THE STELLAR POPULATIONS OF THE CETUS DWARF SPHEROIDAL GALAXY

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ABSTRACT

We present Hubble Space Telescope Wide Field Planetary Camera 2 photometry in the V and I passbands of the recently discovered Local Group dwarf spheroidal galaxy in Cetus. Our color-magnitude diagram extends from above the first-ascent red giant branch (RGB) tip to approximately half a magnitude below the horizontal branch (HB). Given a reddening of $E(B-V) = 0.03$, the magnitude of the RGB tip yields a distance modulus of $(m-M)_0 = 24.46 \pm 0.14$. After applying the reddening and distance modulus, we have utilized the color distribution of RGB stars to determine a mean metal abundance of $[\text{Fe/H}] = -1.7$ on the Zinn & West scale, with an intrinsic internal abundance dispersion of $\sim 0.2$ dex. An indirect calculation of the HB morphology of Cetus based on the mean dereddened HB color yields $(B-R)/(B+V+R) = -0.91 \pm 0.09$, which represents an HB that is redder than what can be attributed solely to Cetus’s metal abundance. Thus, Cetus is affected by the “second-parameter effect,” in which another parameter besides metallicity is controlling the HB morphology. If we adopt the conventional “age hypothesis” explanation for the second-parameter effect, then this implies that Cetus is 2–3 Gyr younger than Galactic globular clusters at its metallicity.

Subject headings: galaxies: abundances — galaxies: dwarf — galaxies: individual (Cetus) — galaxies: stellar content — Local Group

1. INTRODUCTION

It is truly remarkable that dwarf galaxy members of the Local Group are still being uncovered over 60 yr after the discovery of the first such system, Sculptor, by Shapley (1938). Ongoing efforts to search for these systems have led to our current census, which includes 32 dwarf galaxies in the Local Group (Grebel 2000) distributed over a roughly 4 Mpc$^3$ volume. These searches have primarily been fueled by the realization that dwarfs may represent the building blocks of much larger galaxies, such as spirals and ellipticals (see, e.g., Côté et al. 2000). Furthermore, there is the question of whether environmental effects play a role in the formation and evolution of the dwarf systems themselves. Thus, understanding their properties is likely to shed light on the process of galaxy formation in general.

Within this framework, the Hubble Space Telescope (HST) Cycle 8 and 9 programs entitled “A Snapshot Survey of Probable Nearby Galaxies” (GO 8192 and GO 8601; PI, P. Seitzer) were initiated to improve our understanding of nearby dwarf galaxies—their numbers, spatial distribution, structural properties, and stellar populations, among other things (Seitzer et al. 2001). Previous papers reporting the results of our survey include Dolphin et al. (2001) and Karachentsev et al. (1999, 2000a, 2000b).

In the present work, we turn our attention to the Cetus dwarf spheroidal (dSph) galaxy, which was discovered by Whiting, Hau, & Irwin (1999); hereafter WHI as part of their comprehensive program using sky survey plates to search for low surface brightness dwarf galaxy candidates. It is located at $\alpha_{2000} = 00^h26^m11^s$, $\delta_{2000} = -11°02'40''$ in a relatively isolated region of the Local Group. Follow-up observations of Cetus with the Cerro Tololo Inter-American Observatory 1.5 m telescope allowed WHI to determine a distance modulus of $(m-M)_0 = 24.45 \pm 0.15$, based on the magnitude of the red giant branch (RGB) tip, and a metallicity of $-1.9 \pm 0.2$ dex, from the color of the RGB. In addition, from the surface brightness profile of Cetus, WHI estimated a core radius of $1.5 \pm 0.1$ and a tidal radius of $4.8 \pm 0.2$. Subsequent work by Tolstoy et al. (2000; see also Tolstoy 2001) presents a deep BR color-magnitude diagram for Cetus based on observations with the ESO Very Large Telescope. Their data reveal that Cetus possesses a predominantly red horizontal-branch (HB), with the possible presence of a small blue HB component.

The remainder of this paper is organized as follows. The next section describes how the observations were obtained and the techniques employed to derive our color-magnitude diagram for Cetus. Section 3 presents an analysis of our results regarding the distance ($\S$ 3.2), metallicity ($\S$ 3.3), and horizontal-branch morphology ($\S$ 3.4) of Cetus. Finally, our conclusions are summarized in $\S$ 4.

2. OBSERVATIONS AND DATA REDUCTION

The observations of Cetus were obtained on 2001 January 16 UT as part of our Cycle 9 HST snapshot survey...
focusing on nearby dwarf galaxies (GO 8601; Seitzer et al. 2001). The data consist of two 600 s exposures, one each using the F606W ($\sim V$) and F814W ($\sim I$) filters, with Cetus centered in the WF3 CCD. Figure 1a shows our observed WFPC2 field overlaid on the Digitized Sky Survey, while Figure 1b displays a cosmic-ray-cleaned mosaic of our combined F606W and F814W WFPC2 images.

The photometric reduction of these observations has already been fully described by Dolphin et al. (2001). To summarize, the calibrated images obtained from STScI were input into the HSTphot package (Dolphin 2000a). After removing cosmic rays with the HSTphot CLEANSEP routine, simultaneous photometry was performed on the F606W and F814W frames using MULTIPHOT, with aperture corrections made to an aperture of radius 0:5. CTE corrections and calibrations were then applied using the Dolphin (2000b) formulae, producing $VI$ photometry for all stars detected in both images. Because of the relatively small field of the PC1 CCD, very few bright stars were available for the computation of an aperture correction, leading to larger-than-acceptable uncertainties in the PC1 photometry. As a result, we have excluded the PC1 results from further analysis. In the case of the WF photometry, we estimate an uncertainty of 0.02 mag in the photometric zero point, based on the results of Dolphin (2000b). In contrast to previous papers in this series, instead of setting a lower limit of 3.5, we have also adopted in the present study, along with an assumed error of 0.01 mag. In addition, given that $A_V = 3.1E(B-V)$, for the HST filters used herein Schlegel et al. (1998) give $A_I = 1.85E(B-V)$, so that $E(V-I) = 1.25E(B-V)$.

Because the location of the first-ascent RGB tip (TRGB) seems to be well determined in our CMD, we will obtain an estimate of the distance using $l(\text{TRGB})$. Our RGB cumulative luminosity function is shown in Figure 3, to which we have applied a slope-finding algorithm that isolates the TRGB (dashed line). This technique yields $l(\text{TRGB}) = 20.50 \pm 0.10$, in good accord with the WHI value. Assuming an absolute magnitude of $M_I(\text{TRGB}) = -4.05 \pm 0.10$ (Da Costa & Armandroff 1990, hereafter DCA; Sakai, Madore, & Freedman 1996; Bellazzini, Ferraro, & Pancino 2001), this yields $(m-M)_0 = 24.46$.
increasing magnitude.

The right panels show the variation of photometric error with Cetus dSph, based on photometry for 3101 stars derived from the three WF chips. The derivative of this LF, represented by the solid line \[ I \] and \[ I \] color-magnitude diagrams for the Cetus population producing its red HB is not significantly different from those of 47 Tuc and NGC 362, then we can use equation (6) of Carretta et al. (2000) and our mean metal abundance \( \langle [\text{Fe/H}] \rangle \) to calculate \( M_f(\text{HB}) = 0.51 \pm 0.08 \). Fitting a Gaussian to our \( V \) luminosity function, we find \( V(\text{HB}) = 25.01 \pm 0.02 \) \( \langle [\text{Fe/H}] \rangle \), which produces a distance modulus of \( (m - M)_0 = 24.41 \pm 0.09 \), consistent with the TRGB distance obtained above.

3.3. Metallicity

At this point, because we have estimates for the reddening and distance of Cetus, it is a relatively simple matter to compare our RGB photometry with globular cluster RGB sequences. The two panels of Figure 4 show our Cetus photometry in the \( [M_f, (V - I)_0] \) and \( [M_f, (V - I)_0] \) planes, along with the empirical RGBs of Saviane et al. (2000) for metallicities of \( [\text{Fe/H}] = -2.2, -1.6, \) and \(-1.2 \) on the Zinn & West (1984) abundance scale and assuming the Lee, Demarque, & Zinn (1990) distance scale (both the same as DCA). These sequences are based on their \( VI \) database of Galactic globular cluster photometry and agree quite well with the RGBs published by DCA for M15, M2, and NGC 1851. From this figure, the mean metal abundance of Cetus would seem to be somewhere between \(-2.2\) and \(-1.6 \).

To obtain a more quantitative assessment, we have utilized equations (2)–(6) of Saviane et al. (2000), along with the relevant coefficients in their Table 5, to calculate the metallicity for all Cetus RGB stars with \(-4.0 \leq M_f \leq -2.0 \). In addition, the error in metal abundance is estimated by multiplying the HSTphot error in \( V - I \) by \( d[\text{Fe/H}]/d(V - I)_0 \). The resultant metallicity distribution function (MDF) for stars with \(-4.0 \leq M_f \leq -3.0 \) is shown in Figure 5a, while the MDF for stars with \(-3.0 < M_f \leq -2.0 \) is included in Figure 5b.

We note that inspection of globular cluster \( VI \) CMDs and theoretical isochrones suggests that the AGB merges into the RGB at \( M_I \) about \(-2.0 \); this indicates that our MDF should not be significantly affected by (bluer) AGB stars simulating an excess of metal-poor stars. We will now show that the characteristics of the MDF are unaffected by the magnitude range, as long as only stars brighter than \( M_I \) about \(-2.0 \) are used.

The dashed curves in Figure 5 are Gaussian fits to the plotted MDFs. For 107 stars with \(-4.0 \leq M_f \leq -3.0 \) (Fig. 5a), we find a peak abundance of \( [\text{Fe/H}] = -1.71 \), with a 1 \( \sigma \) dispersion of 0.22 dex. Among these same stars, the mean \( [\text{Fe/H}] \) error per star is 0.15 dex, leading to an intrinsic 1 \( \sigma \) abundance spread of 0.17 dex. In the case of the 144 RGB stars with \(-3.0 < M_f \leq -2.0 \) (Fig. 5b), the peak abundance is \( [\text{Fe/H}] = -1.65 \), with a 1 \( \sigma \) spread of 0.36 dex,
which, when coupled with the abundance dispersion introduced purely by the photometric errors of 0.30 dex, yields an intrinsic $1\sigma$ metallicity dispersion of 0.19 dex. Thus, we conclude that Cetus exhibits a mean metallicity of $[\text{Fe/H}] = -1.7$. In addition, we find an intrinsic $1\sigma$ abundance dispersion of $\sim0.2$ dex in Cetus; Table 2 of Grebel (2000) suggests that metal abundance dispersions of this order are quite common among the dwarf galaxies in the Local Group. With high-resolution spectroscopy, even larger dispersions are being uncovered (see, e.g., Shetrone, Côté, & Sargent 2001).

We acknowledge that our measured values of the mean metallicity and metallicity dispersion can be influenced by age effects, because many (or most) dwarf spheroidals formed their stars over extended periods of time. Based on the Girardi et al. (2000) isochrones, we estimate that for ages greater than 10 Gyr this effect is minimal ($\Delta t$ of 5 Gyr corresponds to $\Delta [\text{Fe/H}]$ of roughly 0.1 dex in terms of RGB color), thus leaving our metallicity measurements largely unchanged. However, we cannot completely rule out the presence of younger stars without observing the main-sequence turnoff; if stars of age $\sim7$ Gyr or younger are present, the resulting effect on our metallicity measurement is $0.2$ dex or greater, also adding a large uncertainty to our metallicity dispersion measurement. Although this scenario is possible, there is no a priori reason to assume the presence of younger stars, and thus we will continue to use our measured value of $\langle [\text{Fe/H}] \rangle = -1.7$, with a $1\sigma$ dispersion of $0.2$ dex.

We have also utilized the data in Table 2 of Grebel (2000) to plot the mean metallicity of Local Group dwarfs as a
function of their absolute magnitude (Fig. 6a) and central surface brightness (Fig. 6b), excluding the Sagittarius dwarf galaxy and M32. The plotted data represent dwarf spheroidals (crosses), dwarf irregulars (filled circles), and dwarf ellipticals (open circles). There is a well-known relation among mean abundance, absolute $V$ magnitude, and central surface brightness for these systems, in the sense that more luminous galaxies with higher central surface brightness tend to enrich themselves in heavy elements to a greater degree (Caldwell et al. 1998 and references therein). The square represents the location of Cetus, based on our new mean metal abundance coupled with the luminosity and surface brightness estimates of WHI. It is clear that Cetus occupies its expected location in these diagrams.

3.4. Horizontal Branch

As first illustrated in Figure 2, the HB of Cetus seems to be primarily populated redward of the RR Lyrae instability strip. As a comparison, Figure 7 shows our Cetus CMD compared with the fiducial sequences of the globular clusters Rup 106 (Sarajedini & Layden 1997), M3 (Johnson & Bolte 1998), and M54 (Sarajedini & Layden 1995). While the metallicity of Cetus is similar to those of Rup 106, M3, and M54 (the RGBs match), there is no question that its HB morphology is significantly redder than those of these clusters. We are probably missing some blue HB stars in Cetus (especially those that may be present along the blue HB tail, i.e., fainter than $M_V \sim 1$) because of photometric incompleteness, but there are unlikely to be as many blue HB stars as red ones. We also point out that the $(I, V-I)$ CMD (Fig. 2, bottom left panel) shows that the photometric incompleteness along the RGB is not severe even at the faintest levels, i.e., the luminosity function of RGB stars is steadily increasing at these magnitudes. This suggests that photometric incompleteness on the HB at similar magnitude levels is not likely to be problematic.

It has been traditional to use the numbers of stars blueward of the instability strip ($B$) and those redward of it ($R$), along with stars within the strip itself (RR Lyrae variables, $V$), in order to construct the $(B-R)/(B+V+R)$ index (Lee, Demarque, & Zinn 1994). However, this approach is not practical in our case because of the lack of information on the numbers of RR Lyrae stars in Cetus. Instead, we adopt a different procedure, one that takes advantage of the peak HB color as defined by Buonanno et al. (1997). For clusters with metallicities between $-1.80 \leq [\text{Fe/H}] \leq -1.60$, as given in Table 1 of Buonanno et al. (1997), Figure 8 displays the relation between the peak $(B-V)_0$ color of Galactic globular clusters and their $(B-R)/(B+V+R)$ values (Lee et al. 1994). The plotted quantities are listed in Table 1. The peak $(B-V)_0$ values come from Buonanno et al. (1997), except for Rup 106, which is calculated using the photometry of Kaluzny, Krzemenski, & Mazur (1995).

The next step is to measure the peak $(V-I)_0$ of the Cetus HB and convert it to $(B-V)_0$. First, we construct luminosity functions of our photometry in $V$ and $I$, to which we

![Graph showing the behavior of the mean metal abundance for dwarf galaxies in the Local Group with absolute $V$ magnitude and central surface brightness in the $V$ band. As indicated in the inset key, the filled circles are the dwarf irregulars, the open circles are the dwarf ellipticals, and the crosses are the dwarf spheroidals. The location of Cetus is indicated by the square.](image-url)
Fig. 7.—Comparison of our Cetus CMD with the fiducial sequences of Rup 106 (Sarajedini & Layden 1997), M3 (Johnson & Bolte 1998), and M54 (Sarajedini & Layden 1995). These clusters have metallicities similar to that of Cetus, and thus their RGBs match that of Cetus reasonably well. However, Cetus seems to have an HB significantly redder than those of these globular clusters.

We fit Gaussian distributions in order to isolate the magnitude of the HB. We find $V(\text{HB}) = 25.01 \pm 0.02$ and $I(\text{HB}) = 24.22 \pm 0.02$, where the errors represent a combination of the standard errors of the mean and an estimate of the uncertainty in the fitting process. Subtracting these and including an estimated error of 0.02 mag in the photometric zero point, along with our adopted Cetus reddening, yields $(V - I)_0 = 0.75 \pm 0.03$. We prefer this method, rather than directly measuring the peak color of the HB, for two reasons. First, the color distribution of the HB stars is more susceptible to contamination from the color peak of the RGB stars, which are slightly redward. Second, the luminosity function peaks of the HB in $V$ and $I$ are more closely Gaussian, so fitting them with such a distribution is more straightforward. A conversion from $(V - I)_0$ to $(B - V)_0$, however, is somewhat more uncertain. Zinn & Barnes (1996) provide a horizontal-branch color conversion equation; however, it is based on M15 and M68, whose horizontal branches are both predominantly blue. Thus, the value we calculate for red HB stars (which is what we have in Cetus) is extrapolated between their blue HB stars and RGB stars at the level of the HB. Using their relation, we find $(B - V)_0 = 0.55 \pm 0.03$. Another empirical relation is given by equations (8) and (10) of von Braun et al. (1998), based only on RGB stars; this yields $(B - V)_0 = 0.48 \pm 0.05$. Finally, one can use the Kurucz (1994) model atmospheres, convolved with the Bessell (1990) passbands and normalized with the Hamuy et al. (1992) spectrophotometric standards, to obtain theoretical transformations; this procedure results in a color of $(B - V)_0 = 0.55 \pm 0.03$. Because our use of the von Braun et al. (1998) relations is an extrapolation from RGB stars, we utilize the other two values to measure $(B - V)_0 = 0.55 \pm 0.03$ for the peak color of our horizontal branch. Using the relation plotted in Figure 8, this color produces a horizontal-branch index $(B - R)/(B + V + R)$ of $-0.91 \pm 0.09$.

Based on its intermediate metallicity and red HB morphology, Cetus joins a long list of other Local Group dSphs that are affected by the second-parameter effect (see, e.g., Harbeck et al. 2001) in much the same way as the Galactic globular clusters in the outer halo (Sarajedini, Chaboyer, & Demarque 1997 and references therein). That is to say, the

![Figure 7](image-url)
HB morphology of Cetus is too red for its mean metal abundance. Although there is still no general agreement on the cause of the second-parameter effect, the conventional explanation is based on the age hypothesis, in which the stellar population of Cetus would be younger than a typical Galactic globular cluster. Utilizing new HB models published by Rey et al. (2001; see their Fig. 4), we estimate that this age difference amounts to some 2–3 Gyr.

4. CONCLUSIONS

Using HST/WFPC2 in snapshot mode, we have constructed a deep CMD of the Cetus dwarf spheroidal galaxy. Based on this CMD, which extends from the tip of the RGB to about 0.5 mag below the HB, and an adopted reddening of $E(B-V) = 0.03$ based on the Schlegel et al. (1998) extinction maps, we are able to determine a number of fundamental properties for this galaxy. First, we exploit the tip of the first-ascent RGB to derive a distance modulus of $(m-M)_0 = 24.46 \pm 0.14$, which agrees very well with that of WHI. After correction for the reddening and the distance, a comparison of the Cetus RGB with empirical sequences yields a mean metal abundance of $[\text{Fe/H}] = -1.7$ on the Zinn & West (1984) scale, with an intrinsic internal abundance dispersion of 0.2 dex. The HB of Cetus is populated predominantly redward of the RR Lyrae instability strip; we calculate an HB morphology index of $(B-R)/(B+V+R) = 0.91 \pm 0.09$, based on a technique that utilizes the mean dereddened color of the HB. As such, the mean metallicity and HB morphology of Cetus suggest that the stellar populations of this galaxy manifest the second-parameter effect. If we accept the explanation that this is due to age, then Cetus is about 2–3 Gyr younger in the mean than typical Galactic globular clusters at its metallicity.

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