ON THE DISTANCE AND REDDENING OF THE STARBURST GALAXY IC 10

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ABSTRACT

We present deep and accurate optical photometry of the Local Group starburst galaxy IC 10. The photometry is based on two sets of images collected with the Advanced Camera for Surveys and with the Wide Field Planetary Camera 2 on board the Hubble Space Telescope. We provide new estimates of the tip of the red giant branch (TRGB) magnitude, $m_{\text{TRGB}}^{F555W} = 21.90 \pm 0.03$, and of the reddening, $E(B-V) = 0.78 \pm 0.06$, using field stars in the Small Magellanic Cloud (SMC) as a reference. Adopting the SMC and two globulars, ω Cen and 47 Tuc, as references we estimate the distance modulus to IC 10: independent calibrations give weighted average distances of $\mu = 24.51 \pm 0.08$ (TRGB) and $\mu = 24.56 \pm 0.08$ (RR Lyrae). We also provide a new theoretical calibration for the TRGB luminosity, and using these predictions we find a very similar distance to IC 10 ($\mu \approx 24.60 \pm 0.15$). These results suggest that IC 10 is a likely member of the M31 subgroup.

Subject headings: galaxies: individual (IC 10) — Local Group — stars: distances

1. INTRODUCTION

The dwarf galaxy IC 10 is a very interesting stellar system in the Local Group. It has been classified as an Ir IV by van den Bergh (1999), but it has also been suggested that it is the only analog of a poststarburst dwarf galaxy in the Local Group (Gil de Paz et al. 2003). This means that IC 10 is a very good laboratory to investigate episodic star formation over a broad time interval (Hunter 2001; Demers et al. 2004). Moreover, spectroscopic estimates based on H II regions indicate that the present-day interstellar medium metal abundance is [Fe/H] $\sim -0.71 \pm 0.10$, (Garnett 1990). We cannot exclude the possibility of a range of metallicity in IC 10, but comparison with stellar isochrones (Hunter 2001) also indicates a mean metallicity of [Fe/H] $\sim -0.7$. This metal content is very similar to that of the Small Magellanic Cloud (SMC; [Fe/H] $\approx -0.7$, Zaritsky et al. 1994, based on H II regions; [Fe/H] $\sim -0.75 \pm 0.08$, Romaniello et al. 2008, based on classical Cepheids).

However, IC 10 is located at very low Galactic latitude ($l = 119.0^\circ$, $b = -3.3^\circ$), and is therefore affected by significant foreground extinction. This circumstance has made estimates of both reddening and distance quite difficult and controversial. Distance determinations based on different standard candles cover a wide range, from closer than M31—$d = 0.5$ Mpc based on the tip of the red giant branch (TRGB; Sakai et al. 1999)—to well outside the Local Group, $d = 1.8$ Mpc based on the luminosity function (LF) of planetary nebulae (Jacoby & Lesser 1981). A similar disparity is found among the reddening determinations, with estimates ranging from $E(B-V) \sim 0.8$ based on spectra of H II regions (Richer et al. 2001), to $E(B-V) \sim 1.2$ based on classical Cepheids (Sakai et al. 1999). Moreover, a spread in distance and reddening values can be found even when using the same distance indicator and stellar tracer (see Table 1 in Demers et al. 2004). Therefore, we still lack firm constraints on the random and systematic errors affecting these important parameters.

2. OBSERVATIONS AND DATA REDUCTION

Our photometric catalog is based on archival Hubble Space Telescope (HST) data sets collected with both the Advanced Camera for Surveys (ACS, pointings α and β) and with the Wide Field Planetary Camera 2 (WFPC2, pointing γ).12 Pointing α is located at the galaxy center and consists of six F606W- and six F814W-band images of 360 s each. Pointing β is located ~2′ NW from the galaxy center and includes 32 F555W-band images of 620 s each and 16 F814W-band images of 595 s each. Pointing γ is again located at the galaxy center and includes 10 F555W- and 10 F814W-band images of 1400 s each. Pointings α and β (ACS) overlap by about one chip, while pointing γ (WFPC2) almost entirely overlaps with pointing α. We combined the ACS images using an updated version of the MultiDrizzle package (Koekemoer et al. 2002), which provides an automated method for correcting distortion and combining dithered images. The WFPC2 images were prereduced using the HST pipeline. Initial photometry on individual images was performed with DAOPHOT IV, followed by simultaneous photometry over the 80 images with ALLFRAME (Stetson 1994). We ended up with a catalog including ~720,000 stars with at least one measurement in each of two different bands. The ACS data in the F555W and F814W bands were transformed into the VEGAMAG system following Sirianni et al. (2005). To provide a homogeneous photometric catalog the F606W-band images collected with the ACS were transformed into the F555W band using local standards. The same approach was adopted to transform the F555W and the F814W images col-

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Fig. 1.—$F814W, F555W - F814W$ CMD of IC 10 based on data collected with HST (fields C and E). Using different selection criteria (sharpness, separation, photometric error) we ended up with $\approx 150,000$ candidate galaxy stars (CGS). The error bars on the right display the mean intrinsic error.

selected with WFPC2 to the corresponding ACS systems. On average the precision of the above transformations is $F555W - F606W(ACS) = -0.006 \pm 0.049$, $F555W(ACS) - F555W(WFPC2) = 0.009 \pm 0.054$, $F814W(ACS) - F814W(WFPC2) = 0.003 \pm 0.050$ mag (N. Sanna et al. 2008, in preparation). To overcome possible changes in the internal reddening when moving from the center toward the external regions of the galaxy we split the final catalog into two different regions. Region C is located at the galaxy center, while the field lying at a radial distance larger than two arcminutes is our region E. Data plotted in Figure 1 show that the current photometry ranges from very bright main-sequence stars ($F814W \sim 21, F555W - F814W \sim 1$) to faint RG stars ($F814W \sim 25.5, F555W - F814W \sim 2$) with very good precision.

3. RESULTS AND DISCUSSION

To estimate the TRGB in IC 10 we adopted the approach used in Bono et al. (2008, hereafter B08). In particular, we selected stars with $21.5 \leq F814W \leq 22.4$ and $F555W - F814W \geq 2.8$. Note that the stellar samples in the central and external regions include, respectively, $\sim 3000$ and $\sim 2400$ stars within one $F814W$-band magnitude of the tip. This is more than an order of magnitude larger than the number required for a robust detection of the TRGB (Madore & Freedman 1995). The top panels of Figure 2 show a well-defined jump in the star counts for $m_{F814W} \sim 21.90$, which we take to mark the position of the TRGB. This identification is supported by the smoothed LF.
We found that the selective absorptions in the two ACS filters are: $A_{F555W} = 1.03 \times A_V$ and $A_{F814W} = 0.55 \times A_V$. If we assume an SMC reddening of $E(B-V) = 0.08$ (Sabb et al. 2007), this means a mean reddening of $E(F555W - F814W) = 1.16 \pm 0.06$ for IC 10, and in turn $E(B-V) = 0.78 \pm 0.06$. The error budget includes generous estimates on the relative reddening ($\pm 0.05$), on the SMC reddening ($\pm 0.02$) and on the reddening law (Fitzpatrick 1999). The left panel of Figure 3 shows the comparison between the SMC (green dots) and IC 10 (gray dots) using the above differential reddening and relative distance based on the TRGB (see infra). The new reddening estimate is in very good agreement with the reddening estimates based on spectra of H II regions $[E(B-V) = 0.77 \pm 0.07]$; Richer et al. 2001], TRGB stars $[E(B-V) \sim 0.85]$; Sakai et al. 1999], carbon stars $[E(B-V) \sim 0.79]$, and a change across the field of $\sim$0.38 mag; Demers et al. 2004], and Wolf-Rayet stars $[E(B-V) = 0.75-0.80]$; Massey & Armandroff 1995]. We do not support a reddening as high as estimated from classical Cepheid variables.

We also estimated the relative distance between IC 10 and the SMC. For the SMC, we adopted the TRGB estimate provided by Cioni et al. (2000), i.e., $m_{(SMC)} = 14.95 \pm 0.03$. With the reddening quoted above for SMC $[E(B-V) = 0.08]$, the color-metallicity relation for TRGB stars provided by Bellazzini et al. (2001), and the transformations from the Cousins $I$-band to the ACS VEGAMAG system by Sirianni et al. (2005), we found $m_{F814W,0}^{(SMC)} = 14.81 \pm 0.05$. Using the above reddening, we found that $m_{F814W,0}^{(IC 10)} = 20.57 \pm 0.07$ and the error budget includes the same sources.

The reason is threefold: (1) accurate spectroscopic measures indicate that its iron abundance is very similar to IC 10, i.e., $[Fe/H] = -0.66 \pm 0.04$ (Gratton et al. 2003); (2) it is minimally affected by reddening: $[E(B-V) = 0.04 \pm 0.02]$; Solaris et al. 2007]; (3) an accurate estimate of the TRGB has been recently provided by B08. By transforming the Cousins $I$-band into the ACS VEGAMAG system (Sirianni et al. 2005), we found that the TRGB in 47 Tuc is located at $m_{F814W,0}(47 \text{ Tuc}) = 9.40 \pm 0.08$. The error budget accounts for uncertainties in the reddening, in the TRGB detection, and in the photometric transformation. Therefore, the relative distance is $\Delta \mu = 5.76 \pm 0.09$. The arrow plotted in the middle panel of Figure 3 shows that the magnitudes of TRGB stars in SMC and in IC 10 agree within the uncertainties.

To further constrain the relative distance to IC 10, we also compared it to the Galactic globular cluster (GGC) 47 Tuc. The reason is threefold: (1) accurate spectroscopic measures indicate that its iron abundance is very similar to IC 10, i.e., $[Fe/H] = -0.66 \pm 0.04$ (Gratton et al. 2003); (2) it is minimally affected by reddening: $[E(B-V) = 0.04 \pm 0.02]$; Solaris et al. 2007]; (3) an accurate estimate of the TRGB has been recently provided by B08. By transforming the Cousins $I$-band into the ACS VEGAMAG system (Sirianni et al. 2005), we found that the TRGB in 47 Tuc is located at $m_{F814W,0}(47 \text{ Tuc}) = 9.40 \pm 0.08$. The error budget accounts for uncertainties in the reddening, in the TRGB detection, and in the photometric transformation. Therefore, the relative distance is $\Delta \mu = 5.76 \pm 0.09$. The arrow plotted in the middle panel of Figure 3 shows that the magnitudes of TRGB stars in 47 Tuc and IC 10 agree within the uncertainties.

We also estimated the relative distance between IC 10 and the GGC $\omega$ Cen. Again, the reason is threefold: (1) it is the most massive GGC and it hosts a sizable sample of bright RG stars ($\sim$220) close to TRGB, so the TRGB detection is particularly robust; (2) accurate distance estimates are available using several different standard candles (Del Principe et al. 2006]; (3) an accurate estimate of the TRGB has been recently provided by B08. We found that the TRGB in $\omega$ Cen is located at $m_{F814W,0}(\omega \text{ Cen}) = 9.73 \pm 0.09$. The error budget accounts for uncertainties in the reddening, in the TRGB detection, and in the photometric transformation. Therefore, the relative distance is $\Delta \mu = 11.17 \pm 0.11$. A glance at the data plotted in the middle panel of Figure 3 shows very good agreement between the magnitudes of TRGB stars in 47 Tuc and IC 10. Moreover, the RGs in 47 Tuc also attain very similar colors to RGs in IC 10, thus supporting the reddening (and metallicity) estimate.

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for uncertainties in the reddening \([E(B - V) = 0.11 \pm 0.02]\), in the TRGB detection, and in the photometric transformation. Moreover, we also accounted for the difference in metallicity between \(\omega\) Cen \([\text{[Fe/H]} \sim -1.7, \text{metal-poor peak; Johnson et al. 2008}\) and IC 10, and their uncertainties \((\text{B08})\). The relative distance is then \(\Delta \mu = 10.84 \pm 0.11\). The right panel of Figure 3 shows that the magnitudes of TRGB stars in \(\omega\) Cen and in IC 10 agree quite well. The bright RGs in \(\omega\) Cen are, as expected, bluer when compared with RGs in IC 10. To evaluate the true distance to IC 10, we used the TRGB calibrations provided by Bellazzini et al. \((2004)\) and Lee et al. \((1993)\). For the SMC, we found a true modulus of \(\mu = 18.77 \pm 0.13\) or \(\mu = 18.73 \pm 0.12\); \(\mu = 18.75 \pm 0.09\) is the weighted average. Thus, the true modulus of IC 10, based on the TRGB scale of SMC, is \(\mu = 24.51 \pm 0.13\). Using the same TRGB calibrations we found for 47 Tuc a true modulus of \(\mu = 13.36 \pm 0.14\) and \(\mu = 13.32 \pm 0.12\) \((\mu = 13.34 \pm 0.10, \text{weighted average})\). Thus, the modulus of IC 10, based on the TRGB scale of 47 Tuc, is \(\mu = 24.51 \pm 0.15\). Finally, using the same TRGB calibrations the true moduli for \(\omega\) Cen are: \(\mu = 13.67 \pm 0.14\) and \(\mu = 13.65 \pm 0.13\) \((\mu = 13.66 \pm 0.10, \text{weighted average})\). Therefore, the modulus of IC 10, based on the TRGB scale of \(\omega\) Cen, is \(\mu = 24.50 \pm 0.15\). On the other hand, if we use the \(K\)-band period-luminosity \((\text{PL})\) relations provided by Del Principe et al. \((2006)\) and Sol- lima et al. \((2005)\), the true modulus of 47 Tuc based on the variable V9 is \(\mu = 13.38 \pm 0.06\) and \(\mu = 13.47 \pm 0.11\) \((\mu = 13.40 \pm 0.05, \text{weighted average})\). Therefore, the modulus of IC 10, based on the RR Lyrae scale, is \(\mu = 24.57 \pm 0.12\). Using the same \(K\)-band PL relations, the true modulus of \(\omega\) Cen is \(\mu = 13.70 \pm 0.06\) or \(\mu = 13.75 \pm 0.11\) \((\mu = 13.71 \pm 0.05, \text{weighted average})\). Therefore, the modulus of IC 10, based on the RR Lyrae scale to \(\omega\) Cen, is \(\mu = 24.55 \pm 0.12\). The weighted average true moduli of IC 10 agree within \(1 \sigma\) and are: \(\mu = 24.51 \pm 0.08\) \((\text{TRGB scale})\) and \(\mu = 24.56 \pm 0.08\) \((\text{RR Lyrae scale})\). These estimates agree within \(1 \sigma\) with previous distance determinations based on carbon stars \(\mu = 24.35 \pm 0.11, E(B - V) = 0.79; \text{Demers et al. 2004}\); on optical \(\mu = 24.59 \pm 0.30, E(B - V) = 0.97; \text{Saha et al. 1996}\) and NIR \(\mu = 24.57 \pm 0.21, E(B - V) = 0.8; \text{Wilson \\

As a final test of the systematic errors that might affect the distance estimates to IC 10, we calculated new theoretical TRGB calibrations. We adopted the homogeneous set of cluster isochrones for scaled-solar abundances provided by Pietrinferni et al. \((2004)\); in particular, we adopted isochrones with \(t = 12\) Gyr, mass loss \(\eta = 0.4\), and iron abundances from \(-2.3\) to \(-0.5\). However, theory was transformed into the observational plane using only scaled-solar atmospheres based on ATLAS9 models \((\text{Castelli \\

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