ON THE HELIUM CONTENT OF GALACTIC GLOBULAR CLUSTERS VIA THE R-PARAMETER

M. Zoccali, S. Cassisi, G. Bono, G. Piotto, R. M. Rich, and S. G. Djorgovski

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ABSTRACT

We estimate the empirical R-parameter in 26 Galactic globular clusters covering a wide metallicity range, imaged by Wide Field Planetary Camera 2 on board the Hubble Space Telescope. The improved spatial resolution permits a large fraction of evolved stars to be measured and permits accurate assessment of radial population gradients and completeness corrections. In order to evaluate both the He abundance and the He-to-metal enrichment ratio, we construct a large set of evolutionary models by adopting similar metallicities and different He contents. We find an absolute He abundance that is lower than that estimated from spectroscopic measurements in H II regions and from primordial nucleosynthesis models. This discrepancy could be removed by adopting a 12C(α,γ)16O nuclear cross section about a factor of 2 smaller than the canonical value, although different assumptions for mixing processes also can introduce systematic effects.

The trend in the R-parameter toward solar metallicity is consistent with an upper limit to the He-to-metal enrichment ratio of the order of 2.5. Detailed calculations of central He burning times as a function of the horizontal-branch (HB) morphology suggest that He lifetimes for hot HB stars are on average ∼ 20% longer than for RR Lyrae and red HB stars. Therefore, the increase in the empirical R-values of metal-poor clusters characterized by blue HB morphologies is due to an increase in the HB lifetime and not due to an increase in the He abundance.

Subject headings: globular clusters: general — stars: abundances — stars: evolution — stars: horizontal-branch

1. INTRODUCTION

The He abundance is fundamental in several astrophysical problems. Big bang nucleosynthesis models supply tight predictions on the primordial He content, and therefore empirical estimates of this parameter are crucial for constraining their plausibility (Hogan, Olive, & Scully 1997). At the same time, stellar evolutionary and pulsational models require the assumption of an He-to-metal enrichment ratio ΔY/ΔZ in order to reproduce the observed properties of both metal-poor and metal-rich stellar structures (Bono et al. 1997a). Observational constraints on this parameter can improve the accuracy of several theoretical observables and in particular of stellar yields predicted by Galactic chemical evolution models (Tsujimoto et al. 1997; Pagel & Portinari 1998).

One of the most widely used methods for measuring the He abundance is to measure fluxes of nebular emission lines in planetary nebulae (Peimbert 1995) or in extragalactic H II regions (Pagel et al. 1992; Izotov, Thuan, & Lipovetsky 1997; Olive, Steigman, & Skillman 1997). Independent estimates based on high signal-to-noise measurements of He abundance give very similar results (Y = 0.23–0.24), thus suggesting that the empirical uncertainties are quite small. However, by adopting detailed radiative transfer calculations of H and He, Sasselov & Goldwirth (1995) supported the evidence that current He measurements could be affected by large systematic errors. The He content can also be obtained by direct spectroscopic measurements in hot horizontal-branch (HB) stars. Unfortunately, these stars are affected by gravitational settling and by radiation levitation (Michaud, Vauclair, & Vauclair 1983; Moehler et al. 1999), and therefore they might present peculiar abundance patterns. Nevertheless, there seems to be a consensus that the primordial He abundance should not be lower than Y = 0.22 (Olive, Steigman, & Walker 1999).

Both absolute and/or relative He abundances can also be estimated because the evolution of Population II stars is sensitive to the primordial helium abundance. The first helium-sensitive indicator to be identified was the R-parameter, defined as the ratio between the number of stars along the HB and the number of red giant branch (RGB) stars brighter than the HB luminosity (R = N_{HB}/N_{RGB}; Iben 1968). Additional parameters also use the helium-burning stars of the HB as abundance indicators. The Δ-parameter is the magnitude difference between HB stars and main-sequence (MS) stars (Carney 1980), and the A-parameter is the mass-luminosity exponent of RR Lyrae stars (Caputo, Cayrel, & Cayrel de Strobel 1983). The fine structure of the main-sequence locus of Population II stars (Faulkner 1967) is also a potentially powerful method to constrain ΔY/ΔZ. On the basis of Hipparcos parallaxes, Pagel & Portinari (1998) investigated the fine structure of solar neighborhood MS stars and found that the current estimates of ΔY/ΔZ are still affected by large uncertainties. The other three methods have been recently applied by Sandquist (2000, hereinafter S00) to a sample of 42 Galactic globular clusters (GGCs). Sandquist also comprehensively...
discusses the pros and cons of these abundance indicators and in particular the statistical and systematic errors affecting both absolute and relative He estimates. The results by S00 support the evidence that both the $\Delta$-parameter and the $A$-parameter can give reliable relative He abundances only because of current uncertainties on the metallicity scale and on the RR Lyrae temperature scale. At the same time, S00 brought out that absolute He abundances based on the $R$-parameter ($Y \approx 0.2$) could also be affected by additional systematic errors and that both relative and absolute estimates do not show, within current uncertainties, clear evidence of a trend with metallicity. The latter finding does not support the results by Renzini (1994), Minniti (1995), Bertelli et al. (1996), and Desidera, Bertelli, & Ortolani (1997), who suggest that in the Galactic bulge the He abundance scales with metallicity according to a slope ranging from 2 to 3.5. Moreover, detailed comparisons between solar standard models and accurate helioseismic data (Ciabattini, de l'Ignocenti, & Ricci 1997; de l'Ignocenti et al. 1997; Christensen-Dalsgaard 1998) are more consistent with $\Delta Y/\Delta Z \approx 2$. The large spread in the empirical values suggests that current He estimates are still hampered by large uncertainties that do not allow us to disentangle the intrinsic variation, if any, from systematic effects.

The empirical evaluation of the $R$-parameter relies only on star counts. Nevertheless, misleading effects can be introduced by the method adopted for fixing the zero-age horizontal branch (ZAHB) luminosity, by differential reddening, as well as by the occurrence of population gradients inside the cluster (Buzzoni et al. 1983; Caputo, Martinez Roger, & Paez 1987; Djorgovski & Piotto 1993; Bono et al. 1995; S00). The He abundance is estimated by comparing observed values with the ratio of HB and RGB evolutionary times, which relies on evolutionary predictions characterized by a negligible dependence on stellar age (Iben & Rood 1969). The He burning lifetimes do depend on input physics such as equation of state, opacity, and nuclear cross sections (Brogato, Castellani, & Villante 1998; Cassisi et al. 1998) adopted to construct HB models as well as on the algorithm adopted for treating the mixing processes (Sweigart 1990 and references therein).

The main aim of this investigation is to derive the $R$-parameter for a sample of 26 GGCs and to compare empirical values with theoretical predictions in order to gather information on both the He content and its trend with metallicity. In order to accomplish this goal, we specifically calculate a large set of HB models, adopting the most up-to-date input physics. We rely on the high number of stars sampled in each cluster, on the wide metallicity range covered by clusters, and on the high homogeneity of theoretical predictions and data to constrain the behavior of both $R$- and $\Delta Y/\Delta Z$-parameters.

2. THE CLUSTER DATABASE

We evaluate the $R$-parameter in 26 GGCs of our Hubble Space Telescope (HST) database (Zoccali et al. 1999, hereinafter Z99, and references therein), including images from the HST projects GO-6095 and GO-7470 and similar data retrieved from the HST archive. To avoid systematic uncertainties in the star counts, we exclude from the sample the clusters affected by strong foreground contamination (NGC 6522, NGC 6441) as well as those having hot HB stars close to the magnitude limit and for which the completeness correction was not estimated (NGC 6205).

The $R$-parameter is defined as $N_{\text{HB}}/N_{\text{RGB}}$, where $N_{\text{RGB}}$ is the number of RGB stars brighter than a reference luminosity, generally fixed according to the luminosity of RR Lyrae stars (Buzzoni et al. 1983) or to the ZAHB luminosity (Bono et al. 1995). However, the accurate determination of this luminosity is often a thorny problem. In fact, together with the well-known difficulties in estimating the RR Lyrae luminosity and/or the ZAHB luminosity for clusters with only red or blue HB morphologies, we are also dealing with the problem of the differential bolometric correction between HB and RGB stars. This means that, as soon as the HB luminosity/magnitude is fixed, the proper RGB magnitude at this luminosity can be estimated only by accounting for the change in the bolometric correction between HB and RGB structures. Current estimates have been derived by adopting different assumptions on the value of the bolometric correction and on its variation with metallicity. Therefore, comparison among the $R$-values available in the literature is not straightforward even for the same clusters.

To overcome systematic errors introduced by both metallicity and gravity variations, in the present analysis we choose to “save the observables,” i.e., we define $N_{\text{RGB}}$ as the number of RGB stars brighter than the ZAHB $V$ magnitude ($V \leq V_{\text{ZAHB}}$). As a consequence, values of both $t_{\text{HB}}$ and $t_{\text{RGB}}$ are estimated after theoretical predictions are transformed to the observational plane. Table 1 lists the cluster name, its global metallicity, and the other observed quantities. Owing to calibration problems with WFPC2 images (Stetson 1998, 1999), the values of $V_{\text{ZAHB}}$ adopted for this work could be affected by an uncertainty $\pm 0.1$ mag, and therefore the values in Table 1 have to be considered only as relative evaluations. Cluster metallicities are based on the Cohen et al. (1999) metallicity scale, while global metallicities were estimated by assuming a mean $\alpha$-element enhancement of $[\alpha/Fe] = 0.3$ for $[Fe/H] \leq -1$ and $[\alpha/Fe] = 0.2$ for $[Fe/H] > -1$ (see Z99).

The observed star counts have been corrected for completeness. Since crowding effects depend on the distance from the cluster center, we divide each field in three radial annuli and then correct the counts in each annulus by using the completeness correction appropriate for each magnitude level. As a consequence, we compute three independent radial values of $R$, and our final $R$-value is their weighted mean. This approach also gives a check for spurious radial trends that could be caused either by population gradients (Djorgovski & Piotto 1993) or by an overestimate (underestimate) of the completeness correction. Interestingly enough, two clusters (NGC 6273 and NGC 6934) show a strong variation of $R$ with the distance from the cluster center. Because of the small area covered by the WFPC2 field and the different pixel size—hence different sampling—of the most central chip (PC) when compared with the outer ones (WFs) we cannot firmly assess whether this behavior is intrinsic—i.e., caused by a radial population gradient—or caused by systematic errors in the completeness correction. Radial color gradients in NGC 6934 have been already found by Sohn, Byun, & Chun (1996); we are not aware of wide field investigations on NGC 6273. The peculiar behavior of star counts in these clusters deserves a detailed investigation; we therefore exclude both of them from the sample.

The completeness correction for red HB stars is assumed to be identical to that for RGB stars at the same magnitude. However, completeness correction for blue HB stars could
be significantly different from those derived for the RGB stars. In fact, at fixed V magnitude, blue HB stars have brighter B magnitudes and thus a higher probability to be detected. For some very blue HB clusters, namely, NGC 2808, NGC 6273, and NGC 7078, we perform several direct experiments by adding to the frames artificial stars along the HB fiducial line. We find that the completeness correction for blue HB stars is a factor of 1.046 higher than the completeness for RGB and MS stars located at the same V magnitude. This difference appears fairly constant in different clusters and over a large magnitude range. As a consequence, the artificial star tests for the other clusters are performed only for RGB/MS stars, and the completeness correction for HB stars was scaled according to the same factor of 1.046. It is worth noting that such a completeness correction is significant only for extreme blue HB stars and that the correction to the R-parameter is always smaller than 5%. The only exception is NGC 2808, a cluster that shows a very long and populated HB blue tail and a very high central density. By applying the completeness correction to this cluster, the R-parameter changed by 11%.

3. DISCUSSION

Figure 1 shows the comparison between empirical R-values and theoretical predictions at fixed age (14 Gyr) for three different assumptions about the He content and for metal abundances ranging from [M/H] = -2.2 to solar chemical composition. At fixed composition, a large set of evolutionary models for both H and He burning phases was constructed by adopting the input physics already discussed by Cassisi & Salaris (1997). As usual, the HB lifetime is estimated on the basis of the HB model located at log T_e = 3.85, i.e., by assuming as representative of f_{HB} the central He burning time of a structure whose ZAHB is inside the RR

| Cluster | [M/H] | V_{ZAHB}^* | N_{HB}^b | N_{RGB}^c | R^d | N_{HB}/N_{RGB}^e |
|---------|-------|------------|---------|---------|-----|-----------------|
| NGC 104 ...... | -0.54 | 14.26 | 358 | 235 | 1.52 ± 0.13 | 0/358 |
| NGC 362 ...... | -0.84 | 15.66 | 247 | 197 | 1.25 ± 0.12 | 17/215 |
| NGC 1851 ...... | -0.93 | 15.33 | 297 | 237 | 1.24 ± 0.11 | 89/180 |
| NGC 1904 ...... | -1.19 | 16.31 | 177 | 116 | 1.53 ± 0.18 | 0/172 |
| NGC 2808 ...... | -1.03 | 16.50 | 851 | 606 | 1.26 ± 0.06 | 462/389 |
| NGC 4590 ...... | -1.68 | 15.72 | 34 | 35 | 0.93 ± 0.23 | 23/11 |
| NGC 5634 ...... | -1.45 | 18.04 | 146 | 105 | 1.33 ± 0.17 | 131/2 |
| NGC 5694 ...... | -1.49 | 18.73 | 249 | 159 | 1.50 ± 0.15 | 241/5 |
| NGC 5824 ...... | -1.48 | 18.55 | 520 | 372 | 1.46 ± 0.10 | 480/20 |
| NGC 5927 ...... | -0.17 | 16.94 | 95 | 136 | 1.47 ± 0.17 | 0/195 |
| NGC 5946 ...... | -1.24 | 17.45 | 113 | 96 | 1.13 ± 0.11 | 113/0 |
| NGC 5986 ...... | -1.31 | 16.54 | 237 | 154 | 1.48 ± 0.15 | 224/4 |
| NGC 6093 ...... | -1.27 | 16.46 | 263 | 221 | 1.25 ± 0.11 | 251/12 |
| NGC 6139 ...... | -1.29 | 18.50 | 299 | 223 | 1.28 ± 0.11 | 290/9 |
| NGC 6235 ...... | -1.06 | 17.42 | 35 | 37 | 0.90 ± 0.22 | 31/2 |
| NGC 6284 ...... | -0.99 | 17.36 | 132 | 104 | 1.33 ± 0.17 | 132/0 |
| NGC 6287 ...... | -1.67 | 17.29 | 92 | 59 | 1.49 ± 0.25 | 82/9 |
| NGC 6293 ...... | -1.55 | 16.56 | 137 | 101 | 1.30 ± 0.17 | 130/4 |
| NGC 6342 ...... | -0.43 | 17.66 | 73 | 42 | 1.74 ± 0.34 | 0/73 |
| NGC 6356 ...... | -0.30 | 18.15 | 370 | 231 | 1.60 ± 0.13 | 0/370 |
| NGC 6362 ...... | -0.82 | 15.63 | 38 | 33 | 1.15 ± 0.27 | 6/27 |
| NGC 6388 ...... | -0.39 | 17.41 | 1353 | 747 | 1.74 ± 0.07 | 202/1151 |
| NGC 6624 ...... | -0.22 | 16.30 | 123 | 86 | 1.43 ± 0.20 | 0/123 |
| NGC 6652 ...... | -0.72 | 16.21 | 62 | 47 | 1.32 ± 0.26 | 0/62 |
| NGC 6981 ...... | -1.19 | 17.32 | 65 | 56 | 1.16 ± 0.21 | 21/24 |
| NGC 7078 ...... | -1.82 | 15.93 | 390 | 242 | 1.57 ± 0.13 | 292/50 |

* For the V_{ZAHB} determination see the discussion in Z99.
* The total number of HB stars.
* The total number of RGB stars.
* The error budget on R includes the Poisson error on the raw star counts, the completeness correction, and the weighted mean of the three radial determinations.
* Number of stars bluer/redder than the RR Lyrae gap.
* Because of a misidentification of some blue RR Lyrae stars, the V_{ZAHB} of these clusters was underestimated by a few hundredth of magnitude in Z99.

FIG. 1.—R-parameter vs. global metallicity. Theoretical predictions are estimated at fixed age (14 Gyr) and for three different initial He abundances. The horizontal error bar accounts for current uncertainties on metallicity.
Lyrae instability strip. Our calculations confirm Iben’s (1968) original finding that the $R$-parameter is virtually independent of the adopted cluster age. The comparison between theory and observations also confirms the finding by S00 that the absolute He content resulting from the $R$-method is $Y \approx 0.20$. As discussed in § 1, this value is significantly lower than the canonical He abundance expected from the primordial nucleosynthesis and measured in the H II regions, showing that there is some systematic uncertainty affecting the calibration of $R$ as a function of $Y$.

As discussed in Brocato et al. (1998) and Cassisi et al. (1998), among the physical input parameters that govern the HB lifetime, the nuclear cross section for the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction is affected by the largest uncertainty. In order to investigate the dependence of $t_{\text{HB}}$ on the poorly measured $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ cross section, we performed several numerical experiments. Figure 2 displays the dependence of the theoretical $R$-values on an increase/decrease by a factor of 2 in the efficiency of the quoted reaction when compared with the value provided by Caughlan et al. (1985). Even though the range of the nuclear cross section values used in Figure 2 is quite large, it is still inside the current error of its empirical measurements (Buchmann 1996). This fact clearly shows the sensitivity of the predicted $R$-values on input physics and suggests that the $R$-method cannot be presently used for the determination of the absolute He abundance. Instead, we can use the $R$-parameter to constrain the input parameters of the model. If we rely on primordial He abundance measurements in extragalactic H II regions and we assume that mixing processes have been properly accounted for in current HB models, the data plotted in Figure 2 suggest that the current value of the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ nuclear cross section should be roughly a factor of 2 smaller.

This notwithstanding, we can still use the $R$-parameter to constrain the still controversial value of $\Delta Y/\Delta Z$. First of all, we note that even for constant $Y$, the $R$-values plotted in Figure 1 present a trend with metallicity. For $[\text{M/H}] > -1$, the empirical $R$-values show an increase and then a flat distribution. As already noted by Desidera et al. (1997), this behavior is due to the fact that an increase in metallicity causes the luminosity of the RGB bump to become fainter than the ZAHB luminosity, as shown by Z99, and it is well reproduced by the models (Fig. 4). In order to investigate the trend of the relative He content with the global metallicity, in Figure 3 we plot the residuals of the measured $R$-values with respect to the model that better reproduces the data in Figure 1, i.e., $Y = 0.20$. We emphasize that the absolute value of $Y$ adopted as reference changes only the vertical zero point of Figure 3. We would obtain the same distribution using a $Y = 0.23$ model with a $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ smaller by a factor of 2. The two dashed lines show the expected variation in the He abundance using two different assumed values for $\Delta Y/\Delta Z$. The present data suggest that the upper limit to the He-to-metal enrichment ratio should be $\approx 2.5$. In particular, the data would appear to exclude $\Delta Y/\Delta Z \sim 5$ because this would require counting, at metallicity $[\text{M/H}] \sim -0.3$, a number of HB stars lower than that observed by about 30%, or conversely, a number of RGB stars higher by the same amount. Although toward higher metallicity our counts could be contaminated by upper asymptotic giant branch (AGB) stars, the stellar lifetimes of these objects cannot account for such a high effect. On the other hand, the number of red HB stars can be affected by systematic error, although not as high as 30%, only for the clusters affected by strong differential reddening, such as NGC 6388 (because the HB red clump merges into the RGB). The color-magnitude diagram (CMD) of other metal-rich clusters (NGC 5927 and NGC 6624) show a very well separated HB and RGB (Sosin et al. 1997) and cannot be affected by such a problem. Our finding of $\Delta Y/\Delta Z \leq 2.5$ confirms the original results by Peimbert & Torres-Peimbert (1976) and more recently by Peimbert & Peimbert (2000 and references therein).

Figure 3 shows another interesting feature: metal-poor GGCs present on a larger average $R$-value. A similar conclusion was recently reached in S00, who also notes that GGCs with blue HB morphology also have systematically large $R$-parameters; no explanation is offered for this effect. Keeping in mind this problem, we investigate the behavior of each single term in the predicted time ratio. Figure 4 shows the key theoretical ingredients of this parameter, i.e., $t_{\text{HB}}$ (top), $f_{\text{RGB}}$ (middle), and the magnitudes of both ZAHB and RGB bumps (bottom) as a function of metallicity. The dependence of both $M_1$ (ZAHB) and $M_2$ (bump) on metallicity accounts for the slope disclosed by both empirical and theoretical $R$-values (see Fig. 1). In fact, for metallicity

![Figure 2](image-url)  
**Fig. 2.**—Same as Fig. 1, but theoretical predictions refer to HB models at fixed age and He content constructed by assuming an increase/decrease of a factor of 2 in the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ nuclear cross section.

![Figure 3](image-url)  
**Fig. 3.**—Relative He abundance vs. global metallicity. The residuals are obtained by differencing the $R$-values from the theoretical line for $Y = 0.20$ in Fig. 1. The different symbols for the cluster correspond to low, intermediate, and high metallicity. The short-dashed line gives the helium-to-metal enrichment ratio using $\Delta Y/\Delta Z = 2.5$, while the upper long-dashed line (which clearly misses the metal-rich clusters) is for $\Delta Y/\Delta Z = 5$. 

\[ Y = 0.23 \quad \text{and} \quad 14 \text{Gyr} \]

\[ [\text{M/H}] \]

\[ 0.5 \]

\[ 1 \]

\[ 1.5 \]

\[ 2 \]

\[ 2.5 \]
larger than $[\text{M/H}] \approx -1$, the $t_{\text{RGB}}$ presents a sudden decrease caused by the fact that the RGB bump becomes fainter than the ZAHB. This occurrence implies a strong decrease in $t_{\text{RGB}}$ since, for clusters in this metallicity range, the RGB bump phase alone contributes $\approx 20\%$ to the total value of $t_{\text{RGB}}$. This means that small changes in $M_V(\text{ZAHB})$ can cause substantial variations in the $R$-value. This effect explains why the $R$-values of the intermediate-metallicity clusters present a large scatter.

The values of $t_{\text{HB}}$ shown in Figure 4 refer to a star located in the middle of the RR Lyrae instability strip ($\log T_\circ = 3.85$). However, current evolutionary calculations (Castellani et al. 1994) suggest that the lifetime of blue tail HB stars is roughly $30\%$ longer when compared with the lifetimes of HB stars located inside the instability strip. As a consequence, to assess whether predicted $R$-values are affected by systematic uncertainties, we must explore in more detail the dependence of the $R$-parameter on $t_{\text{HB}}$ and in particular on HB morphology. We split the HB into three different regions, namely, the HB stars bluer than RR Lyrae variables ($\mathcal{B}$), the RR Lyrae variables ($\mathcal{V}$), and the HB stars redder than RR Lyrae variables ($\mathcal{R}$) (Lee, Demarque, & Zinn 1994). As a plausible estimate for the blue and the red edge of the RR Lyrae instability strip, we adopted, according to Bono et al. (1997b), $T_\circ \approx 7300$ and $5900$ K, respectively. On the basis of these ingredients, and by assuming a linear mass distribution along the HB, we estimated the average HB lifetime, $t_{\text{HB}}$, at a fixed He abundance $Y = 0.20$, for stars belonging to $\mathcal{B}$, $\mathcal{V}$, and $\mathcal{R}$ regions, respectively. Figure 5 shows the theoretical $R$-parameters for the three different HB morphologies. The $R$-values based on the HB lifetime of RR Lyrae stars—$t_{\text{HB}}(\mathcal{V})$—are almost identical to those based on $t_{\text{HB}}(\mathcal{R})$, thus suggesting that $t_{\text{HB}}(\log T_\circ = 3.85)$ is representative of central He burning lifetime for GCs characterized by HB stars with $\log T_\circ \leq 3.86$. On the other hand, we find that the lifetimes of blue HB stars—$t_{\text{HB}}(\mathcal{B})$—are approximately $20\%$ longer than $t_{\text{HB}}(\mathcal{V})$ and $t_{\text{HB}}(\mathcal{R})$. This means that the $R$-values of GCs with blue HB morphologies are expected to be $\approx 0.25$ units higher than those with red HBs. Therefore, the observed high $R$-values in metal-poor clusters are not due to a real increase in the He abundance, but are likely the consequence of their blue HB morphology. The large scatter among metal-poor clusters is mainly due to the different stellar distributions along the blue tail (see Fig. 9 in Piotto et al. 1999).

In conclusion, a correct measure of the absolute He content on the basis of the $R$-parameter requires the construction, for any given cluster, of a synthetic CMD which properly reproduces the distribution of the stars along the HB and in turn a meaningful evaluation of the $t_{\text{HB}}$. However, this approach is beyond the scope of the present investigation.

4. CONCLUSIONS

We have measured the helium-sensitive $R$-parameter in 26 GCs imaged with WFPC2 on board HST. Our calculated $R$-values are based on star counts that are corrected for completeness and tested for radial variations within each cluster. The high-quality HST photometry also permits a more clear separation of the HB, AGB, and RGB stars.

The comparison between predicted and empirical $R$-values appears to be consistent with the absolute He abundance being lower than that found from the observations of H II regions and from the primordial nucleosynthesis models. One approach to overcome this discrepancy is to adopt a $^{12}\text{C}(x, \gamma)^{16}\text{O}$ nuclear cross section about a factor of 2 smaller than current canonical values. We note that HB lifetimes depend not only on nuclear reaction rates but also on the efficiency of mixing processes and on the algorithms adopted for handling these physical mechanisms. In fact, as recently suggested by Cassisi et al. (2000), current algorithms adopted for quenching the „breathing pulses” intro-
duce a $\approx 5\%$ uncertainty of $t_{\text{HB}}$. As a consequence, the $R$-parameter cannot presently be absolutely calibrated in terms of a helium abundance.

The only trend in our data set is an unphysical trend toward higher helium abundance in the clusters of lowest metallicity. These clusters tend to have blue HBs, and we argue that longer HB lifetimes in high-temperature HB stars likely account for this trend. In fact, the global trend in $R$ with metallicity is well accounted for by changes in HB lifetime as a function of metal abundance.

The trend in $R$-values of the metal-rich globular clusters in our sample is consistent with an upper limit of 2.5 for the helium-to-metal enrichment ratio ($\Delta Y/\Delta Z$). The increased dispersion in $R$ for the intermediate-metallicity clusters may be caused by the RGB bump fading below the HB luminosity at $[\text{Fe/H}] \approx -1$, causing a drop in the calculated RGB lifetime. We conclude that these factors make the $R$-values of low and intermediate globular clusters less useful in constraining the helium abundance. Accurate photometric data for metal-rich globular clusters, however, do place an interesting constraint on $\Delta Y/\Delta Z$.

The GGCs in the Galactic bulge are certainly a key target to accomplish these measurements. It is not a trivial effort to collect high-quality data for such clusters, since they are often affected by high absolute and differential extinction (Ortolani et al. 1999), but the new near-infrared detectors should allow us to overcome these difficulties and to secure accurate data for a sizable fraction of cluster stars. A reconsideration of the bulge clusters and field population would also be in order given the results of Minniti (1995); when his counts are corrected for the contribution of AGB stars, the bulge fields have $R$-values of 1.7–2, higher than those of the most metal-rich clusters in our sample.

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