A similar discrepancy is present in the distance to the LMC derived with the supernova SN 1987A ($\mu_{0,\text{LMC}} < 18.37$ mag, Gould & Uza 1998; $\mu_{0,\text{LMC}} = 18.56$ mag, Panagia et al. 1997). Recently, Udalski et al. (1998) used red clump stars observed in the LMC by the OGLE 2 project (Udalski, Kubiak, & Szymański 1997) and obtained a value of $\mu_{0,\text{LMC}} = 18.08 \pm 0.03 \pm 0.12$ mag (statistical plus systematic error). This distance modulus is ~0.4 mag smaller than the “long” distance modulus used, for example, by the HST Extragalactic Distance Scale Key Project team (see, e.g., Rawson et al. 1997 and references therein). Because errors in the distance to the LMC can propagate into errors in such key quantities as distances, luminosities, masses, and sizes of extragalactic objects, it is important to check the result of Udalski et al. (1998) using independent data, in order to investigate possible systematic errors.

Red clump stars are the metal-rich equivalent of the better known horizontal branch stars, and theoretical models predict that their absolute luminosity only weakly depends on their age and chemical composition (Seidel, Demarque, & Weinberg 1987; Castellani, Chielli, & Straniero 1992; Jimenez, Flynn, & Kotoneva 1998). Indeed, the absolute magnitude-color diagram from Hipparcos data (Perryman et al. 1997, their Fig. 3) clearly shows a compact red clump—the variance in the I-band magnitude is only ~0.15 mag (Stanek & Garnavich 1998; Udalski et al. 1998).

Despite their large number and the theoretical understanding of their evolution, red clump stars have seldom been used as distance indicators. However, Stanek (1995) and Stanek et al. (1994, 1997) used these stars to map the Galactic bar. Paczynski & Stanek (1998) used the red clump stars observed by the OGLE project (Udalski et al. 1995) to obtain the distance to the Galactic center. Stanek & Garnavich (1998) used red clump stars observed by the HST in M31 to obtain a one-step distance to this galaxy. In this Letter we follow the approach of Paczyński & Stanek (1998) and present an estimate of the distance to the LMC based on the comparison between the red clump giants observed locally by the Hipparcos (Perryman et al. 1997) satellite and those observed in the LMC by the $UBVI$ digital photometric survey of the Magellanic Clouds (Zaritsky, Harris, & Thompson 1997). In § 2 we describe the data used in this Letter and select low-extinction regions for further analysis. In § 3 we analyze the red clump distribution in the LMC and derive the distance to this galaxy. In § 4 we discuss the possible reasons for the discrepancy with the Cepheid distance to the LMC and how it can be resolved.

2. THE DATA

Zaritsky et al. (1997) have undertaken a large-scale $UBVI$ photometric CCD survey of the Magellanic Clouds, with the ultimate goal of imaging the central $8'' \times 8''$ of the LMC and $4'' \times 4''$ of the SMC. The initial results for a $2'' \times 15''$ region were presented by Zaritsky et al. (1997), and the extinction map for the same region was constructed by Harris, Zaritsky, & Thompson (1997). The area of the LMC observed by Zaritsky et al. (1997) is shown in Figure 1, along with the four fields used by Udalski et al. (1998) to determine the red clump distance to the LMC.

As noted by Udalski et al. (1998), uncertainties in the extinction estimates are the largest contributor to their systematic error. We therefore select low-reddening regions from the area observed by Zaritsky et al. (1997). Harris et al. (1997) used ~2000 OB main-sequence stars to construct a map of the reddening in the region observed by Zaritsky et al. (1997). They
find a mean reddening of \( \langle E(B-V) \rangle_{\text{LMC}} = 0.20 \) mag, with a non-Gaussian tail to high values. As discussed by Harris et al. (1997), it is possible that the reddening map is biased to high reddening values, since it is based on the reddening toward OB stars, a population that may reside in dustier-than-average regions of the ISM. On the other hand, the nature of their interpolation may partially counter this bias by smoothing over reddening spikes.

Recently, Schlegel, Finkbeiner, & Davis (1998, hereafter SFD) published a new all-sky reddening map, based on the COBE/DIRBE and IRAS/ISSA maps. With its high spatial accuracy, the SFD map might be potentially useful for selecting low-reddening regions in the Magellanic Clouds. However, as discussed by SFD, the LMC, SMC, and M31 are not removed from their map, nor are sources within their Holmberg radius. The reddening estimates from the SFD map are unreliable within these objects because of the lack of spatial temperature resolution from DIRBE and confusion with internal IR sources. However, because neither of these two effects artificially creates large areas of low reddening in the map, the map can be used as a guide to select regions of low total extinction. If the total column density of dust is low, then the dispersion of reddening values of a population distributed along the line of sight will also be low. We therefore decided to select regions of low DIRBE/IRAS reddening from the area observed by Zaritsky et al. (1997) and then determine the reddening using the map of Harris et al. (1997).

Examining the SFD map in the region observed by Zaritsky et al. (1997) we selected two circular regions with 7' radii (defined by the low-extinction region), which we hereafter call A1 and A2. These regions are centered on (R.A., decl.) = (5h1442, -67\textdegree452) and (R.A., decl.) = (5h1239, -67\textdegree716), respectively, and are shown as small circles in Figure 1. The SFD map gives an average reddening of \( E(B-V) \approx 0.18 \) mag for each of these regions. The Harris et al. (1997) map gives

\[ E(B-V) = 0.16 \] for region A1 and \( E(B-V) = 0.17 \) for the region A2. We find the good agreement between the maps reassuring. However, we assume a conservative error of the \( E(B-V) \) reddening to be 0.04 mag, following the discussion by Harris et al. (1997). This leads to the values of the extinction \( A_V = 0.31 \pm 0.08 \) mag and reddening \( E(V-I) = 0.20 \pm 0.05 \) mag for the region A1 and \( A_V = 0.33 \pm 0.08 \) mag and \( E(V-I) = 0.22 \pm 0.05 \) mag for the region A2.

In Figure 2 we show the red clump-dominated parts of the \( I_0 \) color-magnitude diagrams (CMDs) for both regions A1 and A2, corrected for the extinction and the reddening using the above values of \( A_V \) and \( E(V-I) \). The dashed rectangle corresponds to the region of the CMD selected for comparison with the local red clump stars observed by Hipparcos (see the next section). The LMC red clump is clearly bluer than the local one (Paczynski & Stanek 1998, their Fig. 2), indicating a lower average metallicity of the LMC (see Jimenez et al. 1998, their Fig. 5). However, there is a sufficient overlap with the Hipparcos color range to allow for meaningful comparison, which we perform in the next section.

### 3. THE ANALYSIS

Following Paczynski & Stanek (1998), we selected the red clump stars in the color range \( 0.8 < (V-I)_0 < 1.25 \) and the magnitude range \( 16.6 < I_0 < 19.1 \) in the A1 region (1725 stars) and in the A2 region (1273 stars). The color range was selected to correspond to the color range of the red clump stars observed locally by the Hipparcos (Paczynski & Stanek 1998, their Fig. 2). Following Stanek & Garnavich (1998), we fitted both distributions with a function

\[
\begin{align*}
    n(I_0) &= a + b(I_0 - I_{0,m}) + c(I_0 - I_{0,m})^2 \\
    &+ \frac{N_{RC}}{\sigma_{RC}\sqrt{2\pi}} \exp \left[ -\frac{(I_0 - I_{0,m})^2}{2\sigma_{RC}^2} \right],
\end{align*}
\]

The first three terms describe a fit to the "background" distribution of the red giant stars, and the Gaussian term represents a fit to the red clump itself. \( I_{0,m} \) corresponds to the peak magnitude of the red clump population. We obtained the values of \( I_{0,m} = 17.832 \pm 0.012 \) for the A1 region and \( I_{0,m} = 17.843 \pm 0.020 \) for the A2 region.

The distribution of the LMC red clump stars as a function of their \( I_0 \) magnitude is shown in Figure 3 along with the fitting function described by equation (1). The Gaussian fitted to the A1 field red clump distribution has a smaller dispersion,
σ_{RC} = 0.17 mag, than the Gaussian fitted to the A2 red clump, σ_{RC} = 0.25 mag. The red clump is less pronounced and has a correspondingly larger dispersion in the A2 field because the red clump is bluer and mostly falls outside the color cut. Indeed, when we select the red clump stars within the color range 0.55 < (V − I)_0 < 0.8, both fitted distributions have the same σ_{RC} = 0.18 mag. This different color selection also moves the red clump peaks \( \langle I_{0,m} \rangle \) to slightly fainter magnitudes, \( I_{0,m} = 17.87 \pm 0.008 \) for the A1 region (1907 stars) and \( I_{0,m} = 17.891 \pm 0.007 \) (2497 stars) for the A2 region. This slight color dependence in the \( I \)-band magnitudes of the red clump stars is consistent with the results of Paczyński & Stanek (1998), Stanek & Garnavich (1998), and Udalski et al. (1998).

We now proceed to obtain the LMC distance modulus using the red clump, by assuming that the absolute \( I \)-band brightness of the red clump stars is the same for the local stars observed by Hipparcos and those in the LMC. The straight average of the red clump peak apparent magnitudes \( I_{0,m} \) for the two regions is \( \langle I_{0,m} \rangle = 17.837 \pm 0.008 \), and the weighted mean is \( I_{0,m} = 17.835 \pm 0.008 \). Combining \( I_{0,m} \) with the distribution of local red clump stars, which have \( M_{I,m} = -0.23 \pm 0.03 \) (Stanek & Garnavich 1998), we obtain the distance modulus for the LMC, \( \mu_{0,\text{LMC}} = 18.056 \pm 0.031 \) mag, or \( R_{\text{LMC}} = 41.02 \pm 0.59 \) kpc (statistical error only). After adding the systematic error of 0.08 mag, owing to the uncertainty in the \( A_I \) determination, and 0.04 mag, owing to the zero-point uncertainty in the \( I \)-band photometry (Zaritsky et al. 1997), we arrive at the final value of \( \mu_{0,\text{LMC}} = 18.056 \pm 0.031 \pm 0.09 \) mag (statistical plus systematic error). This is indistinguishable from the value of \( \mu_{0,\text{LMC}} = 18.08 \pm 0.03 \pm 0.12 \) mag determined by Udalski et al. (1998), but ~0.4 mag below the generally accepted value of \( \mu_{0,\text{LMC}} = 18.50 \pm 0.15 \) mag (Madore & Freedman 1998). We discuss possible reasons for this discrepancy and how it can be resolved in the next section.

4. DISCUSSION

As with all distance-ladder techniques, our analysis includes the assumption that the calibrating and target objects being compared are intrinsically similar. In our red clump analysis, this assumption is manifested by the assertion that the \( I \)-band brightness of red clump stars is independent of the age, chemical composition, and mass differences that may exist between the red clump stars near the Sun and those in the LMC. Indeed, the LMC red clump is systematically bluer than the local one, indicating the somewhat different properties of these stars. However, Paczyński & Stanek (1998), Stanek & Garnavich (1998) and Udalski et al. (1998) found that the \( I \)-band peak magnitude of the red clump depends very weakly on their \( (V − I)_0 \) color in the range 0.7 < \((V − I)_0 < 1.4\) and therefore is independent of the metallicity (Jimenez et al. 1998). This is confirmed in this Letter as well, by comparing the peak brightness of the red clump for two color ranges 0.55 < \((V − I)_0 < 0.8\) and 0.8 < \((V − I)_0 < 1.25\) (see the previous section). The fact that the observed red clump distributions are so narrow (\( σ_{RC} = 0.15 \) mag) indicates that the age dependence of the red clump \( I \)-band peak luminosity is also small (≤0.1 mag). Otherwise, in a system with a complex star formation history, such as the LMC (Holtzman et al. 1997; Geha et al. 1998), the resulting red clump should have considerable width. Stanek & Garnavich (1998) compared three different lines of sight that probe a large range of M31 galactocentric distances and locations, and hence a range of metallicities and possibly ages and star formation histories. The fact that the derived distance moduli for their three fields varied by only ~0.035 mag indicates that the red clump is a potentially stable standard candle. The mostly empirical support for using the red clump stars as a distance indicator should also be verified using modern theory of the stellar structure and evolution. In particular, \( I \)-band predictions are seldom given by such theoretical calculations.

So why does the red clump distance to the LMC disagree with the Cepheid distance (Madore & Freedman 1998)? As usual, there are several possible answers. Contrary to our arguments given above, there might still be something “unusual” about the red clump population in the LMC. It is worth mentioning that Beaulieu & Sackett (1998) preferred a distance modulus of \( \mu_{0,\text{LMC}} \sim 18.3 \) when fitting a CMD in the LMC using the evolutionary models of Bertelli et al. (1994). While the red clump and Cepheid distances to the LMC are discrepant, the distances to M31 derived from the two methods are in good agreement \((m − M = 24.471 \pm 0.035 \pm 0.045\) from Stanek & Garnavich 1998 and 24.44 ± 0.13 from Freedman & Madore 1990), although recent determination by Feast & Catchpole (1997) favors a higher value of the M31 distance modulus, 24.77 ± 0.11 mag. Another possibility is that the Cepheid distance to the LMC is simply poorly determined, as there are few Cepheids with well-determined parallaxes in the Hipparcos catalog. In their recent study, Madore & Freedman (1998) find \( \mu_{0,\text{LMC}} = 18.44 \pm 0.35 \) mag, from a sample of 19 Cepheids observed by Hipparcos with good \( BV \) data, and \( \mu_{0,\text{LMC}} = 18.57 \pm 0.11 \) mag, from a sample of only seven Cepheids with good \( BVIJK \) data. Yet a third possibility, as discussed by Madore & Freedman (1998), is that there are other effects on the Cepheid PL relation (e.g., extinction, metallicity, and statistical errors), which are as significant as any reassessment of the zero point based on Hipparcos. The metallicity effect on the Cepheid PL relation, determined by Kennicutt et al. (1998) \((d(m − M)/d[O/H]) = −0.24 \pm 0.16 \) mag dex\(^{-1}\), reduces the discrepancy between the red clump and Cepheid distances to the LMC by ~0.1 mag, while the somewhat larger metallicity dependence found by Sasselov et al. (1997) and Kochanek (1997) reduces it by ~0.15 mag. To illustrate the effect of the assumed reddening on the derived distance modulus, we note that the value of the LMC distance modulus, \( \mu_{0,\text{LMC}} = 18.54 \) mag, derived recently by Salaris & Cassisi (1998) and based on the \( V \)-band brightness of the RR Lyr stars, becomes \( \mu_{0,\text{LMC}} = 18.22 \) mag if their assumed reddening of \( E(B − V) = 0.10 \) mag is increased to \( E(B − V) = 0.20 \) mag, corresponding to the mean reddening found by Harris et al. (1997). It is disturbing that the distance to a key calibrator of the entire distance scale is uncertain by up to 20%.

As described by Udalski et al. (1998), the ~0.4 mag dis-
crepancy between their (and now our as well) “short” distance to the LMC and the “long” distance to the LMC from the Cepheids can be resolved by using detached eclipsing binaries as a direct distance indicator (Paczynski 1997). The Cepheids in the LMC can also be used to get a direct distance estimate through a modified Baade-Wesselink method (see, e.g., Krockenberger 1996; Krockenberger, Sasselow, & Noyes 1997). Both these methods require no intermediate steps in the distance ladder, therefore avoiding the propagation of errors usually crippling the distance scale. With the 6.5–8 m telescopes now being built in the Southern Hemisphere, the necessary spectroscopy of the detached eclipsing binaries and Cepheids can be quite easily obtained for these 14–18 mag stars. It is worth mentioning here that the effort to obtain direct distances with the detached eclipsing binaries and Cepheids to the M31 and M33 galaxies is already under way, and the first results look promising (project DIRECT: Kaluzny et al. 1998; Stanek et al. 1998; Krockenberger et al. 1998; Sasselow et al. 1998).

To summarize, among the various stellar distance indicators the red clump giants might be the best for determining the distance to the LMC and other nearby galaxies because there are so many red clump stars. In particular, Hipparcos provided accurate distance determinations for almost 2000 such stars, but unfortunately I-band photometry is available for only ~30% of them, so it is important to obtain I-band photometry for all Hipparcos red clump giants. We also need to test the metallicity dependence of Hipparcos red clump giant absolute luminosities and colors. There are many stars within 100 pc of the Sun for which very high-resolution spectroscopy is possible.

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