The Stellar Populations of the Carina Dwarf Spheroidal Galaxy:  
I. A New Color-Magnitude Diagram for the  
Giant and Horizontal Branches

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ABSTRACT

We report on the first in a series of studies of the Carina dwarf spheroidal galaxy, a  
nearby satellite of our Galaxy. Our two major results are: 1) precise $BI$ photometry  
($\sigma_{B-I} \lesssim 0.05$ for $V \lesssim 22$) for 11,489 stars in the Carina field, and 2) the detection of  
two, morphologically distinct, horizontal branches in Carina, which confirms that star  
formation occurred in two well-separated episodes. The old horizontal branch and RR  
Lyrae instability strip belong to a $\gtrsim 10$ Gyr stellar population, while the populous  
red-clump horizontal branch belongs, presumably, to a $\sim 6$ Gyr stellar population. We  
derive a distance modulus $(m - M)_0 = 20.09 \pm 0.06$ for Carina from the apparent  
magnitudes of the old horizontal branch and the tip of the red giant branch (RGB),  
and discuss modifications to the previously estimated distance, total magnitude, and  
stellar ages of Carina. Using the color of the RGB, we estimate the metallicities of the  
younger and older populations to be $[\text{Fe}/\text{H}] \simeq -2.0$ and $-2.2$, respectively.

Subject headings: galaxies – stellar populations

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1. Introduction

The dwarf spheroidal galaxies (dSphs) in the Local Group offer a unique opportunity for studying stellar populations and testing models of galactic evolution, because their size and proximity allow us to make detailed measurements of their ages and metallicity distributions on a star-by-star basis. Color-magnitude diagrams and spectroscopic abundance determinations for limited numbers of stars in the dSph companions of the Galaxy show that each exhibits a different and, in most cases, complex history of star formation. Some dSphs have predominately old stellar populations with small ranges of age and metallicity (e.g., Ursa Minor and Sculptor: Stetson 1984, Da Costa 1984), similar to Galactic globular clusters. Others have predominantly metal-poor, old populations, but still exhibit some internal dispersion in age and/or metallicity (e.g., Draco: Zinn 1978, Stetson 1984, Carney & Seitzer 1984, Smith 1984, Lehnert et al. 1992). However, Carina and Fornax are examples of dSphs whose stellar populations have a large range in both metallicity and age, and evidence of a dominant intermediate-age (∼6-9 Gyr) stellar population (Carina: Mould & Aaronson 1983 - Fornax: Aaronson & Mould 1980, Buonanno et al. 1985, and references therein).

The Carina dwarf spheroidal galaxy\(^3\) is particularly intriguing because it is suspected to have undergone two distinct “bursts” of star formation. From the frequency of carbon stars, Mould & Aaronson (1983, hereafter MA83) found that a large fraction of Carina stars were of intermediate age. However, Saha et al. (1986, hereafter SMS86) demonstrated the presence of an old stellar population by detecting RR Lyrae stars in Carina. Evidence for two distinct ages and, hence, two bursts of star formation, also came from photometry of the main-sequence turnoff (Mighell 1990). Modelling two peaks detected in the luminosity function of the main-sequence turnoff region, Mighell estimated that the first burst of star formation formed ∼ 17% of Carina’s stars ∼ 15 Gyr ago, and the second burst formed the majority of the stars (∼ 83%) only ∼ 7.5 Gyr ago. However, the small size of the sample and comparatively large photometric errors were enough to render this finding significant at only the ∼ 2σ level. However, if such a long delay between two star-forming events did indeed occur, then Carina presents some puzzles. What physical mechanism prevented the gas from cooling and forming stars in the interim few Gyr, when we would expect the cooling timescale to be of order 1 Gyr? How did the dark matter in Carina moderate its evolution?

One possible explanation for the present appearance of the dSphs is that supernovae drove large-scale galactic winds which halted star formation, transforming dwarf irregulars into today’s gas-poor dSphs (cf. Dekel & Silk 1986; Vader 1986; Silk, Wyse & Shields 1987). At present, Carina is devoid of cold gas, with the upper limit on the mass of HI being 10\(^3\) M\(_\odot\) (Mould et al. 1990). Massive dark-matter halos inferred from velocity dispersion measurements (cf. Pryor 1992) may have played a crucial role by providing stability and allowing the stellar systems to remain

\(^3\) Carina (\(\alpha_{1950} = 6^h 40.4^m; \delta_{1950} = -50^\circ 55'; l = 260.1^\circ; b = -22.2^\circ\)) was discovered by Cannon et al. (1977) from inspection of ESO/SRC Sky Survey plates.
intact even after copious gas loss. Indeed, the total mass-to-light ratio of Carina is inferred to be $M/L = 39 \pm 23$ from the 6.8 km s$^{-1}$ velocity dispersion (Mateo et al. 1993), which suggests the presence of dark matter. Dekel & Silk (1986) show that this formation hypothesis successfully predicts the observed correlation between the mass-to-light ratio and the luminosity of dwarf spheroidal and dwarf irregular galaxies. However, galactic winds may not be required to explain the metal abundances of the dwarf galaxies (Gilmore & Wyse 1991), while the existence of long delays between bursts of star formation might argue against galactic wind theories because dSphs are in low-density environments and are unlikely to have accreted fresh gas.

To test theories of dynamical and chemical evolution of dwarf galaxies, one must determine their star-formation history and metallicity distributions. Color-magnitude diagrams alone cannot unravel a complicated star formation history because isochrones are degenerate in distance, reddening, age, and metallicity, but spectroscopic chemical abundances in concert with color-magnitude diagrams can. Therefore, we have begun a detailed study of Carina, which involves photometry of the giant branch and main-sequence turnoff, as well as spectroscopy of individual giants to determine the metal abundance distribution. In this first paper, we report on a color-magnitude diagram which contains $\sim 95\%$ of the giants in Carina. Two morphologically distinct horizontal branches are seen, which supports the conclusion of two discrete star-formation episodes in Carina. In addition, we derive a new distance modulus and a rough estimate of the metallicities of the stars, and discuss the resulting revisions in the distance, stellar ages, total magnitude and mass-to-light ratio of Carina.

2. Observations

Direct images of Carina in $B$- and $I$-bands were obtained with the CTIO 1.5-m telescope and TEK2048 CCD on 18–21 December 1992. The usable area of the CCD was $1830 \times 2040$ pixels due to vignetting, and the pixel scale was 0.434$''$/pixel. Photometric conditions prevailed on the first two nights, and mild cirrus set in on the third night. Observations on the fourth night were interrupted by intermittent cloud, although the data provided good relative photometry within frames. The mean seeing during the run was 1.5 arcseconds. We obtained 30 $B$-band and 42 $I$-band direct images in a pattern covering the central $30'2 \times 24'6$ of Carina, and in additional fields along the major and minor axes. In total, the area covered is roughly 47% of the area enclosed within the tidal radius of Carina. (For reference, Demers et al. [1983] derived $r_t = 33'8$ and $r_c = 10'7$ by fitting King models to the surface density of Carina.) Figure 1 shows a montage of the total area surveyed. Note that there is significant contamination by foreground Galactic stars at this latitude.

A typical sequence of observations at a given position consisted of approximately $2 \times 900s B$ and $3 \times 500s I$ images, with individual frames dithered by a few arcseconds in right ascension or
declination to move stars to different pixels and thereby average out small-scale flat-fielding errors and contamination by detector blemishes. Our mosaic pattern resulted in various total exposure times for individual stars. In the central body of Carina, the average exposure time per star is approximately 2 hrs in each filter. In the major and minor-axis fields, the average exposure times were 45 and 30 min in the $B-$ and $I$-bands, respectively.

Numerous standard-star fields from Landolt (1992) and Graham (1982) E regions were observed throughout each night for photometric calibration. Shutter tests were made during the afternoons to map the non-uniform exposure time across the TEK2048 CCD, which is a critical correction required for high-precision photometry from short integrations such as standard star exposures (Stetson 1989). Other standard calibration data included bias frames, and flat field exposures taken with scattered sunlight reflected from the inside of the dome, and twilight sky flats to correct for non-uniformities with low spatial frequencies.

3. Data Reductions

The standard CCD data reductions were performed with personally written software, and photometric data reductions were performed with ALLFRAME (Stetson 1994). A mild non-linearity in the CCD was identified (see Walker 1993) and satisfactory corrections applied to the calibrations.

4. Results

Figure 2 shows the color-magnitude diagram (CMD) of the 11,489 stars observed in the Carina fields, and photometric standard errors as a function of magnitude, and Figure 3 shows a schematic in which we have identified the salient features of the CMD. We have plotted an approximate $V$ magnitude in order to display the CMD on a familiar scale. To convert to $V$, we have calculated $(B - V)/(B - I) = 0.48$ to be the slope of the color-color relation applicable over most of our CMD using photometry of the globular clusters NGC7006 and M92 courtesy of L. Davis (private communication to PBS). Evident in the CMD is a sheet of foreground Galactic stars, which are primarily disk dwarfs. A sharp main-sequence turnoff in the thin/thick disk is prominent at $(B - I) \approx 1.2$ for the full range of $V$ magnitude. Hereafter, we concentrate on the Carina stars.

The most striking features of the Carina CMD are the two, morphologically distinct, horizontal branches (HBs). The old HB with blue and red extensions and an RR Lyrae strip is typical of old, metal-poor globular clusters, e.g., M15. In fact, the old HB may indeed have an extended
blue HB, as does M15. However, Carina also possesses a red HB clump that is redder and more luminous than the old HB, and has 2.6 times the number of stars, which suggests that the red HB clump population is both more metal-rich and younger than the old HB population (e.g., Iben & Rood 1970, Dorman 1992).

Another notable feature of the CMD of Carina is the clearly defined upper red giant branch (RGB) which is surprisingly thin, i.e., comparable to those of globular clusters. Interestingly, the color distribution of stars on the lower RGB shows tantalizing evidence for two stellar populations. To illustrate, we have calculated a cubic fit to the locus of the RGB and plotted the distribution of stars away from the mean locus, i.e., \( \delta_{B-I} \equiv (B - I) - (B - I)_{RGB} \), for stars with 20.8 \( \leq V \leq 21.9 \) (this range of \( V \) avoids contamination by HB and turnoff stars). Figure 4 shows the resulting histogram and the best fitting model assuming a superposition of two Gaussian functions and a sloping background. The dispersion of the Gaussian functions are \( \sigma = 0.062 \) and 0.038 mags, which should be compared to the median photometric standard errors for these stars which is \( \sigma_{(B-I)} = 0.028 \) mags. The data appear to suggest the presence of two stellar populations. The first has an intrinsic dispersion in color that is a factor of two larger than our photometric errors, which may signify an intrinsic dispersion in metallicity as color in this region of the RGB is highly sensitive to metallicity and only marginally sensitive to age. The second RGB appears to contain \( \sim 10\% \) of the stars in this region of the CMD, and it is approximately 0.16 mags bluer than the first RGB. Are we resolving the older, more metal-poor stellar population? It is possible. However, we regard these tentative conclusions as merely suggestive of further areas to examine when we combine the present data with new, deeper photometry which we are currently reducing.

The CMD also contains an additional sequence which is probably the asymptotic giant branch (AGB) of the younger population (plausible because of the appearance of a gap between the red HB clump and foot of the sequence) and/or the RGB of the old population. The clump of stars appearing at the bottom of our CMD with \( V \sim 22.5 \) and \( (B - I) \approx 0.75 \) is likely to be the tip of the main-sequence turnoff of the younger population.

The dichotomy in the two HBs supports the conclusion reached by Mighell (1990) — from the double peaked color distribution in the main-sequence turnoff region — that star formation in Carina occurred in two distinct bursts. However, the appearance of two distinct HBs is not conclusive evidence for two distinct stellar ages, because metallicity and mass loss on the giant branch also play roles in HB morphology. We therefore hesitate to derive more quantitative estimates of the ages of the two populations from the HBs. The evolution of the main-sequence turnoff is highly sensitive to age, and better understood theoretically than evolution to the HB. Therefore, we postpone detailed analysis of the CMD until we analyze the deep photometry of the main-sequence turnoff region which we have obtained with the CTIO 4m telescope (November 1993). We will then compare these CMDs with new theoretical isochrones spanning the main-sequence turnoff to the asymptotic giant branch, to constrain the ages and metallicities of the stellar populations of Carina.
4.1. Spatial Distribution of Carina Stars

To illustrate the spatial distribution of Carina stars, we show in Figure 5 the boundaries in the CMD which we have chosen to designate probable Carina stars. We used DAOPHOT to subtract the designated foreground stars from our montage image (Figure 1) to show the Carina dSph unveiled from most of the foreground contamination in Figure 6.

We can use the two distinct types of HBs stars as tracers of the young and old stellar populations to test whether their spatial distributions differ. From this we may be able to extract information about the spatial extent of star formation in the two bursts. For example, gas dissipation could result in a second generation of stars that is more centrally concentrated than the first. However, if the spatial distributions of the two HB types are similar, then it is probable that star formation in both bursts occurred over roughly the same areas, because the relaxation timescale, $T_E$, in Carina is longer than a Hubble time. To illustrate, the two-body relaxation timescale is

$$T_E = \frac{1}{16} \sqrt{\frac{3}{\pi}} \frac{v^3}{G^2 \rho m_2 \ln \Lambda},$$

where

$$\Lambda = \frac{Dv^2}{G(m_1 + m_2)},$$

(Chandrasekhar 1942) for a body of mass $m_1$ in a density $\rho$ of particles of mass $m_2$ with velocity dispersion $v$ in a system of dimension $D$. On the one hand, the relaxation timescale due to stellar interactions in Carina is approximately $4 \times 10^{12}$ yr assuming $m_1 = m_2 = 1 M_\odot$, $D = 33.8$ is the tidal radius (Demers et al. 1983), the central velocity dispersion is 6.8 km s$^{-1}$ (Mateo et al. 1993), and the stellar mass density is calculated using the central luminosity density of 0.011 $M_\odot$ pc$^{-3}$ (Mateo et al. 1993) and a solar mass-to-light ratio. On the other hand, one might appeal to massive dark matter particles to stir the stars efficiently since the derived mass-to-light ratio of Carina is 39 (Mateo et al. 1993). To estimate the relaxation timescale of the stars due to interactions with dark matter particles, we estimate $\rho$ from the total mass of Carina which $1.1 \times 10^7 M_\odot$ (Mateo et al. 1993), and assume it is distributed uniformly over a sphere of radius $D$. In order for the relation timescale to be shorter than $10^{10}$ yr, the dark matter must be composed of black holes with mass $m > 10^8 M_\odot$. But if the dark matter in Carina and the solar neighborhood are composed of similar objects, then this is not a viable hypothesis, because the observed velocity dispersion in the solar neighborhood places a limit of $m < 10^6 M_\odot$ on dark matter particles (Lacey & Ostriker 1985). Therefore, lacking a mechanism to mix the two stellar populations in a few Gyr, if the spatial distribution of the two stellar populations of Carina are similar, then they must have formed over a similar spatial extent.

Thus we identified the old HB stars and the red clump HB stars from their positions in the CMD. We examined the distribution of the stars inside a limiting radius for which our sampling is complete (10 arcmin), which included 513 red clump HB stars and 185 old HB stars. The
surface densities as a function of radius for the two HB types (normalizing the densities by
the total number of stars of each type) are shown in Figure 7. No significant difference in the
surface densities is detected. In addition, we show in Figure 8 the fraction of old HB stars as
a function of radius, in which each radial bin was chosen to contain 69 HB (= old HB + red
HB clump) stars. The mean fraction of old HB stars is 0.27 and the most deviant point differs
only by $2\sigma$ ($\sigma$ (one bin) = 0.07). Again, no systematic radial dependence is seen. Therefore, we
conclude that inside 10 arcmin the radial distributions of the old and young stellar populations
are indistinguishable. We infer that star formation in the two bursts occurred with roughly the
same spatial distribution inside the core radius.

5. Conclusions

Here we use the absolute magnitude of the old HB and the absolute magnitude of the tip of
the red giant branch in our CMD to derive a distance modulus to Carina, and the color of the
red giant branch to estimate of the metallicities of Carina stars. We also discuss the resulting
modifications to the previously estimated distance, stellar ages, total magnitude and mass-to-light
ratio of Carina.

5.1. Deriving a New Distance Modulus

Past studies of Carina have usually assumed a distance modulus of $(m - M)_0 = 19.7$, which
was derived by MA83. However, their derivation was based on comparing the apparent magnitude
of the red clump HB to the absolute magnitude of old HBs/RR Lyrae stars in globular clusters.
The old HB of Carina was not detected by MA83, because their small CCD size gave very limited
spatial coverage of the galaxy. However, SMS86 obtained B-band photographic plates of Carina,
identified RR Lyraes, and derived $(m - M)_0 = 20.14$. Part of the reason for the preference of the
MA83 estimate in past studies may be that the SMS86 data consisted of single-band photographic
photometry, and they misidentified as RR Lyraes a few bright variables which are anomalous
cepheids. Our CMD resolves the discrepancy between these two distance estimates, because
it shows that the red HB clump is approximately 0.25 magnitudes brighter than the old HB.
Therefore, the correct distance modulus of Carina is nearer to that derived by SMS86. Below, we
derive $(m - M)_0 = 20.09 \pm 0.06$ with good agreement from two methods which use the apparent
magnitude of the old HB and the tip of the RGB. In the following, we will assume a reddening
$E(B - V) = 0.025$ and extinction $A_V = 0.08$ for Carina, as assumed by MA83 based on Burstein
& Heiles III data (1982, and 1983 private communication to MA). The assumed extinction laws
are $A_I = 1.98E(B - V)$, $A_V = 3.2E(B - V)$, and $E(B - I) = 2.23E(B - V)$ (Cardelli, Clayton &
Mathis 1989).
5.1.1. Method 1: The Old HB/RR Lyrae Stars

The $M_V$ of the HB and RR Lyrae stars in old stellar populations has been used extensively as a distance indicator. However, $M_V$ depends on metallicity, and the exact dependence is controversial. Theoretical horizontal branch models of Lee, Demarque and Zinn (1990) give the relation

$$M_{V}^{RR} = 0.17\text{[Fe/H]} + 0.82.$$  \hspace{1cm} (1)

If we assume that the metallicity of the old HB stars in Carina is $[\text{Fe/H}] \simeq -2.2 \pm 0.4$, then $M_{V,RR} = 0.45 \pm 0.07$. The apparent magnitude of the old HB/RR Lyrae stars in Carina is $V = 20.65 \pm 0.05$, and hence the derived distance modulus is $(m-M)_0 = 20.12 \pm 0.08$. Additional spectroscopy of individual giants in Carina can provide a metallicity distribution which will give us a firmer constraint on this method for deriving the distance modulus.

5.1.2. Method 2: The Tip of the RGB

The absolute $I$ magnitude of tip of the red giant branch ($M_{I}^{TRGB}$) is also a very good distance indicator (cf. Da Costa and Armandroff 1990, Lee, Freedman & Madore 1993, and references therein), because $M_{I}^{TRGB} = -4.0$ with little variation for stellar populations with $[\text{Fe/H}] < -0.7$, and ages $\gtrsim 7$ Gyr. By definition,

$$M_{I}^{TRGB} = M_{I}^{\text{bol}} - BC_I,$$

where $BC_I$ is the bolometric correction in the $I$-band. Da Costa and Armandroff (1990) give the parameteric fits:

$$BC_I = 0.881 - 0.243(V - I)^{TRGB}_0,$$

$$M_{I}^{\text{bol}} = -0.19[\text{Fe/H}] - 3.81,$$

derived from observed data on globular clusters (whose distances were derived assuming Equation 1 above).

To apply this method to our data, we must estimate the slope of the color-color relation applicable to the upper RGB. We use the semi-empirical calibration of the Revised Yale Isochrones (RYI, Green et al. 1983) which was based on direct observations of globular cluster stars. Considering isochrones for stars with ages $> 6$ Gyr and metallicities $-1.7 \leq [\text{Fe/H}] \leq -2.3$, we adopt $(B - V)/(B - I) = 0.52 \pm 0.01$ for the upper RGB. As a check, the slopes of the color-color relation for the majority of our CMD from the RYI calibration and of L. Davis’ photometry of M92 and NGC7006 agree.
We find that it is straightforward to extract \((B-I)^{TRGB} = 2.85 \pm 0.05\) and \(I^{TRGB} = 16.15 \pm 0.05\) by using either an eye-estimate or by convolving the \(I\)-band luminosity function with a kernel used for edge detection in image processing (cf. Lee et al. 1992). To illustrate the strength of the edge of the TRGB, we plot in Figure 9 the \(I\)-band luminosity function for stars with \(2.4 \leq (B-I) \leq 3.0\), which was chosen to limit contamination by foreground stars. If we assume a metallicity of \([\text{Fe/H}] = -2.0 \pm 0.4\) (see below), then \((V-I)_0^{TRGB} = 1.45\) and \(M_I^{TRGB} = -4.00\). Thus, the distance modulus derived from the TRGB is \((m - M)_0 = 20.05 \pm 0.09\), which is in good agreement with that derived above from the apparent magnitude of old HB/RR Lyrae stars.

Therefore, we advocate a new distance modulus of \((m - M)_0 = 20.09 \pm 0.06\) for Carina. The revised heliocentric distance of Carina is 105 kpc, and the revised Galactocentric distance is 107 kpc, assuming \(R_\odot = 8.5\) kpc.

Note that Mighell & Butcher (1992) use their observed \(V\)-band luminosity function to constrain the distance modulus (and simultaneously the age and metallicity) of Carina from comparison with the Revised Yale isochrones (Green et al. 1987). Considering a range of parameter space (in particular, distance moduli in bins of 0.2 mag), they find models are “consistent” (defined by a reduced chi-square signifying > 95% confidence) only with a distance modulus of 19.8. Hence they estimate the distance modulus to be 19.8 \(\pm\) 0.1. However, we consider this conclusion uncertain for two main reasons: 1) the degeneracy of distance, age and metallicity in a CMD, and 2) selective editing of their data. In particular, Mighell & Butcher chose to delete an apparently discrepant data point at \(V=21.5\) citing possible contamination by foreground stars. However, if this point where to be included in the analysis it would significantly alter the “knee” in the luminosity function and only a single model would have been found barely consistent with the data. In fact, the inclusion of that data point would favor either a larger distance modulus, lower metallicity and/or younger age. Therefore, we do not think their result of 19.8 \(\pm\) 0.1 seriously conflicts with our determination of 20.09 \(\pm\) 0.06 as the distance modulus.

5.2. Estimating the Stellar Metallicity

Da Costa and Armandroff (1990) show that the \((V - I)\) color of the red giant branch at \(M_I = -3\) is a sensitive indicator of the metallicity of a stellar population. They derive the relation

\[
[\text{Fe/H}] = -15.16 + 17.0(V - I)_{-3} - 4.9(V - I)^2_{-3}.
\]

We find \((B-I)_{-3} = 2.40\) for Carina, which gives \([\text{Fe/H}] = -2.18\) as an estimate of the stellar metallicity if the stars are as old as globular clusters.

The giant branch (GB) of Carina is very thin, and the GBs of the old and young populations appear to overlap (see Figure 4). Thus, an estimate of the metallicity of the older population is \([\text{Fe/H}] \approx -2.2\). However, in the following section, we revise the age of the younger population to
∼ 6 Gyr and must derive a correction for the age difference. Consulting Revised Yale Isochrones, we find that using a 12 Gyr calibration for a 6 Gyr population results in a metallicity estimate which is 0.22 dex too metal-poor. Hence our estimate of the metallicity of young stellar population of Carina is \([\text{Fe}/\text{H}] = -2.0\).

Corroborating evidence for these metallicities comes from Da Costa & Hatzidimitriou (see Da Costa [1993]), who have obtained spectroscopic metal abundances for 15 giants in Carina. They find a mean metallicity of \([\text{Fe}/\text{H}] = -1.9\) with a very narrow spread, and one notable outlier with \([\text{Fe}/\text{H}] = -2.3\).

5.3. Revised Stellar Ages

Mighell (1990) identified two distinct main-sequence turnoffs in his photometric data from which he estimated stellar ages. He found the turnoff for the younger population occurs at \(V \approx 23.0\), and that of the older population at \(V \gtrsim 23.5\). From VandenBerg & Bell (1985) isochrones, Mighell derived

\[
\log t(\text{Gyr}) = -0.13[\text{Fe}/\text{H}] + 0.37M_{\text{MSTO}} - 0.51.
\]

If we assume our new distance modulus (0.3 mags greater than that assumed by Mighell based on MA83) and \([\text{Fe}/\text{H}] = -2.0\) for the younger stellar population, then the derived age is 6.2 Gyr, which is 17% younger than Mighell’s original estimate. Assuming \([\text{Fe}/\text{H}] \lesssim -2.2\) for the older population of Carina gives a lower limit of \(\gtrsim 10\) Gyr for its age.

5.4. Revised \(M_V\) and \(M/L\) Ratio

Mateo et al. (1993) derived for Carina a total magnitude of \(M_V = -8.9\) (based on the Demers et al. [1983] data) and a total mass-to-light ratio of \(M/L_V = 39 \pm 23\) from their measured velocity dispersion and derived structural parameters, assuming \((m - M)_0 = 19.7\) and \(A_V = 0.1\). Adopting our new distance modulus and a smaller extinction instead would lead to a total magnitude of \(M_V = -9.3\) and a small decrease in the derived mass-to-light ratio

\[
M/L_V = 39 \times 10^{(-0.2 \Delta(m - M)_0 - 0.4 \Delta A_V)} = 34.
\]

6. Summary
We have obtained precise photometry for most of the giant stars in the Carina dSph galaxy and, for the first time, detect two morphologically distinct horizontal branches, which most probably represent two stellar populations with distinct ages and metallicities. We have derived a new distance modulus of $20.09 \pm 0.06$, and estimate the metallicities of the two populations (young and old, respectively) to be $[\text{Fe/H}] = -2.0$ and $-2.2$. We propose revisions to the stellar ages (6.2 and $>10$ Gyr, respectively), as well as other fundamental parameters for Carina, such as its distance, total magnitude and mass-to-light ratio. We await reduction of our photometry of the main-sequence turnoff region of Carina, at which time we will use stellar evolutionary isochrones and comparison globular clusters of similar metallicity to refine the age estimates for Carina’s stellar populations, and to constrain better the duration of the two bursts. The final observations in this project will be spectroscopy of $\sim 100$ individual giants identified in this survey from which a metal abundance distribution can be derived. Together, these data will provide unprecedented constraints on the evolution of the Carina dSph and insight into the evolution of dwarf galaxies.

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Fig. 1.— Montage $B$-band image of the area surveyed around the Carina dwarf spheroidal galaxy. The central rectangular region is $30.2' \times 24.6'$, and the maximum dimensions of the region surveyed are $41.5' \times 33.3'$. North is (approximately) up and east is (approximately) left.

Fig. 2.— a) Color-magnitude diagram of all Carina and field stars, and b) standard photometric errors returned from ALLFRAME.

Fig. 3.— Schematic illustration of the salient features of the CMD in Figure 2.

Fig. 4.— The distribution of stars about the mean locus of the RGB in the magnitude interval $20.8 \leq V \leq 21.9$, and the best fitting model assuming a superposition of two Gaussian functions and a sloping background.

Fig. 5.— Color-magnitude diagram showing the adopted boundaries for probable Carina giants.

Fig. 6.— Montage $B$-band image containing primarily Carina stars, which was created by subtracting the foreground Galactic stars identified in the making of Figure 4 from the original image (Figure 1). North is (approximately) up and east is (approximately) left.

Fig. 7.— Normalized surface density of the red clump HB stars (solid line) and the old HB stars (dashed line) versus radius.

Fig. 8.— Fraction of old HB stars versus radius, in which each bin was chosen to contain 69 HB stars.

Fig. 9.— The $I$-band luminosity function for stars with $2.4 \leq (B - I) \leq 3.0$, which was chosen to limit contamination by foreground stars.