Wide-Field CCD Photometry of the Globular Cluster M30.

Eric L. Sandquist, Michael Bolte
UCO/Lick Observatory, University of California, Santa Cruz, CA 95064; erics@apollo.astro.nwu.edu, bolte@ucolick.org

G. E. Langer
Department of Physics, Colorado College, Colorado Springs, CO 80903; elanger@cc.colorado.edu

James E. Hesser
Dominion Astrophysical Observatory, Herzberg Institute of Astrophysics, National Research Council of Canada, 5071 West Saanich Road, Victoria, BC V8X 4M6, Canada; hesser@dao.nrc.ca

C. Mendes de Oliveira
Instituto Astronômico e Geofísico (IAG), Av. Miguel Stefano 4200 CEP: 04301-904 São Paulo, Brazil

Received __________; accepted __________

ABSTRACT

We present new $VI$ photometry for the halo globular cluster M30 (NGC 7099 = C2137-174), and compute luminosity functions (LFs) in both bands for samples of about 15,000 hydrogen-burning stars from near the tip of the red giant branch (RGB) to over four magnitudes below the main-sequence (MS) turnoff. We confirm previously observed features of the LF that are at odds with canonical theoretical predictions: an excess of stars on subgiant branch (SGB) approximately 0.4 mag above the turnoff and an excess number of RGB stars relative to MS stars.

Based on subdwarfs with Hipparcos-measured parallaxes, we compute apparent distance moduli of $(m - M)_V = 14.87 \pm 0.12$ and $14.65 \pm 0.12$ for

---

$^1$Current address: Dearborn Observatory, Northwestern University, 2131 Sheridan Road, Evanston, IL 60208

$^2$Visiting Astronomer, Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatories, operated by AURA, Inc., under contract with the NSF.
reddenings of $E(V-I) = 0.06$ and 0.02 respectively. The implied luminosity for the horizontal branch (HB) at these distances is $M_{V}^{HB} = 0.11$ and 0.37 mag. The two helium indicators we have been able to measure ($R$ and $\Delta$) both indicate that M30’s helium content is high relative to other clusters of similar metallicity. M30 has a larger value for the parameter $\Delta V_{TO}^{HB}$ than any of the other similarly metal-poor clusters for which this quantity can be reliably measured. This suggests that M30 has either a larger age or higher helium content than all of the other metal-poor clusters examined. The color-difference method for measuring relative ages indicates that M30 is coeval with the metal-poor clusters M68 and M92.

Subject headings: globular clusters: individual (M30) — stars: luminosity function — stars: abundances — stars: distances — stars: interiors

1. Introduction

This paper is the second in a series investigating the evolved-star populations in nearby globular clusters. With the large-field CCD imagers now available it is possible to measure nearly complete samples of giant stars in clusters, and at the same time measure stars faint enough that we can normalize the luminosity functions (LFs) to the unevolved main sequence. Because the LFs for evolved stars directly probe the timescales and fuel consumed in the different phases of stellar evolution, they provide a stringent test of the models for the evolution of low-mass stars. These models are the basis for our use of globular clusters to set a lower limit to the age of the Universe and are a fundamental tool in the interpretation of the integrated spectra and colors of elliptical galaxies.

The subject of this study is M30 (NGC 7099 = C2137-174), a relatively nearby cluster ($\sim 7$ kpc; Peterson 1993) at high galactic latitude ($b = -46.8^\circ$). M30 has a high central density ($\log (\rho_0/(M_\odot/pc^2)) = 5.9$), a moderate total mass ($\log (M/M_\odot) = 5.3$; Pryor & Meylan 1993), and is at the metal-poor end of the cluster [Fe/H] distribution. It is one of approximately 10% of clusters that have cusps at the core of their surface brightness profiles, and it also has one of the largest radial color gradients of any cluster (Stetson 1991b).

Previous studies of the LF for stars in metal-poor clusters have uncovered unexpected features. In a LF formed from the combination of CCD-based observations of the clusters M68 (NGC 4590 = C1236-264), NGC 6397 (C1736-536), and M92 (NGC 6341 = C1715+432), Stetson (1991a) found an excess of stars on the subgiant branch (SGB)
just above the main-sequence turnoff (MSTO). Bolte (1994) and Bergbusch (1996) both observed M30 using a mosaic of small-field CCD images and found an excess of SGB stars. (The SGB is defined here as the transitional region between the main-sequence turnoff and the base of the red giant branch at the point of maximum curvature.)

Another unexpected observation involving LFs is a mismatch between theoretical predictions and the observed size of the “jump” dividing the main sequence (MS) and the red giant branch (RGB). When normalized to the MS, there is an excess of observed RGB stars compared to models (Stetson 1991a, Bergbusch & VandenBerg 1992, Bolte 1994, Bergbusch 1996), although this has been disputed by Degl’Innocenti, Weiss, & Leone (1997). These results might be explained by the action of core rotation (VandenBerg, Larson, & DePropris 1998), or perhaps (as discussed later) we are witnessing the results of deep mixing and the delivery of fresh fuel into the hydrogen shell-burning regions. Langer & Hoffman (1995) suggested that, if the abundance patterns of light elements seen in bright cluster giants (e.g. Kraft 1994) are due to deep mixing, hydrogen-rich envelope material is almost certainly mixed into the hydrogen burning shell (prolonging the giant phase of evolution), and some of the helium produced is returned to the envelope. Because of the potential importance of such non-standard physics in stars, and because of the caveats associated with earlier LF studies, the most productive next step is to derive better LFs in a number of Galactic globular clusters (GGCs).

In the next section, we describe our observations of the cluster. In §3, we discuss the features observed in the color-magnitude diagram, describe the method of computing the luminosity functions, and present the results of artificial star experiments. In §4, we discuss the constraints that can be put on the global parameters of the cluster — metallicity, distance, and age. The method of data reduction is described in Appendix A.

2. Observations

The data used in deriving the $V$- and $I$-band LFs of M30 were taken on July 7/8, 1994 at the Cerro Tololo Inter-American Observatory (CTIO) 4 m telescope. In all, six exposures of 120 s, one exposure of 60 s and two exposures of 10 s were made in $V$, and six exposures of 120 s, one exposure of 60 s, and one exposure of 10 s were made in $I$. All frames were taken using the 2048 × 2048 pixel “Tek #4” CCD chip, which has a sampling of about 0″.44 per pixel, and a field 15′ on a side. These exposures were reduced individually for the purpose of constructing the color-magnitude diagram. In performing artificial star experiments and deriving the LF, the three best-seeing images in both $V$- and $I$-bands were combined into master long-exposure images. The frames were centered approximately 2′
east of the cluster center, in order to avoid a bright field star nearby.

The night of the 4 m observations was not photometric. In order to set the observations on a standard photometric system, we used observations made at the CTIO 1.5 m telescope on one photometric night (October 18/19, 1996). The detector used was the “Tek #5” 2048 × 2048 CCD, having a field of about 14′8 on a side. Landolt (1992) standard star observations were used to calibrate a secondary field that overlapped the 4 m field. On that night, 10 s and 120 s exposures were taken in each band, along with exposures of 27 standards in 7 Landolt fields. A sample of 118 stars having $12.9 < V < 1.5$ and $-0.03 < (V - I) < 1.31$ was calibrated as secondary standards in this way. The field was centered approximately 5′ south of the cluster center.

During the same run on the 1.5 m telescope, frames were taken of M3 on the non-photometric night of October 16/17. Five additional exposures were taken in each band (20 s, 200s, and 3×600s in V, and 15 s, 180 s, and 3×600s in $I$). The details of the data reduction and calibration are described in Appendix A.

3. The Color-Magnitude Diagram (CMD) and Luminosity Functions (LFs)

3.1. The CMD

In Figure 1, we plot the total $VI$ sample of 25279 stars (upper panel) and a sample that has been restricted in projected radius to $110'' < r < 10'$ from the cluster center (lower panel). The inner radius was chosen in accord with the restriction placed on stars to be used later in the LFs, while the outer radius restriction was chosen to exclude regions that were affected by field star contamination.

Fiducial points for the MS and lower RGB of the clusters were determined by finding the mode of the color distribution of the points in magnitude bins. The fiducial line on the upper RGB was determined by finding the mean color of the stars in magnitude bins. Once a mean was determined, stars falling more than $7\sigma$ from the fiducial point were discarded (so as to eliminate AGB and HB stars, as well as blends and poorly measured stars), and the mean redetermined. This procedure was iterated until the star list did not change between iterations. At the tip of the RGB and on the AGB, the positions of individual stars were included as fiducial points if they appeared to be continuations of the mean fiducial line. The fiducial line for the HB was obtained by determining mean points in magnitude bins for the blue tail, and in color bins for the horizontal part of the branch. No smoothing has been applied. Table 1 lists the fiducial lines for our samples, as well as the number of stars used in computing each point.
3.2. The LFs and Incompleteness

The procedure used to correct the “observed” LF back to the “true” LF is described in detail in Sandquist et al. (1996). As in that paper, we carried out artificial star tests on only four frames: a long exposure frame (composed of the average of the three best-seeing images) and a short exposure frame in both V and I band. In 11 runs, 20965 artificial stars were processed.

ALLFRAME’s coordinate transformations were found to be unable to follow the nonuniform spatial distortions introduced by the 4 m field corrector. To avoid this problem, we reduced all of the frames through ALLSTAR as usual, derived a master detected star list for each filter, and rereduced the frames in ALLSTAR with the improved positions. This procedure improved the overall quality of the photometry (as judged by the scatter around the fiducial lines of the cluster), as ALLFRAME normally does.

In Figures 2 – 4 we plot our computed values for median magnitude biases $\delta_V$, median external error $\sigma_{ext}(V)$, and completeness probability $f(V)$ as a function of magnitude and radius. There is little variation in most of the quantities until the innermost radial region ($r < 2'0$, where crowding of stellar images is worst) is reached.

One change we have made since our first study was in the error estimation. The uncertainty in the incompleteness factor $f$ was previously found by simultaneously varying $F$, $\sigma$, and $\delta$ in such a way as to cause the maximum change in $f$ away from our best value. The magnitude of this change was used as the error estimate. We have improved this, following a suggestion by Bergbusch (1996), by estimating the error by varying $F$, $\sigma$, and $\delta$ individually and adding the resulting error estimates in quadrature.

Using this information, we eliminated stars from consideration for the LF if they fell far enough away from the nearest point on the fiducial line of the cluster. The “distance” was defined in terms of difference in magnitude and color divided by their respective external errors, and then added in quadrature. So, stars were eliminated if $(\Delta V/\sigma_{ext}(V))^2 + (\Delta(V - I)/\sigma_{ext}(V - I))^2 > 25$. On the upper RGB, where contamination by the AGB could be a factor, we adjusted the error cutoff by hand until we were sure the AGB stars were being eliminated, but not at the expense of the RGB stars.

The luminosity functions are listed in Tables 2 and 3. Totals of 14772 and 14507 stars were used in creating the V- and I-band LFs. Stars on the MS and SGB were only included if they fell more than 2'0 from the center of the cluster. This reduced the significance of crowding effects on the photometry. Stars with magnitudes $V < 16.9$ (or $I < 17.0$) were included in the determination of the LF to within 30'' of the center of the cluster. This was done to get a better indication of the “global” LF for the red giants since mass segregation
is expected to occur in M30, which would affect the RGB star counts taken from a small range of radii.

4. Discussion

4.1. Reddening and Metallicity

Most previous studies have made estimates of $E(B - V)$. We will assume $E(V - I) = 1.25E(B - V)$ (Cardelli, Clayton, & Mathis 1989) for the rest of the discussion and refer to the reddening in $E(V - I)$. M30 is situated well out of the Galactic plane ($b = -47$) and the reddening is likely small ($E(V - I) < 0.1$). Reddening maps of Burstein & Heiles (1982) indicate that $E(V - I) < 0.04$. Reed, Hesser & Shawl (1988) derive a negative reddening based on the comparison of M30's integrated color and spectral type. Zinn (1980) gets a value of 0.01 from integrated-light measurements. Reed, Hesser, & Shawl's data indicates that M30 appears to have the bluest intrinsic colors of all of the globular clusters they examined. However, M30 is the cluster that shows the strongest color gradient of any GGC and reddening values measured from integrated colors or spectra will depend on the range of radii over which the observations are made. Given the sense of the gradient, bluer towards the center, it seems likely that these reddening measurements will be biased to lower values.

Dickens (1972) and Richer, Fahlman, & VandenBerg (1988; hereafter RFV) independently derived significantly higher values, $E(V - I) \sim 0.08$, based on the UBV colors of blue HB stars in M30. On the other hand, $U$-band photometry is notoriously difficult to calibrate and the precision of reddening estimates from color-color plots is $\sim 0.04$ mag even in the best cases. Neither the Dickens nor the RFV study appears to have had a photometric calibration good enough to warrant error bars less than this. Differential CMD comparisons with M92 (Vandenberg, Bolte, & Stetson 1990; hereafter VBS) and M68 (Figure 7) imply $E(V - I) \sim 0.05$ to 0.06. The recent reddening maps based on IRAS and COBE measurements of far-IR flux from infrared cirrus suggest $E(V - I) \sim 0.063$.

We can make our own estimate using Sarajedini’s (1994) simultaneous reddening and metallicity method (for $V_{HB} = 15.04 \pm 0.08$ and $(V - I)_g = 0.97 \pm 0.02$, where the quoted errors allow some room for calibration errors). We find $E(V - I) = 0.065 \pm 0.003$. The errors were derived from Monte Carlo tests with the quoted errors on $V_{HB}$ and $(V - I)_g$. Most of the reddening estimates we have thus far indicate a relatively high value $E(V - I) = 0.06 \pm 0.02$.

The compilation of Zinn & West (1984) has $[\text{Fe/H}] = -2.13 \pm 0.13$ and numerous
studies since have determined values between $-1.9$ and $-2.3$ (Geisler, Minniti, & Clariá 1992; Minniti et al. 1993; Carretta & Gratton 1996). From the simultaneous reddening and metallicity method above, we find $[\text{Fe/H}] = -2.01 \pm 0.09$.

Anticipating later discussion of the level of the HB, we examine the effects of an anomalously high $M_V(HB)$ on the simultaneous reddening and metallicity method. A high $M_V(HB)$ value can come about due to a high helium abundance, whether primordial or the result of a “deep mixing” scenario (Langer & Hoffman 1995). If the “true” $M_V(HB)$ value (in the absence of helium enrichment) is fainter by 0.10 mag, then we would have $V_{HB} = 15.14$, and calculate $[\text{Fe/H}] = -2.11 \pm 0.07$ and $E(V-I) = 0.068 \pm 0.002$.

4.2. Distance Modulus

Recently Reid (1997), Gratton et al. (1997) and Pont et al. (1998) have used subdwarf parallaxes measured with the Hipparcos satellite (ESA 1997) to redetermine the distance moduli to several of the best observed clusters. The general result of these studies is to increase cluster distance moduli by 0.2 to 0.4 mag, implying high luminosities for the horizontal branches (as bright as $M_V \sim 0.1$ mag for the $[\text{Fe/H}] \sim -2$ clusters). For M30 specifically, Gratton et al. find $(m-M) = 14.96 \pm 0.10$ (for $E(V-I) = 0.05$) although this is based on only three subdwarfs. We repeat this exercise for M30 with our data and a larger set of subdwarfs. This method is sensitive to uncertainties in the color of the unevolved main-sequence, which result from zero-point errors in the photometric calibration, the reddening uncertainties already mentioned, and uncertainties in the placement of the main-sequence fiducial line. Our data for M30 are not optimum for using subdwarf fitting to measure the distance, primarily because of the uncertainty in the reddening, but also because we suffer from each of the other problems to a small degree.

Nevertheless, we selected subdwarfs that satisfy the following criteria: parallaxes from the Hipparcos mission having relative errors $\sigma_\pi/\pi < 0.15$, metal abundances from the study of Gratton, Carretta, & Castelli (1996), and $VI$ photometry. The restriction on parallax error was chosen to minimize the effect of bias corrections. (As a result, Lutz-Kelker corrections only change our derived distance moduli by 0.01 mag.) The Gratton et al. metallicity scale was chosen for its homogeneity and because it minimizes the possibility of systematic abundance errors with respect to Carretta & Gratton globular cluster metallicities. When available, we used $VI$ photometry for the subdwarfs tabulated in Mandushev et al. (1996). In the remaining cases, we followed their procedure of combining literature values from the following sources: Carney & Aaronson (1979), Carney (1980, 1983b), and Ryan (1989, 1992). The studies involving Carney all used the Johnson $I$ filter,
so we applied the transformation from Carney (1983a) to convert them to the Cousins system. Known spectroscopic binaries were excluded, and, for the cases where it has been measured, any reddening of the subdwarfs (at most a very small amount) has been subtracted. Our sample of subdwarfs and metal-poor subgiants is shown in Table 4. We used the subdwarfs to estimate the distance to M30 in two different ways.

First, to simultaneously estimate the distance and E(V − I) of M30 we created a grid of chi-square-like sums. The M30 main sequence between 19 < V < 22.8 was represented by a third-order polynomial. For ranges of m-M and E(V − I), the minimum distance of each subdwarf from the main-sequence polynomial was calculated. This distance was normalized by the combined errors in the subdwarfs’ colors and magnitudes and the main-sequence fiducial uncertainties in color and magnitude (assumed to be 0.04 mag in color and 0.05 mag in V magnitude). Our “χ^2” sum is:

\[ \chi^2 = \sum_i \frac{(V_i - V_{\text{fiducial}})^2 + ((V - I)_i - (V - I)_{\text{fiducial}})^2}{\sigma^2} \]

We will refer to this as the chi-square sum although it does not match the usual definition of chi-square and it is not normalized in a way to give true confidence intervals. Because the slope of the main-sequence changes with V, there is a different weighting given to ∆V and ∆(V − I) for each subdwarf. The minimum chi-square values are for m − M ~ 14.6 and E(V − I) ~ 0.02, although the reddening in particular is poorly constrained.

Our second approach was to fit the M30 main sequence to the subdwarfs using only the distance modulus as a variable for two E(V − I) values: 0.02 and 0.06. Table 4 shows the changes in this value for different subsets of our sample and for different input data. (The quoted errors include contributions from the scatter of values in the subdwarf fit, a cluster reddening error of 0.02 mag, and the absolute cluster metallicity error of 0.2 dex.) Clearly, reddening uncertainty is dominant in the total uncertainty. Two fits at different reddening are shown in Figure 5. If we use the value of metal content given by Zinn & West ([Fe/H] = −2.13) along with the Carney et al. (1994) abundance scale for the subdwarfs (which has roughly the same zero point as Zinn & West), the distance modulus is increased by only a few hundredths of a magnitude. Restricting the sample to only metal-poor ([Fe/H] < −1.3) subdwarfs also does not significantly change the distance modulus.

Considering the number of distance modulus measurements for M30 in the literature, it is best to try to compare using a common reddening of E(V − I) = 0.02 (and using ∂(m − M)_V/∂E(V − I) ≈ 6 to correct values). From the two methods we presented here we have 14.6 and 14.65. From the pre-Hipparcos ground-based measurements of Bolte (1987) and RFV, we have 14.62 and 14.68 (the RFV value must also be corrected for their
lower assumed metallicity for M30). For the Hipparcos-based distances of Reid (1997) and Gratton et al. (1997), we find 14.75 and 14.87 (although Gratton et al. use only three subdwarfs in their fit). It is clear that our distance moduli are consistent with the ground-based measurements, and over 0.1 mag smaller than the other Hipparcos-based measurements. Nevertheless, the different distance measures are in good general agreement, at least for a fixed reddening value. Although it is not crucial for the conclusions that follow, we will adopt \((m-M)_V = 14.7\) for the rest of the paper. From Figure 5, it is clear that the smaller reddening and distance modulus values are more consistent with the model isochrones and, for our preferred larger reddening value of \(E(V-I) = 0.06\), the models do not match the shape of the M30 fiducial above the turnoff.

4.3. The \(R\) Method

The ratio \(R = N_{HB}/N_{RGB}\), where \(N_{RGB}\) is the number of RGB stars brighter than the luminosity level of the HB, is the traditional quantity used to estimate the helium abundance of stars in globular clusters. Dickens (1972) first noted that M30’s value for “R” was unusually large and Alcaino & Wamsteker (1982) claimed a significant gradient in this ratio in the sense of a small value at the center of the cluster increasing to one of the largest measured in any cluster at large radii. We have sufficient numbers of stars on the red and blue sides of the instability strip to define the level of the HB. From five stars near the blue edge of the instability strip (with colors \(0.25 < (V-I) < 0.35\)), we calculate an average magnitude \(V_{HB,b} = 15.08 \pm 0.06\). From six stars on the red side of the instability strip, we find \(V_{HB,r} = 14.90 \pm 0.06\). All stars used in these averages were found at radii greater than \(1\)' from the center of the cluster, so that the photometry should be quite accurate.

Because the estimate of the HB magnitude is crucial in later arguments, we examine the topic further. Our blue side estimate is consistent with those of Bolte (1987) and Bergbusch (1996), even with the different calibrations of our respective datasets. Because it is possible that the red HB stars in M30 are evolved, it is wise to check this possibility before simply interpolating between the two sides. The number of stars (8 with projected radius \(r > 1\)' compared to 93 on the blue HB) at \(V \sim 14.9\) is roughly consistent with timescales for stars evolving from the blue HB, as the evolutionary tracks tend to parallel each other closely through this part of the CMD as they move toward the AGB. Thus, we have chosen to look at other clusters of similar metallicity with large, well-studied RR Lyrae populations to compute a magnitude correction to go from the red edge of the blue HB into the middle of the instability strip. For the clusters M15 (Bingham et al. 1984), M68 (Walker 1994), and M92 (Carney et al. 1992) we find agreement on a correction of
0.04 mag. Thus, we have \( V_{HB} = 15.04 \pm 0.06 \).

To define the RGB star sample for the \( R \) method, we need to establish the relative bolometric magnitudes of the HB and RGB stars. We have used the HB models of Dorman (1992) in conjunction with the isochrones of Bergbusch & VandenBerg (1992; hereafter BV92). The stellar models involved in these studies were computed with a consistent set of physics and compositions. Although the composition used is somewhat out-of-date, the differential bolometric corrections should be fine. The corrections as a function of [Fe/H] can be approximated by:

\[
\Delta V_{BC} \equiv V_{RGB} - V_{HB} = 0.709 + 0.548[M/H] + 0.229[M/H]^2 + 0.034[M/H]^3.
\]

Because \( \alpha \)-element enhancements influence the position of the HB and RGB in the CMD like a change in [Fe/H] (Salaris, Chieffi, & Straniero 1993), they must be taken into account when computing [M/H].

For M30, we find that \( \Delta V_{BC} = 0.27 \). We have used \([M/H] = -1.70 \) (correcting [Fe/H] by 0.21 dex for \([\alpha/Fe] = +0.3 \)), although for this range of metallicities, changes in metallicity have a very small effect on \( \Delta V_{BC} \). Because of contamination and blending problems toward the center of the cluster, we restrict our samples of RGB and HB stars to \( r > 20'' \). With this choice, we find \( R = 1.45 \pm 0.20 \). This makes M30's \( R \) the highest of any of the clusters examined. In Table 4, we present \( R \) values that have been derived from published photometry for the clusters similar in [Fe/H] to M30 – M68 (Walker 1994), M53 (Cuffey 1965), NGC 5053 (Sarajedini & Milone 1995), NGC 5466 (Buonanno et al. 1984), and M15 (Buonanno et al. 1983) – along with several more metal-rich clusters.

Photometry exists for the central 25'' of M30 from the Hubble Space Telescope (Yanny et al. 1994; hereafter YGSB). By merging their list with ours and eliminating common stars, we have created a master list of HB and RGB stars that completely covers the cluster out to 7'', with portions included out to about 12'. The data for the full sample is presented in Table 4. Using this sample, we find a global value for \( R \) of 1.49 \( \pm 0.18 \). (Even if our value of \( V_{HB} \) is too bright, and if we use the magnitude of the red edge of the blue HB, we find \( R = 1.36 \pm 0.21 \) — still a high value in a relative sense.)

This global \( R \) value for M30 is on firm ground, because there is no place for the bright stars to hide. The photometry is easily good enough to distinguish between the AGB and RGB star samples, so this is not a source of uncertainty. (In fact, M30 may be deficient in AGB stars as well as RGB stars.) The use of the lower Buzzoni et al. (1983) value \( \Delta V_{BC} = 0.15 \) for the differential bolometric correction would increase the high \( R \) value. Approximately 30 additional RGB stars would have to be included to bring M30's value in line with that of other clusters — a 24% change in the sample size.
There are a few potential explanations for a *global* depletion of bright giants in this cluster. First, because the ratio $R$ is a helium abundance indicator, the abnormally high value could indicate a higher-than-average helium abundance in M30 stars more luminous than the HB. This does not necessarily imply high Y for lower luminosity stars, since a deep-mixing mechanism would also be expected to dredge up freshly produced helium (Sweigart 1997). Second, the environment within the cluster may affect the stellar populations by a mechanism that truncates RGB evolution and/or produces additional HB stars. We now consider the arguments for the two sides.

4.3.1. Helium Abundance

Using the Buzzoni et al. (1983) calibration and our M30 $R$ value, we find $Y = 0.24 \pm 0.02$. The value derived using $V_{HB}$ of the blue edge of the instability strip gives $Y = 0.23 \pm 0.02$. That $V_{HB}$ is definitely a faint limit, making $Y = 0.23$ a lower limit. In any case, the $R$ value for M30 is significantly higher than those for other clusters when the revised differential bolometric corrections are used. [The low value of $Y(R)$ for the other clusters is discussed in Sandquist (1998).]

One check we can make is to examine other helium indicators to see if they also indicate a high abundance relative to other clusters. Caputo, Cayrel, & Cayrel de Strobel (1983) introduced two indicators: $A$ (the mass-luminosity relation for RR Lyrae stars of ab type) and $\Delta$ (the magnitude difference between the HB and the point on the MS where the dereddened $B-V$ color is 0.7). While M30’s RRab variables have not been studied to the extent necessary to compute $A$, we can compute a $\Delta$ value from the $BV$ photometry of Bolte (1987) and RFV. Assuming for both that $E(V-I) = 0.06 \pm 0.02$, we find $6.42 \pm 0.12$ and $6.28 \pm 0.13$ respectively, where the primary contributions to the error are the uncertainty in the reddening and the small number of stars used to define the HB magnitude. (The lower RFV value can be traced to a fainter HB magnitude relative to Bolte’s data.)

We have computed comparison values for the clusters M68 (McCleure et al. 1987, Walker 1994), and M15 (Durrell & Harris 1993), as summarized in Table 6. The $\Delta$ values for the other clusters agree with the theoretical value of 6.30 for $[\text{M/H}] = -1.82$ ($[\text{Fe/H}] = -2.03$).

We can directly compare our data with $VI$ for other clusters if we redefine $\Delta$ (hereafter, $\Delta_{B-V}$) by choosing the MS point to have $(V-I)_0 = 0.85$. From isochrones this is approximately equivalent to $(B-V)_0 = 0.7$. From our fiducial line, we find $\Delta_{V-I} = 6.36 \pm 0.10$ for $E(V-I) = 0.06 \pm 0.02$. $VI$ data exist for M92 (Johnson & Bolte 1998) and M68 (Walker 1994). We find that $\Delta_{V-I} = 6.25 \pm 0.12$ ($E(V-I) = 0.025 \pm 0.0125$)
and $6.11 \pm 0.07 \, (E(V-I) = 0.0875 \pm 0.0125)$, respectively. The M92 value relies essentially on one star for the HB magnitude, so the $\Delta_{V-I}$ value is uncertain.

For $\Delta_{B-V}$ and $\Delta_{V-I}$ we see evidence (though not overwhelming) that the M30 value is high compared to other clusters. The values above indicate that M30’s helium abundance is high by about 0.02 for $[\text{M/H}] = -1.7$ if the helium is primordial, or 0.03 if the helium enrichment only affects the level of the HB, as in the deep mixing scenario. (Note that a lower value for the reddening would bring the $\Delta$ values into consistency with the other clusters.) A high helium abundance would tend to make the HB distribution bluer on the whole. According to Fusi Pecci et al. (1993), the color of the peak of the HB star distribution in M30 is one of the bluest, but other clusters are rather close (M53 is bluer, M15 has approximately the same peak color, and M92 and NGC 5466 are slightly redder).

4.3.2. Environmental Effects

Because M30 has a core of high stellar density, we consider the possibility that this environment has influenced the populations of evolved stars in the cluster. M30 has one of the most robustly determined color gradients (approximately linear in log $r$: $\sim +0.20$ mag dex$^{-1}$; Piotto, King, & Djorgovski 1988) of all the globular clusters in the Galaxy. The sense of the color gradient is such that the integrated colors become bluer towards the cluster center. In M30 and other post-core-collapse clusters it has been suggested that the color gradient is due to a decrease in the ratio of RGB-to-BHB stars resulting from stellar interactions in the dense cluster cores. Although Djorgovski & Piotto (1993) claim the color gradient measured in M30 is due to a deficit of RGB stars in the inner few tens of arcseconds, Burgarella & Buat (1996) show that the gradient (which extends to radii $>2'$) is not due to differences in the spatial distribution in the evolved-star populations or in the blue stragglers. Our results are consistent with this latter claim.

Buonanno et al. (1988) claimed to have detected a radial variation in the ratio $R = N_{HB}/N_{RGB}$ on the basis of a smaller sample of stars. From our sample, we find $R$ ranges from about $1.30 \pm 0.26$ in the inner $30''$ to $1.35 \pm 0.27$ for $30'' < r < 100''$ to $1.83 \pm 0.36$ for stars with projected radius $r > 100''$. There may be marginal evidence for a difference between the outer annulus, and the inner two, but over the range of radii for which the bluer-inward color gradient has been observed, there is no evidence of a trend in the bright populations. The sense of the difference between the outer and inner populations is in any case opposite to that required to make the color gradient. The cumulative radial distribution (Figure B) also shows no strong trends in radius, contrary to claims in other studies with smaller samples (Buonanno et al. 1988, Piotto et al. 1988),
but in agreement with studies of the core (Yanny et al. 1994, Burgarella & Buat 1996). A Kolmogorov-Smirnoff test indicates a 33% chance that the two samples are drawn from the same distribution. The inhomogeneity of the RGB sample seems to be responsible for this noncommittal probability.

We conclude that despite the color gradient in M30, and the apparently ripe conditions for interactions to alter the stellar populations, environment-based processes are not responsible for the high R value we measure.

4.4. Age

4.4.1. Relative Age Indicators: $\Delta V_{HB}^{TO}$ and $\Delta(V-I)$

Based on the color-difference method, VBS claimed that the most metal-poor clusters, including M30, are coeval at the level of 1 Gyr. Our comparison (Figure [7]) of the fiducial lines of M30 and M68 (Walker 1994) in the neighborhood of the SGB indicates that the ages of M30 and M68 (assuming similar main-sequence Y and [\(\alpha/Fe\)]) are nearly identical. With our uniform calibration of MSTO and evolved stars in M30, we can determine with good precision the other commonly applied age estimator $\Delta V_{HB}^{TO}$. In computing the values presented in Table 3, we have attempted to use the studies with the largest samples having uniform photometry from the level of the HB to below the TO. We were able to derive values for the clusters M68 (Walker 1994), M53 and NGC 5053 (Heasley & Christian 1991), M92 (Bolte & Roman 1998), and M15 (Durrell & Harris 1993). Although the clusters all have blue HB morphologies, it has not been necessary to make corrections to find the “true” HB level: either the HB is populated on both sides of the instability strip (M53, NGC 5053) or there are a number of well-measured RR Lyrae stars (M15, M68, M92).

From our photometry of M30, we find $V_{TO} = 18.63 \pm 0.05$, and $\Delta V_{HB}^{TO} = 3.59 \pm 0.06$. While M15, M53, M68, M92, and NGC 5053 have $\Delta V_{HB}^{TO}$ values that agree to within the errors (and also agree with the values derived for clusters of higher metallicity), M30 has a value about 0.15 mag higher. This is in disagreement with values given in the extensive tabulation of Chaboyer, Demarque, & Sarajedini (1996). The values for M30 and M92 in particular have been put on firmer ground here since consistent photometry exists from the HB to the TO. Using the more robust V(BTO) (the apparent magnitude of a point 0.05 mag redder than the turnoff; Chaboyer et al 1996), we can compare $\Delta V_{HB}^{BTO}$ values for M30 and M68, which also has $VI$ data. We find $3.16 \pm 0.06$ for M30, and $2.96 \pm 0.02$ for M68.

There are two plausible ways to explain the apparent 0.15 mag excess in $\Delta V_{HB}^{TO}$ for M30 relative to other clusters. First, M30 could be older by $\sim 2$ Gyr. This conclusion would
be in conflict with that inferred by VBS based on the color-difference method. (This is perhaps the first case for which the relative age indicators $\Delta V_{TO}^{HB}$ and the subgiant-branch color extent give significantly different answers.) Alternatively, M30 stars could have a larger initial helium abundance by approximately 0.027. If the higher helium abundance is restricted to the cluster HB stars, as would be the case in a deep-mixing scenario, the increase required is approximately 0.045. (The agreement between the M30 and M68 CMDs everywhere but on the HB would argue against a difference in the initial helium abundances in the two clusters, as would beliefs about Galactic chemical evolution.) The size of the potential helium enhancement is close to what was inferred earlier from the helium indicators $\Delta$ and $R$ for M30.

4.5. Luminosity Functions

In the following, we will be using a combination of oxygen-enhanced (BV92) and $\alpha$-element enhanced (VandenBerg 1997) theoretical LFs to interpret the data. The current state of knowledge indicates that all of the $\alpha$ elements have enhancements (Pilachowski, Olszewski, & Odell 1983; Gratton, Quarta, & Ortolani 1986; Sneden et al. 1992). The available evidence also suggests that the oxygen enhancement remains constant, at least for $[\text{Fe/H}] \lesssim -1.4$ (e.g. Suntzeff 1993, Carney 1996).

On the RGB, stellar evolution is insensitive to the oxygen abundance because the luminosity evolution is driven almost entirely by the helium core mass (Refsdal & Weigert 1970), while the color is primarily determined by H$^-$ opacity. Oxygen has a relatively high ionization potential, and hence does not contribute electrons to the opacity. The fainter one goes on the MS, the more insensitive the evolution is to the oxygen abundance because of the same opacity effect, and because $p - p$ chain reactions are dominant over CNO cycle reactions in influencing the luminosity. As a result, the different distribution of heavy elements causes negligible differences in the theoretical LFs on the RGB and lower MS (see Figure 17 of Sandquist et al. 1996).

It is primarily the turnoff region that is affected by changes in the oxygen abundance, because CNO cycle reactions begin to become important, and because oxygen ionization regions are close enough to the surface to influence surface temperatures. Increased oxygen abundance increases the envelope opacity, creating redder models. Increased CNO cycle activity causes a star to adjust to accommodate the increased luminosity by reducing the temperature and density of the hydrogen burning regions, which results in a net decrease in the luminosity of the turnoff and SGB relative to solar-ratio models. Thus, the SGB “jump” moves in magnitude in the LF. In the CMD, it also changes slightly in slope, but
for metal-poor clusters like M30, this does not cause a significant change in the shape of the SGB jump in the LF.

An examination of BV92 models indicates that the V-band LF is not very age-sensitive for this range of metallicities. It is most sensitive on the SGB and then, as found in Sandquist et al. (1996), only when the SGB is nearly horizontal in the CMD. In V band for a cluster as metal-poor as M30, the SGB has a relatively large slope, and so only a large systematic age error will influence the fit. In light of the Hipparcos parallax data, this possibility should be considered, since derived distance moduli indicate brighter TO magnitudes (and thus, younger ages) for metal-poor clusters. Figure 8 shows a comparison of the V-band LF with theoretical LFs for different ages, using an apparent distance modulus of \((m - M)_V = 14.87\), as derived from one fit to the Hipparcos subdwarf sample.

Previous studies of M30’s V-band LF (Piotto et al. 1987, Bolte 1994, Bergbusch 1996) uncovered two unusual features in comparisons with theoretical models: an excess of faint red giants relative to main-sequence stars, and an excess of subgiant stars. Our photometry goes fainter on the MS, allowing us to verify that the normalization of the theoretical models has not been made in an “abnormal” section, while our wide field allows us to measure the largest sample of red giants in the cluster to date.

Figure 9 shows a comparison of the studies, with magnitude shifts according to measured zero-point differences. In large part there is excellent agreement. Our LF is significantly below Bergbusch’s at his faint end, most likely due to underestimated incompleteness corrections in his study. At the bright end of the RGB \((V < 15)\), our LF points are also below most of Bergbusch’s. However, we observed a larger number of giants, and our bins are larger, making our points more significant statistically.

In the following subsections, we discuss the main features in the LFs.

4.5.1. Red Giant Branch Excesses

There is a apparently a considerable excess of stars on the RGB for \(15 < V < 17\) (we will refer to this as the “lower RGB”) when compared to the models normalized to the unevolved main sequence. To judge the reality of the excess, we need to accurately normalize the theoretical LFs in the horizontal and vertical directions, and choose the photometry subsample to maximize the statistical significance. The horizontal normalization can be accomplished by shifting the theoretical LF in magnitude so that the TO matches that of the observational LF (Stetson 1991a). In the vertical direction, we have normalized to the MS in a range of magnitudes where there are large numbers of measured stars, and where
incompleteness is a relatively small consideration.

The mass function controls how well the normalized theoretical LF is fit to the MS portion in the present example. As shown in Figure 11, fits using small values for the power-law mass function exponent $x$ indicate that the relative numbers of stars on the RGB and lower MS can be matched by canonical stellar evolution models. With such a choice though, bins with $18.3 < V < 20.1$ are not well-modeled. We find that the LF can be modeled from near the faint limit of our survey to the base of the RGB if we use a higher value for $x$. This alleviates the depression in the star counts in this magnitude range seen by Bolte (1994). However, we are still left with an excess of RGB stars relative to MS stars in the range $15.1 < V < 16.6$.

The effects of mass segregation have been previously observed within M30 in the form of a variation of the local mass function exponent $x_{local}$ with radius (RFV, Bolte 1989, Piotto et al. 1990, Sosin 1997). As a result, the best comparison that can be made would be between theory and a faint sample restricted to the outskirts of the cluster. The models of Pryor, Smith, & McClure (1986), as well as observational studies, indicate that restricting the sample to stars more than 20 core radii from the center should minimize the effects of mass segregation on faint end of the LF.

Figure 11 shows the LF we computed for this purpose. The presence of the RGB-MS discrepancy in this case suggests that the problem is not related to the dynamical effects on the mass function, at least in the outskirts. We can get good overall agreement with the shape of the LF on the MS, but there is a relative excess of RGB stars, and the SGB region is not well fit. The SGB comparison is insensitive to age and metallicity using this method of matching the MSTO. Helium abundance, however, has a larger effect (Stetson 1991a). Because the RGB stars in M30 become more populous relative to HB stars (and presumably MS stars) towards the center, we expect that the cluster core would show a larger discrepancy.

As with the SGB excess, this effect has only been observed in metal-poor clusters (in other words, not in the LFs of NGC 288 or M5). To add stars to the canonical number at a point in the red giant LF, one must either increase the hydrogen content of the mass being fed into the hydrogen-burning shell, or reduce the density or temperature of the burning shell. One possibility for the excess stars on the lower RGB is that we are seeing the effects of deep mixing, which brings hydrogen-rich envelope material into the energy generating shell. If this kind of mixing occurred on the lower RGB, it could eliminate the RGB bump by erasing the chemical discontinuity left by a surface convection zone.

Alternately, VandenBerg, Larson, & DePropris (1998) have examined the effects of
rotation on RGB evolution. They found that core rotation can expand the outer portions of the stellar core enough to cause a reduction of the shell temperature. This results in a decrease in the rate of evolution for RGB stars, and hence leads to an increase in the number of stars per luminosity bin. This is in the correct direction to explain the RGB excess. This rotation could be related to deep mixing scenarios that are required to explain abundance anomalies in RGB stars (e.g. Shetrone 1996) — most notably a decline in the $^{12}\text{C}/^{13}\text{C}$ ratio relative to theoretical predictions, and Na-O and Al-O anti-correlations (as surface material is mixed into regions where O is being converted to N in the CNO cycle). [Note that rotation cannot explain subgiant branch excesses because the burning region in core-burning stages is too small to contain a significant amount of angular momentum (VandenBerg 1995). Even if rotation does affect the structure of the star outside the core, and thereby changes the core temperature, this would not produce isothermalization that would lead to SGB excesses.]

The rotation and mixing pictures (with the assumption that mixing is somehow based on internal rotation) receive some support from observations of rotation in HB stars of some clusters. There is definite evidence of stellar rotation in blue HB stars in NGC 288, M3, and M13 (Peterson, Rood, & Crocker 1995). M13 has the fastest rotators, with stars falling into two groups: some with $v \approx 15 \text{ km s}^{-1}$, and some with $v \approx 38 \text{ km s}^{-1}$. M3 has a $v \sin i$ distribution consistent with $v = 13 \pm 2 \text{ km s}^{-1}$, while NGC 288’s stars are consistent with $v = 9 \pm 2 \text{ km s}^{-1}$. Cohen & McCarthy (1997) also found projected rotation rates between 15 and 40 km s$^{-1}$ for five blue HB stars in M92. The presence of stellar rotation on the HB implies that angular momentum may have been stored during the RGB phase in a rapidly rotating core, avoiding loss of angular momentum through the stellar wind. (Such mass loss is needed to be able to create HB stars of appropriate masses to match observed cluster HB morphologies.) If this is true, it would be particularly interesting to compare LFs for M3 and M13 to look for the effects of rotation, and perhaps even different levels of rotation. Further stellar rotation measurements for M30, M68, and M92 would also be helpful in examining rotation as a cause of MS-RGB discrepancy in the combined LF.

4.5.2. The RGB Bump

Figure 12 presents the cumulative LF (CLF) for the cluster. In this graph we have included RGB stars from 1′ to 6′ from the center of the cluster. The RGB bump is typically identified from a break in slope in the cumulative LF. At this point, the shell-burning source begins consuming material of constant, lower helium content (in other words, the shell reaches what was formerly the base of the convection zone at its maximum extent —
Fusi Pecci et al. (1990). Fusi Pecci et al. examined clusters over a range of metallicities, and found a linear relation between $\Delta V_{bump}^{HB} = V_{bump} - V_{HB}$ and $[\text{Fe/H}]$, as predicted by theory. By combining CMDs for three of the most metal-poor clusters (M15, M92, and NGC 5466), they found $\Delta V_{bump}^{HB} = -0.51 \pm 0.05$. In addition, for NGC 6397, the most metal-poor cluster for which they were able to find the bump, they found $\Delta V_{bump}^{HB} = -0.40 \pm 0.16$.

As shown in Figure 12, we have examined data for M68 (Walker 1994), a cluster of nearly the same metallicity as M30, in order to get a better idea of where the bump should be. There is a clear indication of a slope break for M68: $\Delta V_{bump}^{HB} = -0.46 \pm 0.03$, or $V_{TO} - V = 3.87$, for M68. That result shows that the continuation of the Fusi Pecci et al. relation to lower metallicity appears correct. We have chosen to shift M30 and M68 so that their MSTOs align because of the evidence that M30’s HB may be anomalously bright (see § 4.2). The comparison reveals that there may be a feature at the same position as in M68, although we do not see significant signs of slope change in the CLF at the position of the feature.

4.5.3. Subgiant Branch Excesses

We find that a few bins on the SGB ($V \approx 18.17$) show an excess of stars relative to the theoretical predictions for the best fitting models, confirming the result of Bolte (1994). In Figure 13, we plot the LF with a radius cut closer to the cluster center so as to get better statistics on the SGB. As Figure 14 shows, there is little scatter in the vicinity of the SGB in the CMD that would tend to wash out or contribute to the observed excess at $V \approx 18.2$. The excess is based on a single point having a significance of $2.7\sigma$, where the error in almost entirely due to Poisson statistics. Bolte (1994) states the significance of the bump as $4.8\sigma$, and it appears to occupy two LF bins in his Figure 7. The significance of his result is probably smaller than that because of the difficulty in determining the position of the “jump” ($\approx 0.8$ mag brighter than the MSTO in $V$) in his LF.

An examination of the $I$-band LF in Figure 15 shows the presence of a deviation at the same position in the CMD. This is important because the slope of the SGB is steeper in an $(I, V - I)$ CMD than in a $(V, V - I)$ CMD. As a result, the bump can no longer be ascribed to a feature caused by the exact slope: it must be the result of an increase in the number of stars congregating near a point on the cluster’s fiducial line. At the analogous position in the $I$-band LF, there are two bins with excesses of $1.7\sigma$ and $2.8\sigma$ compared to theory, for a combined significance of $3.3\sigma$. The appearance of the subgiant branch excess in both the $V$- and $I$-band LFs indicates that the cause must be due to an excess of stars (rather than being caused by the exact slope of the SGB — thus eliminating the exact metallicity,
helium content, and oxygen abundance as causes).

So, the SGB excess has marginal significance in our LFs. In order to more definitively determine the reality of the feature, photometry reaching into the center of this cluster will be needed. The observation of this feature in the combined LF of M68, M92, and NGC 6397 (Stetson 1991a) lends more credence to the phenomenon, but more investigation is necessary.

Sandquist et al. (1996) found that there was no evidence for an SGB excess in the LF of the more metal rich cluster M5 (which has a good $I$-band LF for easy comparison with Figure 17). Bergbusch (1993) saw no evidence of an excess in his $V$-band LF of NGC 288. These pieces of evidence seem to indicate that any cause must only be effective at low metallicities. There is, however, a general lack of useful LF data covering the SGB for globular clusters with metallicities between M5 and M30, or more metal rich than M5.

If the feature is real, there are at least two potential means of creating such an excess: a fluctuation in the initial mass function, and an unknown physical process isothermalizing the stellar core of turnoff mass stars. The excess in Stetson’s M68-M92-NGC 6397 LF makes mass function fluctuations less likely. A star can be forced to pause on the SGB, but still burning hydrogen in its core, if isothermality is imposed on a large portion of the core (Faulkner & Swenson 1993). If such a process occurred in a large enough fraction of the stars in a cluster, a SGB excess could be created in the LF. A way to create such an excess is to invoke a process that increases the efficiency of energy transfer over a large portion of the core. For this to happen, the mean free path of the transporting particle must be large. No such particle has been identified to date.

5. Conclusions

1. Determinations of the reddening for M30 disagree at a ±0.03 mag level and cases can be made for values ranging from 0.03 to 0.07 in E($V - I$). This uncertainty is the main factor preventing a more accurate determination of the distance modulus. By fitting subdwarfs with Hipparcos parallax data to the $VI$ fiducial line, we find satisfactory fits for $(m - M)_V$; E($V - I$) pairs ranging from 14.87; 0.06 to 14.65; 0.02 with the statistical errors of around 0.12 mag (all for the case $[\text{Fe/H}] = -1.91$). When shifted to a common reddening, we find our distance modulus is consistent with ground-based estimates, and at least 0.1 mag smaller than other Hipparcos-based estimates.

2. M30 has a larger $R$ value [$N_{HB}/N_{RGB}$] than any of the other metal-poor clusters for which this quantity has been measured. This quantity is usually used as a helium indicator
and our measured $R$ value suggests a helium abundance $\sim 0.03 - 0.04$ larger than the mean of the other metal-poor clusters. M30’s value for the helium indicator $\Delta$ is also relatively high although for the case of $E(V-I) < 0.02$, it is consistent with the other metal-poor clusters. If there is a helium abundance enhancement in M30, it is probably not an initial abundance difference since Galactic chemical evolution and the similarity of the M30 and M68 fiducial lines (see next point) argue against it.

3. The $\Delta V_{TO}^{HB}$ value for M30 is demonstrably large relative to clusters of similar metallicity. The M30 fiducial line (except for the HB) overlies that of M68 (see Figure 7) and M92 (VBS) very closely, indicating that M30 probably has the same age as these two clusters. We suggest that the HB luminosity in M30 is high due to a larger-than-average $Y$ for the M30 HB stars.

4. The LFs of the cluster show definite evidence for an excess of RGB stars relative to MS stars, and marginally significant ($\approx 3\sigma$) evidence for an excess of SGB stars, as compared with theory. The SGB feature has slightly higher significance in the $I$ band. The possibility remains that these anomalies are only present in low-metallicity clusters.

   Stellar rotation is a possible explanation for the excess number of RGB stars relative to MS stars. Alternatively, the excess giants could be a signpost for mixing events on the lower RGB in which fresh hydrogen is mixing into the energy generation region. This could also be identified as the source of the envelope $Y$-enrichment we infer from the HB and brighter RGB stars.

5. We do not find an obvious RGB bump in M30, in spite of the size of our RGB sample. Using the cumulative LF, we have detected the bump in the metal-poor cluster M68 with a $\Delta V_{bump}^{HB}$ value that agrees with the linear trend with $[\text{Fe/H}]$ found by Fusi Pecci et al. (1990).

   It is possible that points 2 - 5 are all related to the deep-mixing events inferred for some globulars based on the surface abundances of elements that participate in the energy generation cycles. The hypothesis that we are seeing the effects of the mixing of hydrogen-rich material into the energy-generation regions and helium-rich material out into the stellar envelope can qualitatively explain all of these (2 through 5) observations. If this hypothesis is correct then we predict that detailed abundance studies of the bright giants in M30 should show the characteristic patterns of deep mixing – low oxygen and carbon abundances accompanied by high nitrogen, aluminum, and sodium.

We would especially like to thank D. VandenBerg for providing us with theoretical $\alpha$-enhanced isochrones and luminosity functions prior to publication and P. Stetson for the
use of his excellent software. It is a pleasure to thank P. Guhathakurta, Z. Webster, and R. Rood for useful conversations. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. M.B. is happy to acknowledge support from NSF grant AST 94-20204.

Electronic copies of the listing of the photometry are available on request to the first author.
A. Data Reduction

A.1. Primary Standard Calibration Fields

A.1.1. Aperture Photometry

Aperture photometry was performed using the program DAOPHOT II (Stetson 1987). Using these data, growth curves were constructed for each frame using DAOGROW (Stetson 1990) in order to extrapolate from the flux measurements over a circular area of finite radius to the total flux observable for the star. The aperture magnitudes and the known standard system magnitudes of Landolt (1992) were then used to derive coefficients for the transformation equations:

\[
\begin{align*}
v &= V + a_0 + a_1 \cdot (X - 1.25) + a_2 \cdot (V - I) + a_3 \cdot (V - I)^2 + a_4 \cdot (V - I)^3 \\
i &= I + b_0 + b_1 \cdot (X - 1.25) + b_2 \cdot (V - I),
\end{align*}
\]

where \(v\) and \(i\) are observed aperture photometry magnitudes, \(V\) and \(I\) are the standard system magnitudes, and \(X\) is the airmass. The primary standard stars covered a color range \(-0.35 < (V - I) < 1.67\), completely encompassing the color range of the cluster sample. The coefficients for the transformation equations are given in Table A1. The residuals for the sample of 25 stars are shown in Figure 16, and the average residuals are given in Table A2. (In this and all subsequent comparisons, the residuals are calculated in the sense of ours – theirs.)

A.2. Secondary Standard Calibration

We chose 118 relatively bright and isolated stars in the M30 field observed with the 1.5 m telescope during the photometric night to be “secondary standards”. The stars selected were required to be unsaturated, brighter than the turnoff, in relatively uncrowded regions of the images, and close to the apparent fiducial line of the cluster (since this acts as an additional check on the accuracy of the photometry). Once the list was finalized, all other stars were subtracted from the frames and aperture photometry was obtained. The colors for these standards cover the range \(12.82 < V < 16.54\) and \(-0.069 < (V - I) < 1.280\)

A.3. Object Frames
A.3.1. Profile Fitting Photometry

Both the CTIO 4 m and 1.5 m data for M30 were reduced using the standard suite of programs developed by Peter Stetson (DAOPHOT/ALLSTAR; Stetson 1987, 1989), and following the procedures in Sandquist et al. (1996).

A.3.2. Calibration

We used the secondary standards established with the 1.5 m observations on the single photometric night to determine the coefficients in the transformation equations for all of the 1.5 m profile fitting photometry:

\[
\begin{align*}
v &= V + a_{0,k} + a_1 \cdot (V - I) \\
i &= I + b_{0,k} + b_1 \cdot (V - I),
\end{align*}
\]

where \(v\) and \(i\) are the instrumental magnitudes from the profile fitting, \(V\) and \(I\) are the standard values from the aperture photometry, and \(k\) is an index referring to individual frames. The coefficients of the color terms are given in Table A1, the average residuals and standard deviation of the residuals for the comparison of the profile fitting and aperture photometry are given in Table A2, and individual star residuals are shown in Figure 17.

In the next step, we chose to calibrate the 4 m profile fitting photometry to the 1.5 m profile fitting photometry rather than the aperture photometry of the secondary standards. This was done primarily to ensure that all of our profile fitting was on the same system over as large a range of magnitudes as possible. The M30 frames taken at the 1.5 m telescope on the one photometric night did not go particularly deep, while the 4 m photometry had few unsaturated observations of the brighter stars in the cluster. The data taken on the non-photometric nights at the 1.5 m telescope did, however, cover a range of magnitudes similar to that of the 4 m data.

We selected a sample of 248 stars found in both fields at least 300 pixels away from the cluster center. These stars were used to determine the transformation coefficients for the equations:

\[
\begin{align*}
v &= V + a_{0,k} + a_1 \cdot (V - I) + a_2 \cdot (V - I)^2 \\
i &= I + b_{0,k} + b_1 \cdot (V - I) + b_2 \cdot (V - I)^2,
\end{align*}
\]

where \(v\) and \(i\) are the instrumental magnitudes from the 4 m observations, and \(V\) and \(I\) are the standard values from the 1.5 m observations. The coefficients of the color terms are
given in Table A1, while the residuals of the comparison of the photometry for the 4 m and 1.5 m measurements of the secondary standards are shown in Figure 18.

For the final calibration, we used the transformation equations for the 1.5 m and 4 m profile-fitting data. All of the profile-fitting photometry from both telescopes was combined with weights equal to the inverse square of the internal measurement errors in order to determine our standard-system magnitude and color values.

Because of the large sky coverage of the CTIO frames, most other surveys of M30 overlap the program area at least partially. Table A2 provides a summary of the zero-point offsets for comparisons with these studies. We would particularly like to point out that there is considerable difference among them, highlighting the importance of the calibration. The fields used by Bolte (1987), RFV, and Samus et al. (1995) are completely included on all frames. A comparison with the photometry of Bolte is given in Figure 19. In Figure 20, we show the comparison with the study of M30 by Samus et al. (1995). We do this partly because it involves the same filter bands, and partly because the residuals are the lowest on average (although the scatter in star-to-star residuals is large). As a note, comparisons with the most recent study (Bergbusch 1996) show no signs of color trends in the residuals except within about a magnitude of the tip of the giant branch.
REFERENCES

Alcaino, G., & Wamsteker, W. 1982, A&AS, 50, 141.
Bergbusch, P. A. 1993, AJ, 106, 1024
Bergbusch, P. A. 1996, AJ, 112, 1061
Bergbusch, P. A., & VandenBerg, D. A. 1992, ApJS, 81, 163 (BV92)
Bingham, E. A., Cacciari, C., Dickens, R. J., & Fusi Pecci, F. 1984, MNRAS, 209, 765
Bolte, M. 1987, ApJ, 319, 760
Bolte, M. 1989, ApJ, 341, 168
Bolte, M. 1994, ApJ, 431, 223
Bolte, M. & Roman, C. 1998, in preparation.
Buonanno, R., Buscema, G., Corsi, C. E., Iannicola, G., Fusi Pecci, F. 1983, A&AS, 51, 83
Buonanno, R., Buscema, G., Corsi, C. E., Iannicola, G., Fusi Pecci, F. 1984, A&AS, 56, 79
Buonanno, R., Caloi, V., Castellani, V., Corsi, C. E., Ferraro, I., & Piccolo, F.. 1988, A&AS, 74, 353
Burgarella, D, & Buat, V. 1996, A&A, 313, 129
Burstein, D. & Heiles, C. 1982, AJ, 87, 1165
Buzzoni, A., Fusi Pecci, F., Buonanno, R., & Corsi, C. E. 1983, A&A, 128, 94
Caputo, F., Cayrel, R. & Cayrel de Strobel, G. 1983, A&A, 123, 135
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Carney, B. W. 1980, AJ, 85, 38
Carney, B. W. 1983a, AJ, 88, 610
Carney, B. W. 1983b, AJ, 88, 623
Carney, B. W. 1996, PASP, 108, 900
Carney, B. W. & Aaronson, M. 1979, AJ, 84, 867
Carney, B. W., Latham, D. A., Laird, J. B., & Aguilar, L. A. 1994, AJ, 107, 2240
Carney, B. W., Storm, J., Trammell, S. R., & Jones, R. V. 1992, PASP, 104, 44
Carretta, E. & Gratton, R. G. 1996, A&AS, 121, 95
Chaboyer, B., Demarque, P., & Sarajedini, A., 1996, ApJ, 459, 558
Cohen, J. G. & McCarthy, J. K. 1997, AJ, 113, 1353
Cuffey, J. 1965, AJ, 70, 732
Degl’Innocenti, S., Weiss, A., & Leone, L. 1997, A&A, 319, 487
Dickens, R. J. 1972, MNRAS, 157, 299
Djorgovski, S. & Piotto, G. 1993, in ASP Conf. Ser., 50, Structure and Dynamics of Globular Clusters, ed. S. G. Djorgovski and G. Meylan (San Francisco: ASP), 203
Dorman, B. 1992, ApJS, 81, 221
Durrell, P. R. & Harris, W. E. 1993, AJ, 105, 1420
ESA. 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200
Faulkner, J. & Swenson, F. J. 1993, ApJ, 411, 200
Fusi Pecci, F., Ferraro, F. R., Bellazzini, M., Djorgovski, S., Piotto, G., & Buonanno, R. 1993, AJ, 105, 1145
Fusi Pecci, F., Ferraro, F. R., Crocker, D. A., Rood, R. T., & Buonanno, R. 1990, A&A, 238, 95
Geisler, D., Minniti, D., & Clariá, J. J. 1992, AJ, 104, 627
Gratton, R. G., Carretta, E., & Castelli, F. 1996, A&A, 314, 191
Gratton, R. G., Fusi Pecci, F., Carretta, E., Clementini, G., Corsi, C. E., & Lattanzi, M. 1997, ApJ, 491, 749
Gratton, R. G., Quarta, M. L., & Ortolani, S. 1986, A&A, 169, 208
Heasley, J. N. & Christian, C. A. 1991, AJ101, 967
Johnson, J. A. & Bolte, M. 1998, AJ, 115, 693
Kraft, R. P. 1994, PASP, 106, 553
Landolt, A. U. 1992, AJ, 104, 340
Langer, G. E. & Hoffman, R. D. 1995, PASP, 107, 1177
Mandushev, G. I., Fahlman, G. G., Richer, H. B., & Thompson, I. B. 1996, AJ, 112, 1536
McClure, R. D., VandenBerg, D. A., Bell, R. A., Hesser, J. E., & Stetson, P. B. 1987, AJ, 93, 1144
Minniti, D., Geisler, D., Peterson, R. C., & Clariá, J. J. 1993, ApJ, 413, 548
Peterson, C. J. 1993, in ASP Conf. Ser., 50, Structure and Dynamics of Globular Clusters, ed. S. G. Djorgovski and G. Meylan (San Francisco: ASP), 337
Peterson, R. C., Rood, R. T., & Crocker, D. A. 1995, ApJ, 453, 214
Pilachowski, C. A., Olszewski, E. W. & Odell, A. 1983, PASP, 95, 713
Piotto, G., Capaccioli, M., Ortolani, S., Rosino, L., Alcaino, G., & Liller, W. 1987, AJ, 94, 360
Piotto, G., King, I. R., Capaccioli, M., Ortolani, S., & Djorgovski, S. 1990, ApJ, 350, 662
Piotto, G., King, I. R., & Djorgovski, S. 1988, AJ, 96, 1918
Pont, F., Mayor, M., Turon, C., and Vandenberg, D. A. 1998, A&A, 329, 87
Pryor, C. & Meylan, G. 1993, in ASP Conf. Ser., 50, Structure and Dynamics of Globular Clusters, ed. S. G. Djorgovski and G. Meylan (San Francisco: ASP), 357
Pryor, C., Smith, G. H., & McClure R. D. 1986, AJ, 92, 1358
Refsdal, S. & Weigert, A. 1970, A&A, 6, 426
Reed, B. C., Hesser, J. E., & Shawl, S. J. 1988, PASP, 100, 545
Reid, I. N. 1997, AJ, 114, 161
Richer, H. B., Fahlman, G. G., & VandenBerg, D. A. 1988, ApJ, 329, 187 (RFV)
Ryan, S. 1989, AJ, 98, 1693
Ryan, S. 1992, AJ, 104, 1144
Salaris, M., Chieffi, A. & Straniero, O. 1993, ApJ, 414, 580
Samus, N. N., Ipatov, A. P., Smirnov, O. M., Kravtsov, V. V., Alcaino, G., Liller, W., & Alvarado, F. 1995, Soviet Ast. Lett., 21, 810
Sandquist, E. L. 1998, in preparation
Sandquist, E. L., Bolte, M., Stetson, P. B., & Hesser, J. E. 1996, ApJ, 470, 910
Sarajedini, A. 1994, AJ, 107, 618
Sarajedini, A. & Milone, A. A. E. 1995, AJ, 109, 269
Shetrone, M. D. 1996, Ph.D. Thesis, University of California, Santa Cruz
Sneden, C. Kraft, R. P., Prosser, C. F. & Langer, G. E. 1992, AJ, 104, 2121
Sosin, C. 1997, AJ, 114, 1517
Stetson, P. B. 1987, PASP, 99, 191
———. 1989, ALLSTAR User’s Manual, private communication
———. 1990, PASP, 102, 932
———. 1991a, in ASP Conf. Ser., 13, The Formation and Evolution of Star Clusters, ed. K. Janes (San Francisco: ASP), 88
———. 1991b, in Precision Photometry: Astrophysics of the Galaxy, ed. A. G. D. Philip, A. R. Upgren, & K. A. Janes (Schenectady: L. Davis Press), 69
Suntzeff, N. 1993, in ASP Conf. Ser. 48, The Globular Cluster — Galaxy Connection, ed. G. H. Smith and J. P. Brodie (San Francisco: ASP), 167
Sweigart, A. V. 1997, ApJ, 474, L23
VandenBerg, D. A. 1995, private communication
VandenBerg, D. A. 1997, private communication
VandenBerg, D. A., Bolte, M., & Stetson, P. B. 1990, AJ, 100, 445 (VBS)
VandenBerg, D. A., Larson, A. M., & DePropris, R. 1998, PASP, 110, 98
Walker, A. R.. 1994, AJ, 108, 555
Yanny, B., Guhathakurta, P., Schneider, D. P., & Bahcall, J. N. 1994, ApJ, 435, L59 (YGSB)
Zinn, R. 1980, ApJS, 42, 19
Zinn, R. & West, M. J. 1984, ApJS, 55, 45 (ZW84)
Fig. 1.— The M30 color-magnitude diagram for a) all measured stars, and b) the sample restricted to stars having $110'' < r < 10'$. 

Fig. 2.— Magnitude bias versus $V$ magnitude.

Fig. 3.— External magnitude errors versus $V$ magnitude.

Fig. 4.— Completeness fraction versus $V$ magnitude.

Fig. 5.— Subdwarf fits to the $VI$ main sequence fiducial for two different reddenings, assuming $[\text{Fe/H}]_{M30} = -1.91$ (Carretta & Gratton 1996). The M30 fiducial line is plotted as open boxes. The solid boxes with error bars are local subdwarfs and giants. Only those subdwarfs with $M_V > 4.5$ and $[\text{Fe/H}] < -1.2$ were used in the main-sequence fitting. The isochrones (plotted as solid lines) are preliminary $\alpha$-enhanced versions (VandenBerg 1997) with $[\text{Fe/H}] = -2.01$ and ages 10, 12, 14, and 16 Gyr (from top to bottom). The two reddening values correspond to $E(B - V) = 0.016$ and 0.048.

Fig. 6.— The M30 cumulative radial distributions for RGB stars (solid line) HB stars (dotted line), and AGB stars (dashed line), using wide-field data from this paper, and HST data for the core (YGSB).

Fig. 7.— A comparison of the $(V, V - I)$ fiducial lines for M30 (thick line) with our computed fiducials from M68 (thin line; Walker 1994 data). The M68 fiducial has been shifted 0.45 mag brighter in $V$ and 0.03 mag bluer in color.

Fig. 8.— The $V$-band luminosity function for M30 compared with theoretical $\alpha$-enhanced LFs for $[\text{Fe/H}] = -2.01$ and a distance modulus $(m - M)_V = 14.87$ for ages (from left to right) 10, 12, 14, and 16 Gyr. The theoretical luminosity functions have been normalized to the range $20.4 < V < 20.9$.

Fig. 9.— The $V$-band luminosity function for 14772 stars in M30 as derived here (● with error bars), compared with LFs from Bergbusch (1996; △) and Bolte (1994; □), as well as a theoretical $\alpha$-enhanced LFs for $[\text{Fe/H}] = -2.01$ and $x = 2.0$ with age 12 Gyr and $(m - M)_V = 14.70$ (solid line) and age 10 Gyr and $(m - M)_V = 14.87$ (dotted line) for comparison purposes. All of the luminosity functions have been normalized to the range $18.5 < V < 19$.

Fig. 10.— The $V$-band luminosity function in M30, with theoretical $\alpha$-enhanced LFs for $[\text{Fe/H}] = -2.01$ and age 12 Gyr. The curves are for mass function exponents $x = 1.5$ (solid line), $x = 2$ (dotted line), and $x = 2.5$ (dashed line). The theoretical LFs have been shifted in magnitude using an apparent distance modulus $(m - M)_V = 14.70$. 
Fig. 11.— The $V$-band luminosity function for M30, restricted to $r > 4' \approx 30r_c$ with theoretical $\alpha$-enhanced LFs for $[\text{Fe/H}] = -2.01$, and $x = 2$. The four curves are for ages 10, 12, 14, and 16 Gyr, and they have been shifted so that the theoretical and observational TO magnitudes match, and then normalized to the observed LF in a 0.5 mag bin 2 magnitudes below the turnoff. The implied distance moduli from the isochrone TOs are 14.98, 14.77, 14.61, and 14.47 respectively.

Fig. 12.— The cumulative luminosity functions for M30 and M68 (Walker 1994), shifted so that the main sequence turnoffs have the same magnitude. The dotted lines indicate linear fits to the functions above and below the slope break, which is an indication of the position of the RGB bump.

Fig. 13.— The $V$-band luminosity function for M30 including stars down to a radius 150 pixels (66") from the cluster center. The theoretical $\alpha$-enhanced LFs have $[\text{Fe/H}] = -2.01$ and $x = 2.5$, but have the same combinations of age and distance modulus as Figure 9. The luminosity function has been normalized to the range $19.4 < V < 19.9$.

Fig. 14.— The M30 color-magnitude diagram for all the stars in the $VI$ sample used in computing the $V$-band luminosity function in Figure 13.

Fig. 15.— The $I$-band luminosity function for 14507 stars, with $[\text{Fe/H}] = -2.01$, $x = 2.5$ theoretical $\alpha$-enhanced LFs for age 12 Gyr and $(m - M)_I = 14.67$ (solid line), and age 10 Gyr and $(m - M)_I = 14.81$ (dotted line).

Fig. 16.— Final residuals for the comparison of standard and measured values for Landolt (1992) primary standard stars observed at the CTIO 1.5 m telescope.

Fig. 17.— Residuals for the comparison of 118 M30 secondary standard stars measured using profile fitting and aperture photometry in the CTIO 1.5 m frames. The residuals are in the sense (profile fitting – aperture).

Fig. 18.— Final residuals for the comparison of 248 M30 stars used in the calibration of the CTIO 4 m frames. The residuals are in the sense (4 m – 1.5 m).

Fig. 19.— Residuals for the comparison between the M30 CCD photometry of Bolte (1987) and our dataset. The data for Bolte’s short exposure frames are in the plots on the left, and his long exposure data is used on the right. The residuals are in the sense (ours – Bolte’s).

Fig. 20.— Residuals for the comparison between the M30 CCD photometry of Samus et al. (1995) and our dataset. The residuals are in the sense (ours – Samus’).
Table 1. M30 \([V, (V - I)]\) Fiducial Points

|       | V     | V − I | N  |       | V     | V − I | N  |
|-------|-------|-------|----|-------|-------|-------|----|
| MS-SGB-RGB | 17.275 | 0.820 | 29 | 23.000 | 17.216 | 0.824 | 28 |
|        | 22.800 | 1.293 | 399| 17.077 | 16.925 | 0.840 | 23 |
|        | 22.600 | 1.209 | 556| 16.781 | 16.853 | 0.847 | 14 |
|        | 22.400 | 1.147 | 771| 16.618 | 16.639 | 0.854 | 38 |
|        | 22.200 | 1.115 | 918| 16.574 | 16.589 | 0.863 | 40 |
|        | 22.000 | 1.052 | 1048| 16.391 | 16.415 | 0.863 | 35 |
|        | 21.925 | 1.035 | 827| 16.140 | 16.170 | 0.880 | 20 |
|        | 21.775 | 1.002 | 811| 15.868 | 15.917 | 0.901 | 25 |
|        | 21.625 | 0.967 | 850| 15.621 | 15.667 | 0.913 | 37 |
|        | 21.475 | 0.928 | 896| 15.367 | 15.419 | 0.927 | 18 |
|        | 21.325 | 0.890 | 934| 15.127 | 15.188 | 0.933 | 14 |
|        | 21.175 | 0.859 | 907| 14.877 | 14.952 | 0.969 | 14 |
|        | 21.025 | 0.837 | 910| 14.662 | 14.749 | 0.990 | 11 |
|        | 20.875 | 0.810 | 965| 14.395 | 14.491 | 1.013 | 6  |
|        | 20.725 | 0.779 | 908| 14.117 | 14.227 | 1.052 | 8  |
|        | 20.575 | 0.748 | 876| 13.924 | 13.972 | 1.068 | 6  |
|        | 20.425 | 0.719 | 856| 13.604 | 13.662 | 1.115 | 3  |
|        | 20.275 | 0.699 | 843| 13.319 | 13.378 | 1.143 | 3  |
|        | 20.125 | 0.675 | 740| 13.125 | 13.197 | 1.178 | 7  |
|        | 19.975 | 0.672 | 765| 12.830 | 12.917 | 1.223 | 3  |
|        | 19.825 | 0.646 | 694| 12.634 | 12.738 | 1.260 | 3  |
|        | 19.675 | 0.634 | 620| 12.384 | 12.492 | 1.329 | 1  |
|        | 19.525 | 0.622 | 566| 12.016 | 12.139 | 1.481 | 3  |
|        | 19.375 | 0.605 | 519|       |       |       |    |
|        | 19.225 | 0.588 | 444| 15.821 | 15.800 | 0.980 | 16 |
|        | 19.000 | 0.576 | 527| 15.584 | 15.564 | 1.022 | 6  |
|        | 18.800 | 0.568 | 466| 15.386 | 15.368 | 1.084 | 4  |
|        | 18.600 | 0.558 | 371| 15.302 | 15.284 | 1.124 | 3  |
|        | 18.400 | 0.575 | 305| 15.187 | 15.170 | 1.169 | 2  |
|        | 18.240 | 0.595 | 272| 15.083 | 15.066 | 0.306 | 5  |
|        | 18.094 | 0.645 | 95 | 14.900 | 14.883 | 0.701 | 6  |
|        | 17.968 | 0.695 | 53 |       |       |       |    |
|        | 17.884 | 0.745 | 56 | 14.184 | 14.154 | 0.970 | 4  |

HB: Horizontal Branch
AGB: Asymptotic Giant Branch
Table 1—Continued

| V  | V − I | N  | V  | V − I | N  |
|----|-------|----|----|-------|----|
| 17.800 | 0.764 | 101 | 14.354 | 0.924 | 1 |
| 17.575 | 0.793 | 57  | 14.483 | 0.914 | 1 |
| 17.425 | 0.809 | 44  | 14.564 | 0.894 | 1 |
Table 2.  
V-band Luminosity Function for M30

| V   | N      | σ(N) | N_{obs} | J   | V   | N      | σ(N) | N_{obs} | J   |
|-----|--------|------|---------|-----|-----|--------|------|---------|-----|
| 12.543 | 0.766 | 0.212 | 13 | 1.000 | 18.855 | 191.524 | 14.548 | 184 | 0.960 |
| 13.522 | 1.028 | 0.265 | 15 | 1.000 | 19.005 | 240.516 | 16.396 | 229 | 0.952 |
| 14.275 | 1.957 | 0.449 | 19 | 1.000 | 19.155 | 276.068 | 17.539 | 261 | 0.945 |
| 14.727 | 2.885 | 0.771 | 14 | 1.001 | 19.305 | 285.390 | 17.865 | 267 | 0.934 |
| 15.027 | 4.539 | 0.968 | 22 | 1.001 | 19.455 | 332.817 | 19.475 | 306 | 0.918 |
| 15.328 | 6.614 | 1.169 | 32 | 0.998 | 19.605 | 361.638 | 20.207 | 331 | 0.915 |
| 15.554 | 7.433 | 1.752 | 18 | 1.001 | 19.756 | 386.727 | 20.903 | 351 | 0.907 |
| 15.704 | 5.785 | 1.546 | 14 | 1.000 | 19.906 | 451.675 | 22.748 | 403 | 0.892 |
| 15.854 | 8.263 | 1.848 | 20 | 1.000 | 20.056 | 475.933 | 23.433 | 419 | 0.880 |
| 16.004 | 9.912 | 2.023 | 24 | 1.000 | 20.206 | 556.464 | 25.362 | 488 | 0.877 |
| 16.154 | 8.259 | 1.847 | 20 | 1.000 | 20.356 | 574.396 | 25.920 | 498 | 0.867 |
| 16.304 | 7.433 | 1.752 | 18 | 1.001 | 20.506 | 632.285 | 27.495 | 537 | 0.850 |
| 16.455 | 11.985 | 2.226 | 29 | 1.000 | 20.656 | 664.107 | 28.509 | 555 | 0.837 |
| 16.605 | 11.161 | 2.148 | 27 | 1.000 | 20.805 | 698.896 | 29.602 | 575 | 0.824 |
| 16.755 | 12.813 | 2.302 | 31 | 1.000 | 20.955 | 733.417 | 30.831 | 592 | 0.809 |
| 16.905 | 16.977 | 4.117 | 17 | 1.001 | 21.105 | 781.575 | 32.377 | 622 | 0.798 |
| 17.055 | 12.982 | 3.601 | 13 | 1.001 | 21.254 | 751.962 | 32.336 | 588 | 0.784 |
| 17.205 | 17.971 | 4.236 | 18 | 1.001 | 21.404 | 805.608 | 33.886 | 620 | 0.774 |
| 17.355 | 25.019 | 5.004 | 25 | 0.998 | 21.553 | 779.031 | 34.422 | 580 | 0.749 |
| 17.505 | 16.997 | 4.122 | 17 | 0.999 | 21.702 | 903.370 | 38.618 | 648 | 0.722 |
| 17.655 | 34.968 | 5.912 | 35 | 1.000 | 21.851 | 922.898 | 40.324 | 643 | 0.702 |
| 17.806 | 50.947 | 7.140 | 51 | 1.000 | 22.000 | 986.270 | 44.897 | 643 | 0.658 |
| 17.956 | 63.013 | 7.972 | 63 | 1.000 | 22.148 | 998.885 | 46.770 | 622 | 0.631 |
| 18.105 | 102.573 | 10.276 | 102 | 0.997 | 22.296 | 1036.098 | 48.374 | 601 | 0.584 |
| 18.255 | 117.435 | 11.112 | 116 | 0.990 | 22.445 | 1134.865 | 55.105 | 567 | 0.505 |
| 18.405 | 123.294 | 11.517 | 121 | 0.983 | 22.593 | 1350.132 | 71.038 | 501 | 0.378 |
| 18.555 | 159.431 | 13.317 | 155 | 0.973 | 22.740 | 3956.208 | 404.959 | 500 | 0.129 |
| 18.705 | 191.698 | 14.697 | 185 | 0.964 |
Table 3. $I$-Band Luminosity Function for M30

| $I$ (mag) | $N$ | $\sigma(N)$ | $N_{obs}$ | $\bar{f}$ | $I$ (mag) | $N$ | $\sigma(N)$ | $N_{obs}$ | $\bar{f}$ |
|-----------|-----|-------------|-----------|---------|-----------|-----|-------------|-----------|---------|
| 11.149    | 0.590 | 0.170       | 12        | 1.000   | 17.467    | 76.966 | 8.715       | 78        | 1.000   |
| 12.225    | 0.850 | 0.236       | 13        | 1.000   | 17.619    | 111.136| 10.508      | 112       | 0.999   |
| 12.993    | 1.281 | 0.355       | 13        | 1.000   | 17.770    | 104.511| 10.283      | 104       | 0.992   |
| 13.452    | 2.373 | 0.685       | 12        | 1.000   | 17.921    | 131.605| 11.657      | 130       | 0.985   |
| 13.756    | 2.779 | 0.743       | 14        | 1.000   | 18.071    | 188.224| 14.172      | 183       | 0.972   |
| 14.060    | 3.586 | 0.845       | 18        | 1.000   | 18.221    | 185.096| 14.125      | 178       | 0.964   |
| 14.287    | 4.359 | 1.315       | 11        | 1.001   | 18.370    | 253.828| 16.588      | 243       | 0.959   |
| 14.393    | 6.772 | 1.643       | 17        | 1.000   | 18.520    | 290.213| 17.909      | 273       | 0.943   |
| 14.498    | 9.954 | 1.991       | 25        | 1.000   | 19.117    | 465.390| 23.205      | 414       | 0.894   |
| 15.044    | 6.780 | 1.645       | 17        | 1.000   | 19.968    | 421.574| 21.974      | 380       | 0.905   |
| 15.195    | 9.954 | 1.991       | 25        | 1.000   | 19.266    | 506.015| 24.377      | 441       | 0.881   |
| 15.347    | 5.985 | 1.546       | 15        | 1.000   | 19.415    | 613.201| 27.068      | 526       | 0.860   |
| 15.498    | 9.583 | 1.956       | 24        | 1.000   | 19.564    | 693.000| 29.054      | 583       | 0.853   |
| 15.649    | 8.810 | 1.879       | 22        | 1.000   | 19.712    | 777.236| 31.180      | 637       | 0.832   |
| 15.799    | 8.811 | 1.879       | 22        | 1.000   | 19.859    | 820.648| 32.433      | 657       | 0.819   |
| 15.950    | 12.407 | 2.229      | 31        | 1.000   | 20.006    | 833.922| 33.018      | 656       | 0.807   |
| 16.101    | 11.995 | 2.190     | 30        | 1.001   | 20.152    | 961.583| 36.406      | 730       | 0.779   |
| 16.252    | 14.400 | 2.400      | 36        | 1.000   | 20.298    | 1024.388| 38.171      | 758       | 0.762   |
| 16.403    | 14.773 | 2.429      | 37        | 1.000   | 20.443    | 1042.008| 39.215      | 755       | 0.748   |
| 16.554    | 21.175 | 2.909      | 53        | 0.999   | 20.587    | 1104.607| 42.537      | 743       | 0.708   |
| 16.705    | 21.109 | 2.900      | 53        | 1.000   | 20.730    | 1145.267| 43.849      | 759       | 0.695   |
| 16.857    | 25.699 | 5.040      | 26        | 1.001   | 20.873    | 1314.175| 49.073      | 833       | 0.666   |
| 17.008    | 26.650 | 5.129      | 27        | 1.000   | 21.013    | 1385.530| 55.311      | 777       | 0.610   |
| 17.161    | 41.972 | 6.400      | 43        | 1.000   | 21.155    | 1525.717| 70.014      | 738       | 0.501   |
| 17.315    | 46.912 | 6.771      | 48        | 1.000   |           |         |             |           |         |
| HIP No. | $V$  | $(V - I)$ | $\pi$  | $\sigma_\pi/\pi$ | $[\text{Fe/H}]$ | $M_V$ $^a$ | $(V - I)_{-1.91}$ | Name |
|---------|------|----------|--------|-----------------|-----------------|-----------|-------------------|------|
| **Subdwarfs** | | | | | | | | |
| 14594  | 8.04 | 0.66     | 0.02585| 0.044           | −1.88           | 5.08 ± 0.10| 0.66              | HD19445 |
| 18915  | 8.51 | 1.01     | 0.05414| 0.020           | −1.69           | 7.18 ± 0.04| 0.99              | HD25329 |
| 24316  | 9.43 | 0.65     | 0.01455| 0.069           | −1.44           | 5.19 ± 0.15| 0.61              | HD34328 |
| 38541  | 8.27 | 0.77     | 0.03529| 0.029           | −1.60           | 6.00 ± 0.06| 0.75              | HD64090 |
| 40778  | 9.73 | 0.60     | 0.01036| 0.142           | −1.49           | 4.64 ± 0.31| 0.57              | BD+54 1216 |
| 53070  | 8.22 | 0.63     | 0.01923| 0.059           | −1.38           | 4.61 ± 0.13| 0.59              | HD94028 |
| 57939  | 6.44 | 0.89     | 0.10921| 0.007           | −1.22           | 6.63 ± 0.02| 0.84              | HD103095 |
| 60632  | 9.66 | 0.63     | 0.01095| 0.118           | −1.55           | 4.73 ± 0.26| 0.60              | HD108177 |
| 74234  | 9.46 | 1.01     | 0.03368| 0.050           | −1.57           | 7.08 ± 0.11| 0.99              | HD134440 |
| 74235  | 9.08 | 0.92     | 0.03414| 0.040           | −1.57           | 6.74 ± 0.09| 0.90              | HD134439 |
| 98020  | 8.83 | 0.75     | 0.02532| 0.046           | −1.37           | 5.77 ± 0.10| 0.70              | HD188510 |
| 100568 | 8.66 | 0.67     | 0.02288| 0.054           | −1.00           | 5.43 ± 0.12| 0.60              | HD193901 |
| 100792 | 8.35 | 0.63     | 0.01794| 0.069           | −1.02           | 4.58 ± 0.15| 0.55              | HD194598 |
| 104659 | 7.37 | 0.66     | 0.02826| 0.036           | −0.94           | 4.59 ± 0.08| 0.56              | HD201891 |
| **Subgiants** | | | | | | | | |
| 3026   | 9.25 | 0.64     | 0.00957| 0.144           | −1.17           | 3.97 ± 0.31| 0.54              | HD3567 |
| 33221  | 9.07 | 0.63     | 0.00911| 0.111           | −1.33           | 3.77 ± 0.24| 0.53              | CPD-33 3337 |
| 48152  | 8.33 | 0.55     | 0.01244| 0.085           | −2.07           | 3.69 ± 0.18| 0.55              | HD84937 |
| 55790  | 9.07 | 0.63     | 0.01099| 0.135           | −1.56           | 4.03 ± 0.29| 0.55              | HD99383 |
| 68464  | 8.73 | 0.64     | 0.00977| 0.135           | −1.75           | 3.53 ± 0.29| 0.60              | HD122196 |
| 76976  | 7.22 | 0.69     | 0.01744| 0.056           | −2.38           | 3.32 ± 0.13| 0.77              | HD140283 |

$^a$Lutz-Kelker corrections calculated using $\Delta M_{LK} = -7.60(\sigma_\pi/\pi)^2 - 47.23(\sigma_\pi/\pi)^4$
Table 5. Measured Distance Moduli

| [Fe/H] | E(V − I) | All | M\textsubscript{V} > 4.25 | M\textsubscript{V} > 5 | [Fe/H] < −1.3 |
|--------|----------|-----|----------------|-----------------|--------------|
| −1.91  | 0.06     | 14.93 ± 0.12 | 14.87 ± 0.12 | 14.86 ± 0.11 | 14.92 ± 0.11 |
| −1.91  | 0.02     | 14.70 ± 0.12 | 14.65 ± 0.12 | 14.64 ± 0.11 | 14.76 ± 0.12 |
| −2.13  | 0.06     | 14.93 ± 0.12 | 14.91 ± 0.12 | 14.87 ± 0.11 | 14.93 ± 0.11 |
| −2.13  | 0.02     | 14.69 ± 0.13 | 14.68 ± 0.13 | 14.66 ± 0.12 | 14.71 ± 0.13 |

Table 6. Characteristics of Metal-Poor Globular Clusters

| ID     | [Fe/H]\textsubscript{ZW} | Y Indicators | ∆V\textsubscript{TO} | R\textsubscript{HB} | ∆B−V |
|--------|-----------------|--------------|-----------------|-----------------|-----|
| NGC 104 (47 Tuc) | −0.71           | 1.21 ± 0.13  | 5.32 ± 0.08  | 3.59 ± 0.10  | −1.00 |
| NGC 5904 (M5)    | −1.40           | 1.08 ± 0.09  | 5.78 ± 0.04  | 3.47 ± 0.06  | 0.39 |
| NGC 5272 (M3)    | −1.66           | 1.19 ± 0.10  | 5.84 ± 0.04  | 3.52 ± 0.09  | 0.07 |
| NGC 4590 (M68)   | −2.09           | 0.91 ± 0.17  | 6.34 ± 0.05  | 3.41 ± 0.05  | 0.44 |
| NGC 5024 (M53)   | −2.04           | 1.18 ± 0.18  | ⋮              | 3.46 ± 0.08  | 0.76 |
| NGC 5053         | −2.41           | 0.95 ± 0.25  | ⋮              | 3.44 ± 0.08  | 0.61 |
| NGC 5466         | −2.22           | 1.21 ± 0.27  | ⋮              | ⋮              | 0.51 |
| NGC 6341 (M92)   | −2.24           | 1.26 ± 0.18  | ⋮              | 3.44 ± 0.06  | 0.88 |
| NGC 6397         | −1.91           | 1.15 ± 0.17  | ⋮              | 3.6 ± 0.14    | 0.93 (0.69) |
| NGC 7078 (M15)   | −2.17           | 1.23 ± 0.21  | 6.32 ± 0.11   | 3.46 ± 0.10  | 0.72 |
| NGC 7099 (M30)   | −2.13           | 1.49 ± 0.18  | 6.42 ± 0.13   | 3.59 ± 0.06  | 0.84 |
Table 7. Bright Star Populations and Population Ratios

| Sample | BHB $R$ | RR Lyr $R'$ | RHB $R_1$ | Total HB $R_2$ | AGB | RGB $R_{HB}$ |
|--------|---------|-------------|-----------|----------------|-----|-------------|
| $r < 30''$ | 57 | 1.30 ± 0.26 | 1.22 ± 0.24 | 0.07 ± 0.04 | 60 | 0.05 ± 0.03 | 0.93 ± 0.04 | 3 | 46 |
| $30'' < r < 100''$ | 59 | 1.35 ± 0.27 | 1.25 ± 0.24 | 0.08 ± 0.04 | 65 | 0.06 ± 0.03 | 0.88 ± 0.05 | 4 | 48 |
| $r > 100''$ | 65 | 1.83 ± 0.36 | 1.67 ± 0.32 | 0.10 ± 0.05 | 77 | 0.05 ± 0.03 | 0.73 ± 0.07 | 4 | 42 |
| Total | 181 | 1.49 ± 0.18 | 1.37 ± 0.16 | 0.08 ± 0.03 | 202 | 0.05 ± 0.02 | 0.84 ± 0.04 | 11 | 136 |
| YGSB | 51 | 1.56 ± 0.35 | ⋮ | ⋮ | 53 | ⋮ | ⋮ | ⋮ | ⋮ |

Table A1. Photometric Transformation Equation Coefficients

| Band | Zero Point | Extinction Coeffs. | Color Term | Order |
|------|------------|---------------------|------------|-------|
| $V$  | 2.577 ± 0.001 | 0.1004 ± 0.0046 | 0.0103 ± 0.0026 | 1 |
|      |             |                     | −0.0839 ± 0.0061 | 2 |
|      |             |                     | 0.0408 ± 0.0061 | 3 |
| $I$  | 3.311 ± 0.002 | 0.0532 ± 0.0062 | 0.0002 ± 0.0020 | 1 |
| $V$  | ⋮ | ⋮ | −0.0361 ± 0.0010 | 1 |
| $I$  | ⋮ | ⋮ | −0.0045 ± 0.0018 | 1 |

Primary Standard Calibration: CTIO 1.5 m

Secondary Standard Calibration: CTIO 1.5 m

Calibration: CTIO 4 m
Table A2. Average Residuals for Photometry Comparisons

| Sample 1  | Sample 2     | $V$   | $\sigma_V$ | $I$      | $\sigma_I$ | $(V - I)$ | $\sigma_{V-I}$ | $N$ |
|-----------|--------------|-------|------------|----------|------------|-----------|----------------|-----|
| 1.5 m     | Landolt      | 0.0005| 0.0006     | −0.0004  | 0.0119     | −0.0005   | 0.0010         | 27  |
| PSF       | Aperture     | −0.0005| 0.0204     | −0.0014  | 0.0198     | 0.0004    | 0.0252         | 118 |
| 4 m       | 1.5 m        | −0.0064| 0.0447     | −0.0125  | 0.0635     | 0.0002    | 0.0515         | 248 |
| 4 m + 1.5 m| Bolte 1987 (s)| −0.0201| 0.1067     | · · ·    | · · ·      | · · ·     | 59             |     |
| 4 m + 1.5 m| Bolte 1987 (l)| −0.0554| 0.0928     | · · ·    | · · ·      | · · ·     | 401            |     |
| 4 m + 1.5 m| RFV          | −0.0738| 0.1419     | · · ·    | · · ·      | · · ·     | 1374           |     |
| 4 m + 1.5 m| Samus et al. 1995 | 0.0439 | 0.1449     | 0.0463   | 0.1771     | 0.0030    | 0.1139         | 255 |
| 4 m + 1.5 m| Bergbusch 1996 | −0.1101| 0.0611     | · · ·    | · · ·      | · · ·     | 316            |     |
$E(V-I) = 0.02$
$(m-M)_V = 14.65$

$E(V-I) = 0.06$
$(m-M)_V = 14.87$
\[ \log_{10}(N) + C \]

\[ (V_{TO} - V) \]
