

THE DISTANCE TO THE FORNAX DWARF GALAXY USING RED CLUMP STARS AND THE DISCREPANCY BETWEEN RED CLUMP AND TIP OF THE RED GIANT BRANCH DISTANCES

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ABSTRACT

I determine a distance to the Fornax dwarf galaxy using stars in the red clump and at the tip of the red giant branch. They are in very good agreement, with $\mu_0 = 20.66$ mag. Comparing the magnitudes of the tip of the red giant branch and of the red clump in Fornax, Carina, and the Magellanic Clouds, I propose a possible solution to the problem of the discrepancy between these two types of distance measurements.

Subject headings: galaxies: distances and redshifts —

galaxies: individual (Carina, Fornax, Large Magellanic Cloud) — stars: late-type

1. INTRODUCTION

In recent years, there has been a flurry of activity about the use of red clump stars as a distance indicator. Several authors provided examples of distance determinations with the red clump method to the Magellanic Clouds, the Galactic Center, the Carina dwarf galaxy, and M31 (e.g., Paczyński & Stanek 1998; Stanek, Zaritsky, & Harris 1998; Stanek & Garnavich 1998; Udalski 1998, 2000). There are several strong arguments in favor of this method. First, the red clump is easy to recognize in the color-magnitude diagram (CMD), and this feature is little affected by other structures in the CMD (such as the horizontal branch, the red giant branch, or foreground contamination). Second, there are many red clump stars in a typical galaxy or cluster; this renders the method statistically robust. Third, it is one of very few distance indicators that can potentially be accurately calibrated, with several hundreds of stars having *Hipparcos* parallaxes better than 10% (Paczynski & Stanek 1998). However, there are complications. Several authors (Girardi et al. 1998; Girardi 1999a, 1999b; Cole 1998) presented arguments, mostly theoretical, that the average magnitude of the red clump is sensitive to age and metallicity and thus a detailed knowledge of the average age and metal content of a galaxy are needed before using the red clump method to determine distances. The debate has been heated by the fact that the advocates of the red clump method found very short distances to the Magellanic Clouds, e.g., $\mu_{\text{LMC}} = 18.07$ mag in Stanek et al. (1998) and $\mu_{\text{LMC}} = 18.08$ mag in Udalski (1998), later revised upward to $\mu_{\text{LMC}} = 18.24$ mag (Udalski 2000). The reddening correction in the LMC may also be a source of disagreement since the average red clump magnitude measured by different groups—using different methods to correct for extinction—are markedly different ($I_{0,m} = 17.84$ mag in Stanek et al. 1998, $I_{0,m} = 18.06$ mag in Sakai, Zaritsky, & Kenicutt 2000, and $I_{0,m} = 18.12$ mag in Romaniello et al. 2000).

Most recently, Udalski (2000) and Popowski (2000) calibrated empirically the metallicity dependence of $I_{0,m}$. Their slopes and zero points are in agreement (within 1 σ of each other). For instance, Popowski (2000) obtained

$$M_I^{\text{RC}} = 0.19[\text{Fe}/\text{H}] - 0.23 \text{ mag}, \quad (1)$$

while Udalski (2000) obtained

$$M_I^{\text{RC}} = 0.13[\text{Fe}/\text{H}] - 0.23 \text{ mag}. \quad (2)$$

Accounting for this correction, these authors obtain a distance modulus to the LMC of 18.27 and 18.24 mag, respectively.

The aim of this Letter is twofold: first, to provide a test of the accuracy of the red clump method, and more particularly of the metallicity correction, and second, to explore the influence of reddening corrections by working in very low reddening systems (Fornax and Carina). I also compare red clump distances for four galaxies (Carina, Fornax, and the Magellanic Clouds) with distances obtained via the tip of the red giant branch (TRBG) and discuss the consequences.

2. OBSERVATIONS AND DATA REDUCTION

About 30 epochs of photometry have been obtained on two telescopes with the aim of searching for short-period variable stars in the Fornax dwarf galaxy (Bersier & Wood 1999, 2000). Here I use only about half of the data set that has been calibrated. Full details on the data reduction will appear elsewhere (D. Bersier & P. R. Wood 2000, in preparation); only a short summary is given here. Four fields in Fornax have been observed between 1997 October and December with the 40" telescope at Siding Spring Observatory (Australia), using *V* and *I_C* filters. The detector was a SITe 2048 $\times$ 2048 CCD that gave a field of view of 20' $\times$ 20'. Between 12 and 18 images in *V* and *I* have been obtained for each of the four fields. The photometry has been done with DoPHOT (Schechter, Mateo, & Saha 1993) and calibrated using observations of Landolt standard stars (Landolt 1992). From observations of stars in overlapping fields, I estimate that the absolute photometric zero point is good to ± 0.02 mag for each passband.

Since there is a large number of observations per field, I computed the average of all *VI* measurements for each star. This clearly improves the photometric accuracy; the average error at the magnitude of the red clump ($m_I \approx 20.3$) is ~ 0.1 mag. I then used the maps of Schlegel, Finkbeiner, & Davis (1998) to correct for reddening. This yielded values of $E(B-V)$ between 0.02 and 0.04 for the vast majority of the stars. One then has $E(V-I) = 1.28E(B-V)$ and $A_I = 1.96E(B-V)$. The CMD for the 40' $\times$ 40' field is shown in Figure 1.

3. THE DISTANCE TO FORNAX

3.1. The Red Clump

The red clump appears to be very compact and well limited in color between $(V-I)_0 \approx 0.8$ and $(V-I)_0 \approx 1.0$ (see Fig. 1).

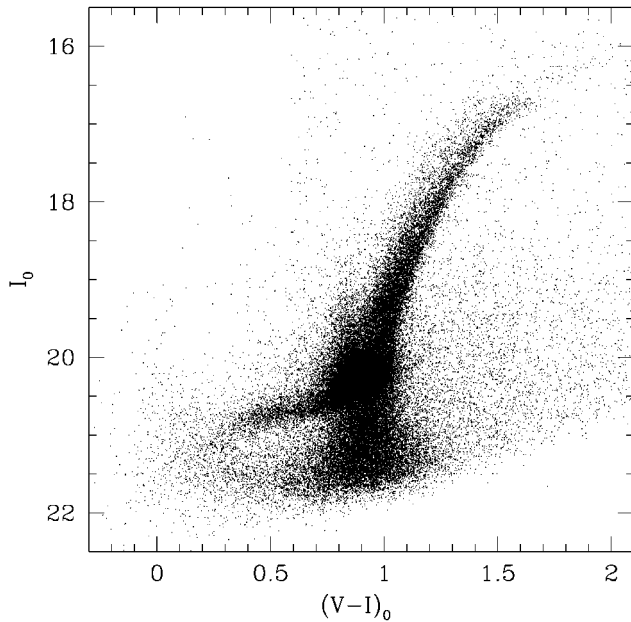


FIG. 1.— I_0 , $(V-I)_0$ CMD for the observed field ($\sim 40' \times 40'$). Almost 60% of the stars are in the red clump.

To obtain a distance, the first step is to fit a function of the type

$$N(I_0) = a + b(I_0 - I_{0,m}) + c(I_0 - I_{0,m})^2 + \frac{N_{RC}}{\sigma_{RC}\sqrt{2\pi}} \exp\left[-\frac{(I_0 - I_{0,m})^2}{2\sigma_{RC}^2}\right] \quad (3)$$

following Paczyński & Stanek (1998). The Gaussian represents the red clump itself, and the parabola accounts for the “background” giants. Usually, stars are selected in the color range $0.8 < (V-I)_0 < 1.25$. It seems that in Fornax the red clump reaches slightly bluer colors than 0.8; however, this is also where the fainter part of the clump merges with the horizontal branch. From the fits performed for different color ranges, it is clear that bluer than $(V-I)_0 = 0.8$ the red clump is significantly fainter than for $(V-I)_0 > 0.8$. The fact that the width of the clump is larger for $(V-I)_0 < 0.8$ than for $(V-I)_0 > 0.8$ is also an indication that the clump is contaminated by the horizontal branch (see Table 1).

Fitting equation (3) to the whole red clump sample ($0.7-1.25$), one obtains $I_{0,m} = 20.25 \pm 0.004$. Restricting the color range to $0.8 \leq (V-I)_0 \leq 1.25$ gives $I_{0,m} = 20.24 \pm 0.004$ (see Fig. 2).

In order to obtain a distance, a metallicity correction to $I_{0,m}$ needs to be applied. I took $[\text{Fe}/\text{H}]_{RC} = -1.0$ for two reasons: (1) The average color of Fornax’s red clump is intermediate between the $[\text{Fe}/\text{H}] = -1.3$ and $[\text{Fe}/\text{H}] = -0.7$ cases of Girardi (1999a), and (2) Saviane, Held, & Bertelli (2000) recently argued that the average metallicity of Fornax is -1.0 . Using Popowski’s relation (Popowski 2000) yields $M_I^{RC} = -0.42$, then $\mu_0^{RC} = 20.66$; using Udalski’s relation, one has $\mu_0^{RC} = 20.60$.

3.2. The Tip of the Red Giant Branch

It has been shown that the TRBG is a reliable and accurate distance indicator (e.g., Lee, Freedman, & Madore 1993; Sakai

TABLE 1
VALUES OF THE AVERAGE CLUMP MAGNITUDE

$(V-I)_0$ Color Range	$I_{0,m}^a$	σ_{RC}^b	Comments
0.8–1.25	20.24	0.153	
	20.30	0.158	No reddening correction
0.8–1.0	20.25	0.155	
0.7–1.25	20.25	0.164	Affected by horizontal branch

^a For all fits the magnitude range was 19.5–21.0.

^b σ_{RC} is the width of the Gaussian (see eq. [1]).

et al. 2000 and references therein). Comparisons between TRGB distances and Cepheid distances in a number of galaxies have shown that there is excellent agreement between these two distance indicators (e.g., Lee et al. 1993; Kennicutt et al. 1998; Ferrarese et al. 2000). The absolute magnitude of the TRGB is almost constant, $M_I^{\text{TRGB}} \approx -4.0 \pm 0.1$ for $[\text{Fe}/\text{H}] \lesssim -0.7$ (Lee et al. 1993).

The average age and metallicity of red giants in Fornax are such that the TRGB method can safely be used. The I -band luminosity function of Fornax is shown in Figure 3. The TRGB is identified as the sharp number increase at $I_0 = 16.65$; the error is estimated to be 0.05 mag. This yields a distance modulus of $\mu_0 = 20.65 \pm 0.11$ mag. It agrees very well with the distance modulus derived above with the red clump. It is also in perfect agreement with the distance derived by Saviane et al. (2000) with the same method.

4. DISCUSSION

The red clump and TRGB distances agree in Fornax; it is thus puzzling that they do not agree in the LMC (Romaniello et al. 2000; Sakai et al. 2000). It might be worth looking at other galaxies with red clump and TRGB distances to see how these distances compare. The difference $\Delta I = I_{RC} - I_{\text{TRGB}}$ does not depend on a particular calibration of the distance scale: it is an observable quantity. Moreover, it should not be sensitive to reddening correction; hence, it can be used to compare the two methods. I collected data in the literature for Carina and the Small and Large Magellanic Clouds. For Carina I took the

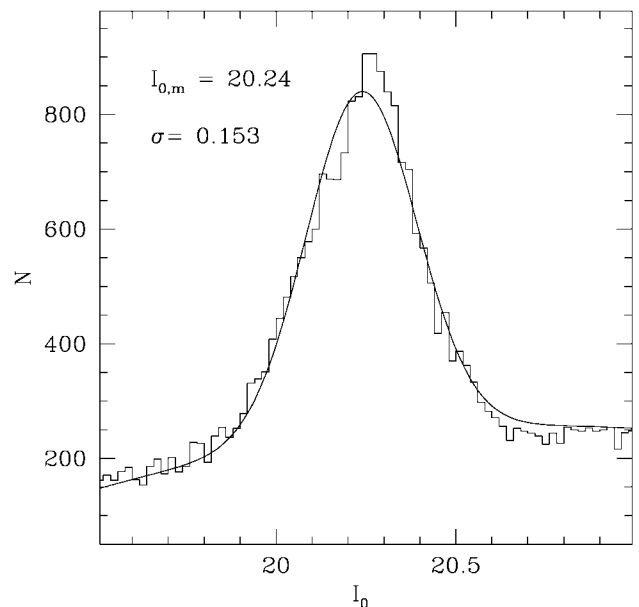


FIG. 2.—Magnitude distribution of red clump stars with colors in the range $0.8 < (V-I)_0 < 1.25$. The solid line is the fit of eq. (1).

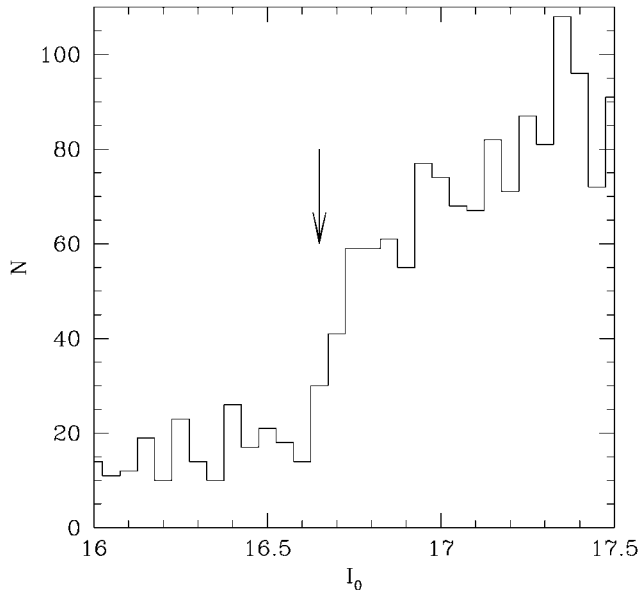


FIG. 3.— I -band luminosity function for bright stars. The tip of the red giant branch is identified by the arrow at $I_0 = 16.65$.

red clump magnitude I_m from Udalski (1998) and the TRGB magnitude from Smecker-Hane, Stetson, & Hesser (1994). These authors used different values for the reddening $E(B-V)$ so I used the observed magnitudes I_m and I_{TRGB} without reddening correction; these magnitudes are given in Table 2. For the SMC, I used the data made publicly available by the OGLE team (Udalski et al. 1998). For the LMC I used the data of Zaritsky, Harris, & Thompson (1997). I also took the TRGB and red clump magnitudes (corrected for reddening) published in Sakai et al. (2000) for the LMC. All these numbers as well as ΔI are given in Table 2.

The TRGB is calibrated with Galactic globular clusters that are old and metal-poor systems (Da Costa & Armandroff 1990). The TRGB is thus calibrated for ages larger than ≥ 2 Gyr and $[\text{Fe}/\text{H}] \leq -0.7$. We know that these conditions are met in Carina and Fornax since these galaxies contain old and metal-poor stars. It is also well known that the LMC has a population of old and metal-poor stars (as attested by the many thousands of RR Lyrae stars known in the LMC). However, stars of intermediate ages (2–3 Gyr) and/or more metal-rich than $[\text{Fe}/\text{H}] = -0.7$ do exist in the LMC and they could contaminate the TRGB. In other words, it could be that the TRGB detected by Sakai et al. (2000) is that of a young population. This seems very unlikely in view of the I -band luminosity function they present. The only possible brighter discontinuity in their luminosity function could be at ~ 14.2 (although it looks more like a noise spike). Furthermore, metal-rich stars younger than ~ 3 Gyr would be distributed over a fairly wide range in magnitude, and they would smooth out the I -band luminosity function; they would not create such a sharp discontinuity. Hence, the magnitude $I_{\text{TRGB}} = 14.54$ (from Sakai et al. 2000) must correspond to the TRGB of the old population, and it is not affected by intermediate-age stars. Only very young red supergiants are as bright or brighter than old red giants; however, there are very few supergiants compared to the number of red giant branch stars. Hence, the TRGB magnitude should be robust, even in a galaxy that contains young and intermediate-age populations such as the Magellanic Clouds.

The magnitude difference ΔI is plotted as a function of

TABLE 2
THE MAGNITUDE DIFFERENCE BETWEEN THE TRGB AND THE RED CLUMP FOR SEVERAL GALAXIES

Parameter	Carina	Fornax	SMC ^a	LMC ^b	LMC ^c
$[\text{Fe}/\text{H}]^d$	-1.9	-1.0	-1.0	-0.6	-0.6
I_{TRGB}^e	16.15	16.65	15.00	14.60	14.54
I_{RC}^f	19.56	20.24	18.51	18.20	18.06
ΔI^g	3.41	3.59	3.51	3.60	3.52

NOTE.—Uncertainties on I_{TRGB} are ~ 0.05 mag; on I_{RC} they are of order 0.03 mag.

^a Based on OGLE data (Udalski et al. 1998).

^b Based on data from Zaritsky et al. 1997.

^c Taken from Sakai et al. 2000.

^d The $[\text{Fe}/\text{H}]$ values are from Smecker-Hane et al. 1994 and Udalski 1998 for Carina, Saviane et al. 2000 and this Letter for Fornax, and Udalski 1998 for the LMC and SMC.

^e I_{TRGB} is the observed magnitude of the TRGB.

^f I_{RC} is the observed average magnitude of the red clump.

^g $\Delta I = I_{\text{RC}} - I_{\text{TRGB}}$.

$[\text{Fe}/\text{H}]$ in Figure 4. The solid line in this figure is the magnitude difference obtained with $I_{\text{TRGB}} = -3.9$ mag and $I_{\text{RC}} = 0.13[\text{Fe}/\text{H}] - 0.23$ (Udalski 2000). Note that in this figure all points except the lower LMC point have not been corrected for reddening. Two facts deserve some comments. First, there is a disagreement between the two LMC measurements. Both are based on the same data set (Zaritsky et al. 1997), but one has been corrected for extinction while the other has not. In his referee report, Udalski used OGLE2 data to determine ΔI after correcting for reddening, using the OGLE reddening map (Udalski et al. 1999). He finds $\Delta I = 3.62$, virtually identical to 3.60 found here without reddening correction. This shows that the source of the discrepancy between TRGB and red clump distance measurements probably lies in the extinction correction rather than in the intrinsic properties of one or the other of these distance indicators.

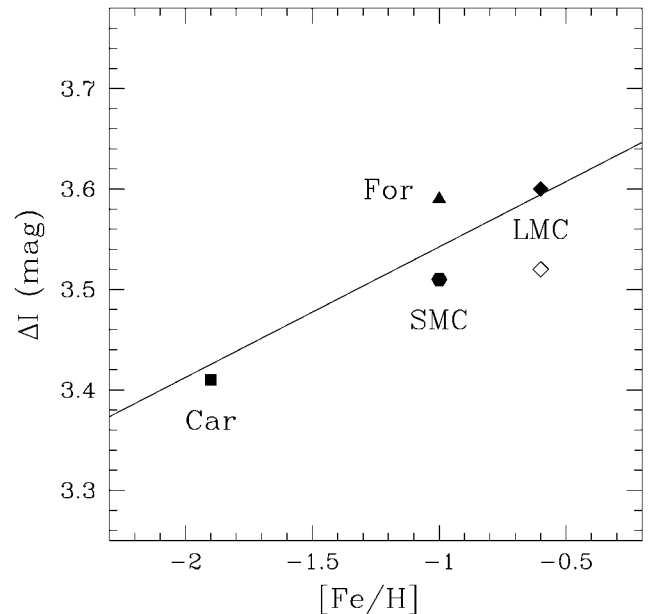


FIG. 4.—Magnitude difference $\Delta I = I_{\text{RC}} - I_{\text{TRGB}}$ plotted as a function of metal content $[\text{Fe}/\text{H}]$. Each galaxy name is indicated. The solid line is the difference in absolute magnitudes when using Udalski's relation for the absolute magnitude of the red clump and with $I_{\text{TRGB}} = -3.9$. Filled symbols indicate that no reddening correction has been applied; the open diamond indicates that a reddening correction has been applied. Error bars have been omitted for clarity.

Second, the solid line seems to represent very well the behavior of the difference $I_{\text{RC}} - I_{\text{TRGB}}$, provided that the same reddening correction is applied to both red clump stars and tip giants, assuming that Udalski's relation correctly predicts the metallicity dependence of the red clump and that the TRGB absolute magnitude is $I_{\text{TRGB}} = -3.9$ mag. Note that using Popowski's relation for the red clump (Popowski 2000) would change ΔI only by a few hundredths of a magnitude. The TRGB is calibrated using RR Lyrae stars (Da Costa & Armandroff 1990); the recent revision of RR Lyrae magnitudes advocated by Popowski & Gould (1998) would decrease the brightness

of the TRGB. If the above procedure is correct, these two distance indicators can be in much better agreement than previously thought.

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