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I Zw 18 REVISITED WITH *HST* ACS AND CEPHEIDS: NEW DISTANCE AND AGE[1]

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ABSTRACT

We present new *V*- and *I*-band *HST* ACS photometry of I Zw 18, the most metal-poor blue compact dwarf (BCD) galaxy in the nearby universe. It has been argued in the past that I Zw 18 is a very young system that started forming stars only ≲500 Myr ago, but other work has hinted that older (≳1 Gyr) red giant branch (RGB) stars may also exist. Our new data, once combined with archival *HST* ACS data, provide a deep and uncontaminated optical color-magnitude diagram (CMD) that now strongly indicates an RGB. The RGB tip (TRGB) magnitude yields a distance modulus $(m-M)_0 = 31.30 \pm 0.17$, i.e., $D = 18.2 \pm 1.5$ Mpc. The time-series nature of our observations allows us to also detect and characterize for the first time three classical Cepheids in I Zw 18. The time-averaged Cepheid $\langle V \rangle$ and $\langle I \rangle$ magnitudes are compared to the *VI* reddening-free Wesenheit relation predicted from new nonlinear pulsation models specifically calculated at the metallicity of I Zw 18. For the one bona fide classical Cepheid with a period of 8.63 days this implies a distance modulus $(m-M)_0 = 31.42 \pm 0.26$. The other two Cepheids have unusually long periods (125.0 and 129.8 days) but are consistent with this distance. The coherent picture that emerges is that I Zw 18 is farther away than previously assumed and older than suggested by some previous works. The presence of an RGB population rules out the possibility that I Zw 18 is a truly primordial galaxy formed recently ($z \lesssim 0.1$) in the local universe.

Subject headings: Cepheids — galaxies: dwarf — galaxies: evolution — galaxies: individual (I Zw 18) — galaxies: irregular — galaxies: stellar content

1. INTRODUCTION

The BCD galaxy I Zw 18 is one of the most intriguing nearby objects. With 12 + log (O/H) = 7.2, corresponding to 1/50 $Z_\odot$ (Skillman & Kennicutt 1993), it has the lowest nebular oxygen abundance of all known star-forming galaxies in the nearby universe. It has a high gas fraction (e.g., van Zee et al. 1998) and extremely high star formation (SF) rate per unit mass (Searle & Sargent 1972), producing a blue young stellar population that dominates the integrated luminosity and color. All these observational evidences make I Zw 18 a chemically unevolved stellar system. As such, it has long been regarded as a possible example of a galaxy undergoing its first burst of star formation and hence a local analog to primordial galaxies in the distant universe.

Many *Hubble Space Telescope* (*HST*) studies have focused on the evolutionary state of I Zw 18. After other groups had already resolved the brightest individual stars in the galaxy, our group managed to detect fainter asymptotic giant branch (AGB) stars in *HST* WFPC2 images with ages of at least several hundred Myr (Aloisi et al. 1999). These results were confirmed by Östlin (2000) through deep *HST* NICMOS imaging. More recently, Izotov & Thuan (2004, hereafter IT04) presented new deep *HST* ACS imaging observations. Their *I* versus $V-I$ CMD shows no sign of an RGB (i.e., low-mass stars with ages ∼1–13 Gyr that are burning H in a shell around a He core) at an assumed distance $D \lesssim 15$ Mpc. Their conclusion is that the most evolved (AGB) stars are not older than 500 Myr and that I Zw 18 is a bona fide young galaxy. This result was subsequently challenged by Momany et al. (2005) and our group (Tosi et al. 2007) based on a better photometric analysis of the same data. This showed that many red sources do exist at the expected position of an RGB, and that their density in the CMD drops exactly where a RGB tip (TRGB, at the luminosity of the He flash) would be expected. However, the small number statistics, large photometric errors, and incompleteness did not allow a more conclusive statement.

The actual nature of I Zw 18 has important cosmological implications. According to hierarchical formation scenarios, dwarf ($M \lesssim 10^9\,M_\odot$) galaxies should have been the first systems to collapse and start forming stars. Indeed, an RGB has been detected in all metal-poor dwarf irregular galaxies of the Local Group and BCDs within $D \lesssim 15$ Mpc that have been imaged with *HST* (e.g., SBS 1415+437; Aloisi et al. 2005 and references therein). I Zw 18 has remained the only elusive case so far.

The lack of RGB evidence has also made it impossible to pinpoint the distance of I Zw 18 via the TRGB method. Its distance therefore continues to be debated. With a recession velocity of 745 ± 3 km s^{-1}, I Zw 18 has often been assumed to be at a distance of ∼10 Mpc ($H_0 = 75$ km s^{-1} Mpc^{-1}). Correction for Virgocentric infall implies a slightly larger distance between 10 and 14.5 Mpc ($30.0 \lesssim m-M \lesssim 30.8$; Östlin 2000). Izotov et al. (2000) argued that I Zw 18 should be as distant as 20 Mpc to provide consistency between the CMD, the presence of Wolf-Rayet stars, and the ionization state of the H II regions. But they suggested in IT04 a shorter distance $D \lesssim 15$ Mpc from the brightness of AGB stars.

In this Letter we present new *V* and *I* time-series photometry of I Zw 18 with *HST* ACS that allows the first detection and study of the galaxy's Cepheid stars. Our new data, once com-

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bined with the archival ones, also yield a better CMD than has been hitherto available, reaching about 1.5 mag below the TRGB. We find that I Zw 18 is actually farther away than previously assumed and the hypothesis that it is a truly young galaxy is no longer tenable.

2. OBSERVATIONS AND DATA REDUCTION

Time-series photometry of I Zw 18 was collected with ACS WFC in 12 different epochs between 2005 October and 2006 January (GO program 10586; PI: Aloisi). Due to the failure of the F814W exposure in one of the 12 visits (subsequently repeated), an additional epoch in F606W is available. Total integration times of ∼27,700 and ∼26,200 s were obtained in F606W and F814W, respectively. The four optimally dithered single exposures per epoch per filter were registered by carefully measuring stars in the individual frames. The pipeline-calibrated exposures were then corrected for geometric distortion and co-added with cosmic-ray rejection using the MultiDrizzle software to create an image per epoch each filter. The images were drizzled onto a smaller pixel scale than the 0.05″ ACS pixels, to take advantage of the small-scale dithers and improve the S/N for photometry. A similar procedure was used on all the single exposures to create a master image in both filters. Similarly, the archival ACS/WFC data in F555W and F814W (GO program 9400; PI: Thuan) taken over a period of 11 days in 2003 May–June were combined into a master image for a total integration time of ∼43,500 and ∼24,300 s in F555W and F814W, respectively. Single images per epoch were also produced for the archival data (five in F555W and three in F814W).

The CMD shown in Figure 1 was obtained by performing PSF-fitting photometry with the DAOPHOT/ALLSTAR package (Stetson 1987) on the master images from our new and the archival data. Aperture corrections were measured from stars in the frame and applied to all photometry. Corrections for imperfect charge transfer efficiency (Riess & Mack 2004) proved to be negligible (e.g., $\lesssim$0.03 mag in all filters for a red TRGB star) and were not applied. Count rates were transformed to the Johnson-Cousins V and I magnitudes using the transformations given by Sirianni et al. (2005), which have been shown to be accurate to ∼0.02 mag. The values shown and discussed hereafter are corrected for $E(B-V) = 0.032$ mag of Galactic foreground extinction, but not for any extinction intrinsic to I Zw 18. For conciseness, we refer to these magnitudes throughout this Letter as V and I instead of V_0 and I_0. The two ACS data sets were combined using several different approaches and rejection schemes. The results discussed here were obtained by demanding that stars should be detected in all the four deep images (V and I for both data sets), yielding a catalog of ∼2100 stars. At the expense of some depth, this approach has the advantage of minimizing the number of false detections and therefore providing a relatively clean CMD. F. Annibali et al. (2007, in preparation) will present more details about the data reduction and photometric analysis, as well as a star formation history (SFH) analysis.

PSF-fitting photometry of the single epochs in both our own and the archival ACS/WFC time-series data was performed with the DAOPHOTII/ALLSTAR/ALLFRAME package (Stetson 1987, 1994) to search for and obtain light curves of the galaxy's variable stars. Candidate variables were identified using four independent methods on the single-epoch images: (1) the optimal image subtraction technique and the package ISIS 2.2 (Alard 2000), (2) the variability index (Welch & Stetson 1993), (3) an independent PSF-fitting photometry performed with the DoPHOT program (Schechter et al. 1993) to search for periodic variables as detailed in Saha & Hoessel (1990), and (4) visual inspection of a χ^2 image, where each pixel is the χ^2 value calculated from the corresponding pixels in the coregistered target images at all epochs. In addition, all suspected variables were examined by visually "blinking" the relevant spots in the images at the various epochs.

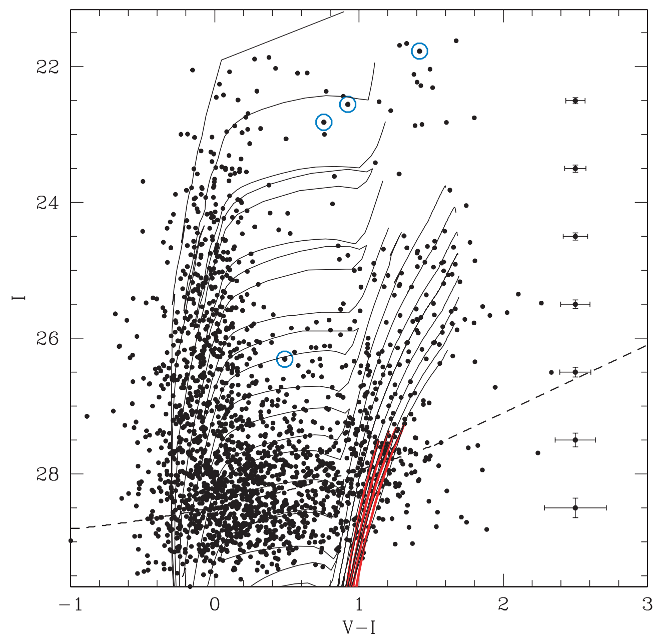

Fig. 1.—Johnson-Cousins I, $V-I$ CMD of the resolved stellar population in both the main and secondary bodies of I Zw 18. The data are corrected for foreground extinction, but not for possible extinction internal to the galaxy. Padua isochrones for *(roughly from top left to bottom right)* log (age) = 6.75, 7.00, 7.25, …, 9.75, 10.00 are overlaid, with the RGB phase for isochrones with log (age) = 9.25, 9.50, 9.75, and 10 colored red (Bertelli et al. 1994). The isochrones have metallicity $Z = 0.0004$ (as inferred from the H II regions of I Zw 18) and are shown for the distance of $D = 18.2$ Mpc ($m - M = 31.30$) inferred from the TRGB. Blue open circles highlight the four confirmed variables (see § 4), which are plotted according to their intensity-averaged magnitudes. Their periods are (*from bottom to top*) 8.63, 129.8, and 125.0 days. The period of the brightest variable is even longer, but its exact value is not well determined. Median photometric errors at $V-I = 1$ (determined by comparison of measurements from GO-9400 and GO-10586) are shown as function of I-band magnitude on the right. The dashed curve is an estimate of the 50% completeness level (obtained by fitting the combination of a parameterized completeness function and a model SFH to the observed CMD). More sophisticated estimates of the errors and completeness based on artificial star tests will be presented in F. Annibali et al. (2007, in preparation).

The four procedures returned four confirmed variables. These are discussed in § 4 below, and they are highlighted with open circles in the CMD of Figure 1. In addition, some 30 other objects were flagged as candidate variables, but we were generally unable to find convincing periods nor otherwise classify them. Most of these objects are in the main body of I Zw 18, where crowding complicates the characterization of variables.

3. THE COLOR-MAGNITUDE DIAGRAM

At magnitudes brighter than $I \simeq 27$ mag, we find in the CMD the same star types previously detected with ACS by IT04: main-sequence (MS) stars and their more evolved counterparts, i.e., young supergiants (SGs) and AGB stars. A "blue plume," which is the combined feature of MS stars and blue SGs (evolved stars at the hot edge of their core He-burning phase), shows up near $V - I \simeq 0.0$ mag. At $V - I \simeq 1.3$ mag, red SGs appear at magnitudes $I \lesssim 24$ mag, while AGB stars dominate in the magnitude range $I \simeq 25$–27 mag and form the upper part of what we will

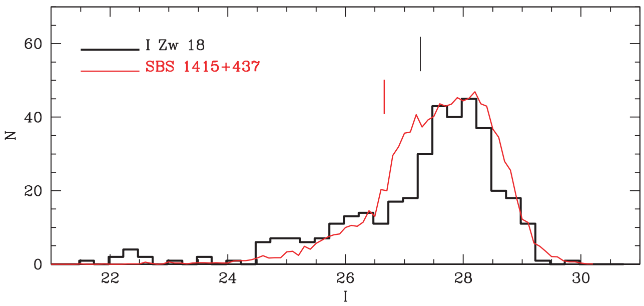

FIG. 2.—*I*-band LF histogram for stars in I Zw 18, showing (*black line*) the number of stars N with colors in the range $V-I = 0.75$–1.5 mag per 0.25 mag *I*-magnitude bin, inferred from the CMD in Fig. 1. For comparison, the LF of SBS 1415+437 from the ACS data presented in Aloisi et al. (2005) is also plotted (*red line*), arbitrarily renormalized. Vertical marks indicate the positions of the TRGB, determined as described in the text. At these magnitudes there is a steep LF drop toward brighter magnitudes, due to the end of the RGB sequence. By contrast, the LF drop toward fainter magnitudes at $I \gtrsim 28$ mag is due to incompleteness in both cases. Apart from a distance shift $\Delta(m-M) \simeq 0.61$, these metal-poor BCD galaxies have very similar LFs.

call a "red plume." The morphology of the AGB star features compares well with the positions at which oxygen-rich and carbon-rich AGB stars are predicted in evolutionary models (e.g., Marigo et al. 2003, Fig. 12). Our ACS data show that both the blue and red plumes extend down to much fainter magnitudes. But more importantly, they reveal the presence of a much older stellar population. Indeed, below $I \simeq 27.3$ mag and around $V-I \simeq 1.3$ mag, we detect faint red stars exactly at the position where an RGB would be expected (see the Padua isochrones overplotted in Fig. 1). The small median error around $I \simeq 27.5$ mag suggests that these faint red stars are not more massive younger stars with large photometric uncertainties.

Figure 2 shows the *I*-band luminosity function (LF) for stars in I Zw 18 CMD with red colors in the range $V-I = 0.75$–1.5 mag. This LF presents a sharp drop toward brighter magnitudes, exactly as would be expected from a TRGB. We used a Savitzky-Golay filtering technique developed by one of us (R. P. v. d. M.) and described in Cioni et al. (2000) to determine the TRGB magnitude. This yields $I_{\rm TRGB} = 27.27 \pm 0.14$ mag, with the error bar being dominated by random uncertainties from the finite number of stars. At the metallicity of I Zw 18, the absolute magnitude of the TRGB discontinuity is $M_{I,\,\rm TRGB} = -4.03 \pm 0.10$ (Bellazzini et al. 2004). This implies a distance modulus $(m-M)_0 = 31.30 \pm 0.17$ mag, i.e., $D = 18.2 \pm 1.5$ Mpc, assuming that the evolved RGB stars have negligible intrinsic extinction (see, e.g., Cannon et al. 2002).

The evidence for an RGB in I Zw 18 is further strengthened by comparison to another BCD, SBS 1415+437, observed by us with a similar *HST* ACS setup (Aloisi et al. 2005). This galaxy is not quite as metal-poor as I Zw 18 [$12 + \log({\rm O/H}) = 7.6$] and is nearer at $D \simeq 13.6$ Mpc. But taking into account the differences in distance, corresponding to a $\Delta(m-M) \simeq 0.61$ mag, the two BCDs have very similar LFs (see Fig. 2). Since SBS 1415+437 has an unmistakable RGB sequence, this suggests that such an RGB sequence exists in I Zw 18 as well. The larger distance of I Zw 18 explains why with a similar observational setup we detect ~10 times fewer stars than in SBS 1415+437.

4. CLASSICAL CEPHEIDS IN I Zw 18

Periods and classification in type of the four confirmed variable stars in I Zw 18 were derived from the study of the V and I light curves separately, using GrATiS (Graphical Ana-

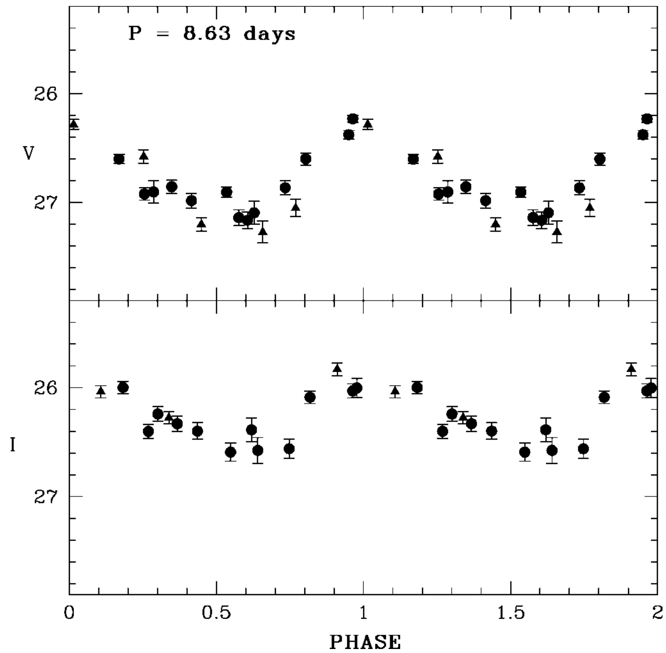

FIG. 3.—V and I light curves, corrected for Galactic foreground extinction, for the 8.63 day Cepheid. The single-epoch photometry was calibrated to the Johnson-Cousins V and I bands by calculating the zero point offset between the intensity-averaged instrumental magnitudes of the light curves and the DAOPHOT/ALLSTAR photometry of the master images. Filled circles represent our data from GO-10586, while filled triangles represent the archival data of GO-9400. Random errors from the photometry performed on the single-epoch images with DAOPHOTII/ALLSTAR/ALLFRAME are also indicated.

lyzer of Time Series), custom software developed at the Bologna Observatory by P. Montegriffo (Clementini et al. 2000 and references therein), which uses both the Lomb periodogram and light-curve fitting with a truncated Fourier series.

Our ACS WFC data along with the archival ones span a total time baseline of about 2.5 yr. The combined data set allowed us to derive reliable periods for three of the four confirmed variable stars. All of them are classified as classical Cepheids, both based on the shape of the light curve and the star's position on the CMD, where they all fall within or close enough to the instability strip for classical Cepheids at the metallicity of I Zw 18. One of these Cepheids has a period of 8.63 days (see Fig. 3), well within the typical range used to statistically define period-luminosity (PL) relations in other galaxies. The other two Cepheids have instead periods of 125.0 and 129.8 days, respectively. This is much longer than typical Cepheid periods of $P \lesssim 70$–80 days (see Udalski et al. 1999; Freedman et al. 2001), although some Cepheids are known in the LMC and SMC with periods P up to 134 days (e.g., van Genderen 1983). The precision of our period determinations is of the order of 1–2 decimal places. The residuals from the truncated Fourier series that best fit the folded light curves are in the ranges 0.02–0.12 and 0.02–0.11 mag, in V and I, respectively.

The fourth confirmed variable is very bright and red. Due to incomplete time sampling, two possible alternative periodicities of 139 and 186 days were found for this variable. In spite of the unusually long period and the red color, probably due to the star being blended by a red companion, both the high luminosity and the shape of the light curve suggest that this variable star is probably a classical Cepheid as well. In absence of a well-determined period, it will not be considered further in our discussion below. A more detailed description of the sample of variable stars, and the data analysis performed to identify and characterize them, will be presented in G. Fiorentino et al. (2007, in preparation). This sample will be unique for probing the properties of variable stars at previously unexplored metallicities. Here we focus merely on the implied distance of I Zw 18.

New nonlocal time-dependent convective pulsating theoretical models of classical Cepheids were computed at the proper metallicity of I Zw 18 ($Z = 0.0004$, $Y = 0.24$) by our group (M. Marconi et al. 2007, in preparation). These models build on our previous modeling expertise at higher metallicities (e.g., Marconi et al. 2005; Fiorentino et al. 2007). The new models were used to obtain a theoretical reddening-free *VI* Wesenheit relation that was directly compared to the Wesenheit relation of the observed Cepheids in order to infer a distance. The 8.63 day Cepheid yields a distance modulus $(m - M)_0 = 31.42 \pm 0.26$ mag if a canonical mass-luminosity relation is assumed in the model computations and of $(m - M)_0 = 31.27 \pm 0.26$ mag in case of overluminous noncanonical models (e.g., Caputo et al. 2005; Fiorentino et al. 2007). We have no models yet that reproduce the very long periods of the other two Cepheids with well-determined periods, so the Wesenheit relation needs to be extrapolated at such long periods to obtain a distance. But if we do this, the average of all three Cepheids yields a very similar distance, $(m - M)_0 = 31.38 \pm 0.17$.

The Cepheid distance estimates of I Zw 18 are in excellent agreement with our new TRGB distance. This agreement supports the view that the feature identified in Figure 1 is indeed the TRGB and therefore that I Zw 18 does indeed have RGB stars. In turn, this implies that the galaxy cannot have formed in the last ~1 Gyr. Moreover, the RGB stars are unlikely to be as young as 1–2 Gyr, because for such ages the TRGB is up to ~2 mag fainter than the standard candle value used here that applies to populations with ages $\gtrsim$2 Gyr (e.g., Barker et al. 2004, Fig. 2).

The extraordinarily long periods of several of the I Zw 18 classical Cepheids deserve some further comments. They could be due to a metallicity effect, since I Zw 18 is the lowest metallicity galaxy in which Cepheids have been observed. They could also be related to the peculiar SFH of this BCD, since I Zw 18 is currently experiencing a strong starburst that makes it more likely to detect more massive (i.e., brighter and shorter lived) and thus longer period Cepheids than in more regular (spiral) galaxies. Particularly striking is also the lack of observed Cepheids with periods anywhere between ~10 and 120 days. We attribute this absence to the lack of a detectable SF activity in I Zw 18 at the epochs when the missing Cepheids should have formed. Indeed, once we scale the SFH derived by Aloisi et al. (1999) from 10 Mpc to the new distance derived here, we expect few stars in the mass range 6–20 $M_\odot$ (corresponding to pulsation periods of ~10–120 days and MS lifetimes of ~10–65 Myr; see Fagotto et al. 1994) currently in the instability strip.

5. DISCUSSION AND CONCLUSIONS

We have obtained new deep *HST* ACS observations of I Zw 18 that provide improved insight into the evolutionary state of this benchmark metal-poor BCD. Our results indicate that this galaxy contains RGB stars, in agreement with findings for other local metal-poor BCDs studied with *HST*. Underlying old ($\gtrsim$1 Gyr) populations are therefore present in even the most metal-poor systems, so they must have started forming stars at $z \gtrsim 0.1$. Deeper studies (well below the TRGB) will be needed to pinpoint the exact onset of SF in these galaxies. We also find that our TRGB distance of I Zw 18, $D = 18.2 \pm 1.5$ Mpc, which is confirmed by our Cepheids results, places the galaxy farther away than the values ~15 Mpc that have often been assumed in previous work. This may explain why it has remained difficult for so long to unambiguously detect or rule out the presence of old resolved (RGB) stars in this galaxy.

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