uvbyCaHβ CCD PHOTOMETRY OF CLUSTERS. V. THE METAL-DEFICIENT OPEN CLUSTER NGC 2243

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ABSTRACT

CCD photometry on the intermediate-band uvbyCaHβ system is presented for the metal-deficient open cluster NGC 2243. Restricting the data to probable single members of the cluster using the color-magnitude diagram (CMD) and the photometric indices alone generates a sample of 100 stars at the cluster turnoff. The average $E(b−y) = 0.039 ± 0.003$ (s.e.m.) or $E(B−V) = 0.055 ± 0.004$ (s.e.m.), where the errors refer to internal errors alone. With this reddening, $[Fe/H]$ is derived from both $m_1$ and $hk$, using $b−y$ and $Hβ$ as the temperature index. The agreement among the four approaches is excellent, leading to a final weighted average of $[Fe/H] = −0.57 ± 0.03$ (s.e.m.) for the cluster, on a scale where the Hyades has $[Fe/H] = +0.12$. Using a combination of photometric and spectroscopic data, 27 probable cluster members are identified and used to delineate the red giant branch and a well-defined clump at $V = 13.70$, while eliminating the so-called second clump at $V = 14.1$. Interpolation between isochrones of appropriate $[Fe/H]$ leads to an apparent modulus of $(m − M) = 13.15 ± 0.1$ and an age of $3.8 ± 0.2$ Gyr.

A differential CMD comparison with Ber 29, a cluster with a galactocentric distance almost twice that of NGC 2243, constrains Ber 29 to be at least as young and as metal-rich as NGC 2243.

Key words: color-magnitude diagrams — open clusters and associations: individual (NGC 2243, Berkeley 29, Berkeley 54)

Online material: machine-readable table

1. INTRODUCTION

This is the fifth paper in an extended series detailing the derivation of fundamental parameters in star clusters using precise intermediate-band photometry to identify probable cluster members and to calculate the cluster’s reddening, metallicity, distance, and age. The initial motivation for this study was provided by Twarog et al. (1997), who used a homogeneous open cluster sample to identify structure within the galactic abundance gradient. The open clusters appear to populate a bimodal abundance distribution with the clusters interior to a galactocentric distance of $≈10$ kpc averaging $[Fe/H] ≈ 0.0$, while those beyond this boundary have average $[Fe/H]$ values of about $−0.3$. The dispersion about each mean is less than 0.1 dex and implies that within each zone no statistically significant abundance gradient exists, in contrast with the traditional assumption of a linear gradient over the entire disk. This structure has since been corroborated through the use of Cepheids by Andrievsky et al. (2002a, 2002b), Luck et al. (2003) and, most recently, with OB stars (Dafon et al. 2004). Further evidence for the lack of a simple linear gradient across the entire galactic disk, particularly in the outer portion, is found in the spectroscopic data for Ber 29 and Saurer 1 (Carraro et al. 2004), a point we return to in the last section of this paper. The exact origin and reason for the survival of the discontinuity remain unresolved issues, though the radial variation in the impact of spiral structure on star formation and stellar dynamics appears to be a likely contributor (Corder & Twarog 2001; Mishurov et al. 2002; Lépine et al. 2003).

Detailed justifications of the program and the observational approach adopted have been given in previous papers in the series (Anthony-Twarog & Twarog 2000a, 2000b, 2004; Twarog et al. 2003; hereafter Papers I, II, IV, and III, respectively) and are not repeated here. Suffice it to say that the reality of the galactic features under discussion will remain questionable unless the error bars on the data are reduced to a level smaller than the size of the effect being evaluated or the size of the sample is statistically enhanced. The overall goal of this project is to do both.

An equally important aspect of this research is detailed testing of stellar evolution theory as exemplified by comparisons to stellar isochrones based on models derived under a variety of assumptions. The agreement with (or the deviation from) the predicted distribution and location of stars within the color-magnitude diagram (CMD) has consistently provided a lever for adjusting our degree of confidence in the specifics of stellar interiors as a function of mass and age. A valuable illustration of this can be found in the discussion of the red giant branch distribution (first-ascent and clump giants) within NGC 3680, in comparison with NGC 752 and IC 4651, clusters of comparable age (Paper IV).

The focus of this paper is the older, metal-deficient open cluster NGC 2243. The key role of this cluster in the sequential development of the project is as a representative of the moderately metal-poor class of open clusters found in the galactic anticenter, a class that contributes significantly to the definition of the galactic abundance gradient beyond the solar circle. In our context, it typifies the metal-poor population found beyond the discontinuity in the galactic abundance gradient at a galactocentric radius between 10 and 11 kpc, a population that, to date, has no cluster counterpart within the solar circle, in sharp contrast with the field-star sample (Twarog et al. 1997).

The early photometric attempts to understand the nature of NGC 2243 from CMDs and color-color diagrams were based on a mixture of photoelectric and photographic data (Hawarden 1975; van den Bergh 1977). While agreeing that the cluster was metal-deficient relative to the Sun, the disagreement over the...
exact value of the metallicity, as well as most of the other key cluster parameters, was significant. There have since been three CCD-based studies, Berghbusch et al. (1991), Bonifazi et al. (1990), and Kaluzny et al. (1996) (hereafter BE, BO, and KA, respectively). The first two used $B^I$ photometry, while the last used $VI$. We defer discussion of their conclusions, as well as those of other investigators, regarding the cluster parameters to the sections of the paper where they are derived within the present analysis.

Section 2 contains the details of the $ubvyCaH\beta$ CCD observations, their reduction and transformation to the standard system, and a search for photometrically anomalous stars. In § 3 we discuss the CMD and begin the process of identifying the sample of probable cluster members. Section 4 contains the derivation of the fundamental cluster parameters of reddening and metallicity. In § 5, these are combined with broadband data to derive the distance and age through comparisons with theoretical isochrones and to allow a differential comparison with the most distant open cluster, Ber 29. Section 6 summarizes our conclusions regarding NGC 2243 and Ber 29 and their role with the most distant open cluster, Ber 29. Section 6 summarizes our conclusions regarding NGC 2243 and Ber 29 and their role with the most distant open cluster, Ber 29.

2. THE DATA

2.1. Observations: CCD $ubvyCaH\beta$

The new photometric data for NGC 2243 were obtained using the Cassegrain-focus CCD imager on the NOAO’s 0.9 m telescope at CTIO. We used a Tektronix 2048 × 2048 detector at the f/13.5 focus of the telescope, with CTIO’s 4’’ × 4’’ $ubvy$ filters and our own 3’’ × 3’’ $H\beta$ and Ca filters. The field size is 13’’/5 on a side. Frames of all seven filters were obtained in both 2000 November and 2002 January and were preprocessed (bias subtraction, trimming, and flattening) through IRAF routines at the telescope. As more than 110 frames were ultimately used, we have elected not to present a detailed exposure log, but it is useful to note that we were able to combine information from 13 to 17 frames in each color (24 for the $u$ filter), with the following exposure totals for $y, b, v, u, Ca, \beta w$, and $\beta h$: 9, 24, 89, 293, 93, 33, and 176 minutes.

2.2. Reduction and Transformation

Previous papers in this series describe the procedures used to produce high-precision, accurately calibrated photometry from CCD data. The ALLSTAR routine within the IRAF DAOPHOT package was used to obtain complete sets of profile-fit magnitudes for all stars on every program frame. Paper I, in particular, provides a comprehensive description of the steps used to produce average instrumental magnitudes and indices of high precision.

Regardless of the internal precision achieved by averaging large numbers of frames, the accuracy of the photometric calibration is limited by other factors, including the breadth of parameter space covered by standard stars and observational conditions. Our approach for these steps is described extensively in Paper IV; since NGC 3680 and NGC 2243 were both observed on photometric nights in 2002 January, the backbone of the calibration described for NGC 3680 is also used to calibrate NGC 2243.

Briefly, standard stars in the field and in clusters, as well as uncrowded stars in program clusters, are observed on photometric nights and reduced using a consistent aperture measurement strategy. This permits the standardization of the aperture photometry in the program cluster; the calibration is extended to the more precise and generally deeper profile-fit magnitudes and indices by determining the average offset between the aperture photometry and profile-fit indices.

As described in Paper IV, the calibration equations developed for photometric nights in 2002 January carry standard errors of the mean for the zero point of 0.007 for $\beta$, 0.005 for $hk$, 0.006 for $V$ and $b - y$, 0.009 and 0.010 for dwarf stars’ $m_1$, and $c_1$ indices, and, with somewhat higher uncertainties, 0.010 and 0.017 for the cool giant stars’ $m_1$ and $c_1$ indices.

Establishing the link between the high-precision set of indices based on profile-fit photometry and the calibrated aperture photometry introduces a modest increment to the zero-point uncertainties for each calibrated index. The mean differences between these sets of indices were established with standard errors of the mean for $V$, $b - y$, $m_1$, $c_1$, $hk$, and $\beta$ of 0.002, 0.002, 0.003, 0.004, 0.003, and 0.012.

Final photometric values are found in Table 1, in which the primary identification and coordinate description follow the WEBDA database conventions for this cluster as of 2004 July. Stars not found in the WEBDA database have identification numbers above 10,000. Following each of the six photometric indices are the standard errors of the mean for each index and a summary of the number of frames in each of the seven bandpasses. For stars with $V \approx 16.5$ and $b - y \geq 0.45$, the $m_1$ and $c_1$ instrumental indices were transformed using the calibration relations appropriate for giant stars. Figures 1 and 2 show the average standard error of the mean for each index as a function of $V$, as well as the dispersion about the average value.

2.3. Potential Variables

The photometry discussed above was obtained to reliably define the cluster in intermediate-band CMDs and color-color diagrams so, while more than 100 frames have been analyzed, the distribution is approximately 15 frames per filter at the bright end and less than half that among the fainter stars. Despite the lack of optimization for detecting variable stars, it should be possible to identify at least some candidates with modest to large amplitude variations over a range of timescales. An example of the appropriate methodology for identifying cluster variables may be found in the study of NGC 2243 by KA; this paper and its six variable stars will also provide a test of our success in finding potential variables.

The obvious criterion for discovering variables is a large photometric scatter in the indices for a star relative to what is expected at a given magnitude. The points that deviate from the well-defined trends in Figures 1 and 2 should generate a first cut for our sample. However, deviant points could exist in Figures 1 and 2 for a variety of reasons, most of which have nothing to do with variability. Since we are plotting the standard error of the mean, two stars at the same magnitude level with identical amplitudes for a star relative to what is expected at a given magnitude. The points that deviate from the well-defined trends in Figures 1 and 2 should generate a first cut for our sample. However, deviant points could exist in Figures 1 and 2 for a variety of reasons, most of which have nothing to do with variability.
| ID        | X     | Y     | V     | b − y | m1   | c1   | Hβ     | hk    | σν   | σν2 | σκ1 | σκ2 | σκκ | N_{photons/σ} |
|-----------|-------|-------|-------|-------|------|------|--------|-------|------|-----|-----|-----|-----|-----------------|
| 11462..... | 697.70| −160.80| 10.275| 0.689 | 0.502| 0.387| 2.598  | 1.259 | 0.004| 0.003| 0.006 | 0.009 | 0.008 | 0.017             |
| 12175..... | 735.50| −397.90| 10.419| 0.553 | 0.271| 0.465| ...    | 0.940 | 0.005| 0.006 | 0.006 | 0.002 | 0.000 | 0.007             |
| 10474..... | −195.00| 333.00| 11.190| 0.412 | 0.189| 0.379| 2.611  | 0.669 | 0.002| 0.003 | 0.003 | 0.002 | 0.002 | 0.004             |
| 10945..... | 587.30| 61.10 | 11.337| 0.418 | 0.184| 0.338| 2.601  | 0.666 | 0.003| 0.004 | 0.006 | 0.006 | 0.002 | 0.007             |
| 11426..... | −466.30| −141.80| 11.576| 0.766 | 0.630| 0.274| 2.582  | 1.315 | 0.003| 0.003 | 0.004 | 0.005 | 0.002 | 0.005             |
| 3668.....  | −108.70| 84.90 | 11.764| 0.645 | 0.514| 0.344| 2.575  | 1.177 | 0.003| 0.004 | 0.006 | 0.006 | 0.002 | 0.005             |
| 3633.....  | −142.40| −16.00| 12.026| 0.888 | 0.650| 0.299| 2.571  | 1.580 | 0.003| 0.006 | 0.007 | 0.003 | 0.004 | 0.004             |
| 2414.....  | 225.90 | 115.90| 12.016| 0.346 | 0.109| 0.408| 2.622  | 0.446 | 0.003| 0.004 | 0.003 | 0.002 | 0.004 | 0.004             |
| 507.....   | −461.70| 31.70 | 12.114| 0.649 | 0.392| 0.372| 2.569  | 1.097 | 0.003| 0.004 | 0.005 | 0.004 | 0.003 | 0.005             |
| 2453.....  | 240.80 | 123.70| 12.149| 0.492 | 0.309| 0.382| 2.595  | 0.837 | 0.002| 0.003 | 0.004 | 0.003 | 0.004 | 0.004             |
| 1820.....  | 30.50 | −207.10| 12.566| 0.403 | 0.152| 0.308| 2.603  | 0.607 | 0.003| 0.004 | 0.006 | 0.005 | 0.002 | 0.005             |
| 1313.....  | −106.80| 14.70 | 12.885| 0.696 | 0.423| 0.361| 2.568  | 1.157 | 0.003| 0.004 | 0.006 | 0.006 | 0.003 | 0.006             |
| 448.....   | −491.50| −327.90| 12.882| 0.357 | 0.165| 0.343| 2.623  | 0.560 | 0.003| 0.004 | 0.005 | 0.004 | 0.003 | 0.005             |
| 10536..... | −629.60| 290.60| 13.163| 0.424 | 0.198| 0.341| 2.598  | 0.731 | 0.005| 0.016 | 0.024 | 0.020 | 0.005 | 0.024             |
| 11713..... | −509.80| −346.70| 13.323| 0.618 | 0.348| 0.371| 2.571  | 1.025 | 0.003| 0.004 | 0.005 | 0.004 | 0.003 | 0.005             |
| 576.....   | −417.00| −685.80| 13.419| 0.415 | 0.166| 0.317| 2.606  | 0.634 | 0.008| 0.009 | 0.011 | 0.008 | 0.007 | 0.011             |
| 875.....   | −274.20| −182.50| 13.520| 0.364 | 0.150| 0.331| 2.622  | 0.543 | 0.004| 0.005 | 0.004 | 0.004 | 0.003 | 0.005             |
| 2410.....  | 225.20 | 145.70| 13.635| 0.598 | 0.266| 0.416| 2.569  | 0.938 | 0.004| 0.007 | 0.005 | 0.002 | 0.002 | 0.007             |
| 11182..... | −539.50| −26.90| 13.670| 0.387 | 0.176| 0.395| 2.630  | 0.630 | 0.004| 0.005 | 0.006 | 0.005 | 0.004 | 0.006             |
| 239.....   | −641.40| −423.50| 13.674| 0.539 | 0.263| 0.376| 2.541  | 0.863 | 0.007| 0.010 | 0.016 | 0.017 | 0.013 | 0.012             |

**TABLE 1**
Extended Strömgren Photometry in NGC 2243
expected to increase in the outer zone of the field, irrespective of the number of frames included in the average.

To tag possible variables, the stars that deviated the most from the mean relations for $V$ and $b - y$ in Figure 1 for $V$ brighter than 18.05 were identified and the errors renormalized to a uniform number of frames; the reason for the artificial choice of the lower bound will become apparent below. If renormalization placed the star near the standard relation, it was excluded. Stars located more than 600 pixels ($\approx 6':1$) from the cluster center were excluded because beyond that distance from the center of the field, photometric errors traceable to spatial variations in the point-spread function begin to make selection of variables difficult. Stars appearing on fewer than two-thirds of the expected frames at a given magnitude were checked for possible contamination/confusion with a neighbor and eliminated if a companion was found. Finally, the individual magnitude errors were checked and a star retained if it exhibited large scatter in $y$ and at least one additional filter among $b$, $v$, and $C_0$ and showed a larger than expected error in $H/\beta$. The final result was the identification of the nine most likely variables within the sample: 372, 1419, 1463, 1558, 1583, 1728, 1746, 2363, and 2445. These stars are noted by filled symbols in Figures 1 and 2.

Of the nine stars, five (372, 1558, 1583, 1728, and 2363) have been identified as variables by KA. The $V$ limit for the search was extended to reach the complete sample of KA with 1583 at $V = 18.05$. The sixth known variable (2853) does not show significant scatter in any index.

2.4. Comparison with Previous Photometry

Only a handful of stars, all red giants, have been observed photoelectrically in $uvby$ (Richtler & Kaluzny 1989), but there have been three broadband CCD surveys of NGC 2243 that allow us, at minimum, to check the $V$-magnitude system and identify potential photometric deviants. The two earlier studies in $BV$, BO and BE, both include two overlapping fields near the cluster center observed with small-format CCDs. The former data were standardized using older photoelectric observations in the cluster (van den Bergh 1977), while the latter were tied to a mixture of field standards from Landolt (1983) and Graham (1982). The $VI$ data of KA cover an area comparable to the current study and were standardized to the system of Landolt (1992).

As in the previous papers in the series, we compare the residuals in the photometry for the entire sample and for the brighter stars alone, since the reliability of the latter sample is more relevant to the determination of the cluster parameters. Our interest in the residuals is twofold: to measure the photometric uncertainties in comparison with what is expected from the internal errors and to identify stars that exhibit significant deviations from one study to another. The deviants will be a mixture of misidentifications, bad photometry, and, of particular value, long-term variables or longer period eclipsing binaries that are not readily exposed by the variable-star searches done to date. Data for the published surveys have been taken from the WEBDA Cluster Data Base.

For each survey, the residuals in $V$, in the sense Table 1 minus references, were calculated for all stars in common to both and for all stars brighter than $V = 17.5$. For the complete samples, all stars with residuals more than 0.1 mag above or below the survey mean were excluded from the analysis and the mean and dispersion among the residuals rederived. For the brighter sample, the procedure was repeated, but the exclusion limit was reduced to 0.075 mag above or below the mean offset. The residuals in all comparisons were checked for color terms and magnitude dependence. Two significant trends were identified. For both the brighter stars and the complete sample comparisons, a magnitude dependence is present in $V$ for the data of KA. The fact that the other two surveys do not exhibit this problem implies that the error lies with the photometry of KA. For the $V$ data of BO, a modest color term was noted in comparisons with the three other data sets.

The $V$ data of KA and BO were transformed to the system of Table 1 using the linear relations noted for each in Table 2 for the brighter stars and the residuals recomputed. The results for the revised data, as well as the other comparisons, may be found in Table 2.

For BO, there are 402 stars that overlap with Table 1; of these 21 have residuals more than 0.10 mag away from the mean. For the remaining 381 stars, the average offset is $-0.011 \pm 0.029$; inclusion of the color term lowers the dispersion to 0.028. Turning to the 215 stars brighter than $V = 17.5$, 206 have residuals within 0.075 of the cluster mean. Of the nine deviants, stars 1761 and 1793 appear to be switched in the WEBDA database, while 1728 and 2363 are known variables from KA. The remaining deviants are 1012, 1419, 1707, 1995, and 2414. Star 1419 has been noted in the previous section as having larger...
photometric scatter than expected for its magnitude. Star 2414 is clearly incorrect in BO, being significantly redder than the published photographic and CCD data for the star, although the error in BO may be a product of severe crowding or misidentification. The photometry in Table 1 for 1012, 1707, and 1995 is in excellent agreement with both BE and KA, while that for 1419 disagrees with all three studies. For the 206 nondeviants, the mean offset is $+0.004 \pm 0.019$. The exact location of the subgiant branch is difficult to define between $b - y = 0.45$ and 0.6 because of the field-star contamination coming from stars in the outer region of the CCD field, but the first-ascent giant branch is discernible from the red limit of the distribution of stars above $V = 15$. The question of the correct location of the red giant clump reasserts itself here. The two options are near $V = 13.7$, $b - y = 0.60$ and $V = 14.1$, $b - y = 0.53$. How these two groups of stars are related, if at all, is a key question that we address in §5.1. Finally, five obvious candidates for blue straggler members can be seen in isolation well blueward of the turnoff and brighter than $V = 15.5$.

### 3. THE COLOR-MAGNITUDE DIAGRAM: THINNING THE HERD

Because of the lack of membership information for any of the stars except the few with radial velocities and the significant distance modulus of the cluster, NGC 2243 will be treated as a program cluster analogous to NGC 6253 (Paper III) rather than NGC 3680 (Paper IV).

The CMD for all stars with at least two observations each in $b$ and $y$ is presented in Figure 3. Open circles are the stars with standard errors in the mean $\leq 0.010$ mag for $b - y$. Although the superposition of so many points makes it difficult to resolve, the majority of stars brighter than $V \sim 17.0$ meet the rather stringent limit on precision in $b - y$. The morphology of the CMD is similar to that found in previous studies. The turnoff region is well defined to $V = 16$ where an obvious change in the distribution of stars in color occurs. This dramatic broadening is the product of a main sequence contaminated in large part by a significant population of binaries; the sloping binary sequence merges with the vertical turnoff to generate the rather pinched-off appearance near the upper turnoff.

The CMD for stars with at least two observations each in $b$ and $y$.
where the ratio of members to field stars is the highest. The stellar radial distribution has been investigated by both van den Bergh (1977), using photographic plates, and KA, using CCD data; the surveys reach $V \sim 21$ and $I = 20.4$, respectively. Taking into account the $V - I$ color of the main sequence, the CCD study has a $V$ limit of $\sim 21.8$. Both studies conclude that while the stellar distribution with radius flattens beyond about 4', the cluster can be traced to at least 6' away from the cluster center. The form of the cluster CMD is readily identified in the sample of stars beyond 5' in Figure 6 of KA. It should be noted, however, that the degree of concentration changes as the sample expands to include fainter stars. To illustrate this point, we superpose the radial distribution from our CCD data, complete to $V = 18.0$ (circles), on top of those of van den Bergh (1977) (squares) and KA (triangles) in Figure 4. The analysis of our sample was done by first identifying the most probable center of the cluster using the same approach as in Paper III, rather than simply eyeballing the location. The surface densities have been normalized to ensure that the extended flat regions of the distribution between 300" and 400" have the same mean level as that of KA. Error bars are generated only for the inner data points for clarity, since the error bars are smaller than the points for the outer regions.

The higher degree of concentration for the brighter sample compared with van den Bergh (1977) is not unexpected given the 3 mag difference in the limiting magnitude of the counts, the increasing likelihood of field-star contamination at fainter $V$, and a possible weakening of the present-day luminosity function toward lower mass stars due to mass segregation and cluster evaporation. The change in profile between van den Bergh (1977) and KA is somewhat surprising given the more modest change in the limiting magnitude. This may indicate that the luminosity function of the cluster undergoes a decline beyond $V = 21$, since the mass difference in the limiting magnitudes of the two surveys is too small to generate large mass segregation effects.

To maximize the membership probability, our spatial cut restricts the sample to stars within 200 pixels of the cluster center, just over $120^{\circ}$ in Figure 4. The improvement in delineating the CMD is easily seen in Figure 5, which has the same symbols as Figure 3, but includes only the cluster core. Note that four of the five probable blue stragglers are retained, the subgiant and giant branches are readily identifiable, and most of the stars that scattered redward of the main sequence are eliminated.

### 3.2. Thinning the Herd: CMD Deviants

For purposes of optimizing the derivation of the cluster reddening and metallicity, our interest lies in using only single stars that evolve along a traditional evolutionary track and that have indexes in a color range where the intrinsic photometric relations are well defined. With this in mind, we further reduce the sample by including only stars with errors in $b - y$ below 0.010 and in the magnitude range from $V = 15.5$ to 17.5 and the color range from $b - y = 0.28$ to 0.42, leaving 119 stars.

Given the high precision of the $b - y$ indexes and the expected dominance of the cluster sample over the field stars, it is probable that the majority of stars at the cluster turnover are members, although not necessarily single stars. However, unlike IC 4651 in Paper I and NGC 3680 in Paper IV, the larger distance of NGC 2243 places the majority of the stars under discussion within the vertical portion of the turnover. Separation of the stars into two parallel sequences, one single and one composed of binaries, becomes a challenge because the single stars evolving away from the main sequence produce an evolutionary track that curves toward and crosses the rich binary sequence composed of unevolved pairs.

In previous papers, we enhanced our ability to delineate the single and binary sequences through the use of $u - y$, the color index with the largest baseline in wavelength and the greatest sensitivity to temperature change. The one weakness of this approach is with the evolved stars at the turnover. As explained in Paper IV, the $u - y$ index for binaries composed of unevolved stars follows a simple relation between effective temperature and color. For single stars in the vertical band at the turnover, evolution off the main sequence alters the energy distribution by decreasing the relative contribution of the ultraviolet region blueward of the Balmer discontinuity. Thus, $c_1$ increases as $M_y$ decreases at a given temperature. The declining contribution of the $u$ filter leads to a redder $u - y$ index because of surface gravity effects, rather than temperature, making the more evolved stars appear redder than less evolved stars at the same temperature. The result is that the binary sequence crosses the vertical turnover at a redder and fainter location than in $b - y$, thereby lessening its value for a cluster sample such as ours in NGC 2243.

An intermediate alternative is to use the $v - y$ index championed by Meibom (2000). The greater baseline gives the index
greater temperature sensitivity than \( b - y \) but, since \( v \) is dominated by metallicity effects rather than surface gravity and all the stars within the cluster supposedly have the same [Fe/H], the merger of the two sequences should be less of an issue. For the 119 stars remaining after our previous cuts, the \( V, v - y \) diagram is illustrated in Figure 6. For stars redder than \( v - y = 0.8 \), the main sequence is displayed as a band 0.75 mag wide in the vertical direction, exactly as expected for a range of pairs with the upper bound generated by two identical stars. For stars redder than \( v - y = 0.82 \) we split this band down the middle and classified all the stars in the upper half (filled circles) as potential binaries and/or nonmember interlopers. To test whether this separation makes any sense, we plotted the same stars with the same symbols in both a \( V, b - y \) and a \( V, u - y \) diagram. Since we drew the same conclusion from both, we will only show the former diagram in Figure 7. The majority of the stars identified as potential binaries in Figure 6 fall redward of the primary sequence on Figure 7, as expected if they were, in fact, binaries or nonmembers. Given the photometric uncertainty and our restricted selection in Figure 6, the relatively small number of nonbinary stars deviating from the blue edge in Figure 7 is reassuring. Only two of the many stars that deviate to the red in \( u - y \) remained classified as single stars in Figure 6. As stated in past papers, the exclusion of some single stars from the final sample is of no consequence if isolating potentially anomalous stars/photometry allows us to exclude a reasonable portion of the data that could distort the final parameters. Removing the filled circles leaves us with 100 probable, single-star members.

4. FUNDAMENTAL PROPERTIES: REDDENING AND METALLICITY

4.1. Reddening

All 100 stars have multiple measures in every filter. The average standard errors of the mean for the various indices are 0.0074, 0.0094, 0.0083, and 0.0062 for \( b - y \), \( m_1 \), \( c_1 \), and H\( \beta \), respectively. For H\( \beta \), only two stars have standard errors above 0.010 mag. None of the remaining stars has been excluded because of larger than average errors.

As discussed in Paper I, derivation of the reddening from intermediate-band photometry is a straightforward, iterative process given reliable estimates of H\( \beta \) for each star. The primary decision is the choice of the standard relation for H\( \beta \) versus \( b - y \) and the adjustments required to correct for metallicity and evolutionary state. The two most commonly used relations are those of Olsen (1988) and Nissen (1988). As found in previous papers for IC 4651, NGC 6253, and NGC 3680, both produce very similar if not identical results. (A correction regarding the citations should be mentioned for Papers III and IV. Although we have used the same procedures for all open clusters and no changes are required in the numbers or the conclusions, the second standard relation cited in Papers III and IV is Schuster & Nissen [1989]; in both cases, this should read Nissen [1988].)

Processing the indices for the 100 stars through both relations generates \( E(b - y) = 0.042 \pm 0.022 \) (s.d.) with Olsen (1988) and \( E(b - y) = 0.037 \pm 0.017 \) (s.d.) with Nissen (1988). We will take the weighted average of the two and use \( E(b - y) = 0.039 \pm 0.003 \) (s.e.m.) or \( E(B - V) = 0.055 \pm 0.004 \) (s.e.m.) in the analyses that follow.

The possibility of variable reddening across the extent of the cluster was considered and addressed by examining a sample of \( \sim 500 \) stars between \( V = 16 \) and 18 with colors typical of the turnoff and errors in \( b - y \) and H\( \beta \) below 0.02 mag. The color excess with respect to a mean relation between \( b - y \) and H\( \beta \) was examined for trends with respect to coordinate position. No significant trend is discernible, presumably since any plausible range in reddening value would not be very large compared with realistic photometric errors in the colors.

4.2. Metallicity from \( m_1 \)

Given the reddening of \( E(b - y) = 0.039 \), the derivation of [Fe/H] from the \( m_1 \) index is as follows. The \( m_1 \) index for a star is compared with the standard relation at the same color, and the difference between them, adjusted for possible evolutionary effects, is a measure of the relative metallicity. Though the comparison of \( m_1 \) is often done using \( b - y \) as the reference color because it is simpler to observe, the preferred reference index is H\( \beta \) because of its insensitivity to both reddening and metallicity. Changing the metallicity of a star shifts its position in the \( m_1 - (b - y) \) diagram diagonally, while moving it solely in the vertical direction in \( m_1 - \text{H} \beta \). Moreover, reddening errors do not lead to correlated errors in both \( m_1 \) and H\( \beta \).

In past papers, we have derived the metallicity using \( b - y \) and H\( \beta \) as the defining temperature index for \( m_1 \) with, on average, no statistically significant difference in the outcome. Since the publication of Paper IV, alternative [Fe/H] calibrations based upon \( b - y \) and \( m_1 \) have been derived by Nordström et al. (2004) for F stars and cooler, calibrations that make use of the reddening-corrected indices rather than differentials compared with a standard relation. This approach was first used...
successfully by Schuster & Nissen (1989), but the primary focus of their work was on metal-deficient dwarfs, and concerns about the application of the function to solar-metallicity dwarfs limited its adoption for disk stars. These concerns proved valid for the metallicity calibration for cooler dwarfs for which [Fe/H] was systematically underestimated at the metal-rich end of the scale (Twarog et al. 2002). The more extensive recalibrations for F dwarfs and cooler by Nordström et al. (2004) are readily applicable to solar and higher metallicity dwarfs at all colors and eliminate the concerns regarding the original functions of Schuster & Nissen (1989). We derive [Fe/H] without reference to Hβ using the Nordström et al. (2004) relation and from δm1(Hβ) as in past papers, supplying an independent check of the calibration relations.

After correcting each star for the effect of \(E(b - y) = 0.039\), the mean [Fe/H] using the F star relation of Nordström et al. (2004) is \(-0.580 \pm 0.028\) (s.e.m.). In contrast, after correcting each star for the effect of \(E(b - y) = 0.039\) and deriving the differential in \(m_1\) relative to the standard relation at the observed Hβ, the average \(\delta m_1\) for 100 stars is \(+0.056 \pm 0.002\) (s.e.m.), which translates into [Fe/H] = \(-0.534 \pm 0.023\) (s.e.m.) for the calibration as defined in Nissen (1988) and adopted in previous papers. Note that the error for an individual estimate from the first approach is larger than the \(\delta m_1(H/β)\) technique because of the enhanced sensitivity of the nonlinear terms in the first [Fe/H] calibration to errors in both \(b - y\) and \(m_1\). The agreement between the averages is quite good, but it improves even more when one takes the zero point of the [Fe/H] scale into consideration.

The zero point of the Hβ metallicity calibration has been fixed to match the adopted value for the Hyades of [Fe/H] = +0.12, i.e., if one processes the data for the Hyades or the standard relation through the [Fe/H] calibration, one is guaranteed to obtain [Fe/H] = +0.12 for any star with \(\delta m_1 = 0.000\). If the standard relation or the observed data for the Hyades are processed through the Nordström et al. (2004) relation, at the cooler end of the scale beyond \(b - y = 0.32\), one obtains [Fe/H] between +0.12 and +0.16. As \(b - y\) decreases, [Fe/H] declines steadily, reaching a minimum near +0.03 near the hotter end of the scale (\(b - y = 0.23\)). For the stars in the color range of interest for NGC 2243, [Fe/H] for the Hyades is systematically underestimated by 0.05 dex relative to the adopted value. Thus, for consistency on the scales, the [Fe/H] estimate based on \(b - y\) and \(m_1\) should be raised to \(-0.53\), essentially identical to the Hβ-based relation.

The primary weakness of metallicity determination with intermediate-band filters is the sensitivity of [Fe/H] to small changes in \(m_1\); the typical slope of the [Fe/H]/\(\delta m_1\) relation is 12.5. Even with highly reliable photometry, e.g., \(m_1\) accurate to \(\pm 0.015\) for a faint star, the uncertainty in [Fe/H] for an individual star is \(\pm 0.19\) dex from the scatter in \(m_1\) alone. When potential photometric scatter in Hβ and \(b - y\) is included, errors at the level of \(\pm 0.25\) dex are common, becoming even larger for polynomial functions of the type discussed above. As noted in previous papers in this series, the success of the adopted technique depends on both high internal accuracy and a large enough sample to bring the standard error of the mean for a cluster down to statistically useful levels, i.e., below \(\pm 0.10\) dex. Likewise, because of the size of the sample, we can also minimize the impact of individual points such as binaries and/or the remaining nonmembers, although they will clearly add to the dispersion.

4.3. Metallicity from \(hk\)

We now turn to the alternative avenue for metallicity estimation, the \(hk\) index. The \(hk\) index is based on the addition of the Ca filter to the traditional Strömgren filter set, for which the Ca filter is designed to measure the bandpass that includes the H and K lines of Ca II. The design and development of the Caby system have been laid out in a series of papers discussing the primary standards (Anthony-Twarog et al. 1991b), an extensive catalog of field-star observations (Twarog & Anthony-Twarog 1995), and calibrations for both red giants (Anthony-Twarog & Twarog 1998) and metal-deficient dwarfs (Anthony-Twarog et al. 2000). Though the system was optimally designed to work on metal-poor stars and most of its applications have focused on these stars (Anthony-Twarog et al. 1995, 2000; Baird 1996), early indications that the system retained its metallicity sensitivity for metal-rich F dwarfs have been confirmed by observation of the Hyades and analysis of nearby field stars (Anthony-Twarog et al. 2002). What makes the \(hk\) index, defined as \((Ca - b) - (b - y)\), so useful for dwarfs, even at the metal-rich end of the scale, is that it has half the sensitivity of \(m_1\) to reddening and approximately twice the sensitivity to metallicity changes. The metallicity calibration for F stars derived in Anthony-Twarog et al. (2002) used \(\delta hk\) defined relative to \(b - y\) as the temperature index. To minimize the impact of reddening on metallicity, this calibration was redone in Paper III using Hβ as the primary temperature index, leading to the preliminary relation [Fe/H] = \(-3.51 \delta hk(H/β) + 0.12\), with a dispersion of only \(\pm 0.09\) dex about the mean relation. Although the derived zero point of the relation was found to be +0.07, it was adjusted to guarantee a Hyades value of +0.12, the same zero point used for the \(m_1\) calibration. Because of the expanded sample of stars with spectroscopic abundances and the revised \(m_1\) calibrations for F and G dwarfs by Nordström et al. (2004), a revised and expanded calibration of the \(\delta hk\) indices based on both \(b - y\) and Hβ is underway (Anthony-Twarog et al. 2005).

Modest changes have been generated in the color dependence of the [Fe/H] slope for \(\delta hk(b - y)\), with even smaller adjustments to the Hβ-dependent relation. To ensure that the metallicities based on \(m_1\) and \(hk\) are on the same internal system, we generated [Fe/H] from the unmodified \(m_1\), \(b - y\) function of Nordström et al. (2004) for all dwarfs with \(hk\) indices and derived linear relations between [Fe/H] and \(\delta hk(b - y)\) and \(\delta hk(H/β)\) for three different color ranges among the F stars.

Applying these modified metallicity calibrations to the \(hk\) data for 100 stars in NGC 2243, the resulting [Fe/H]-values for \(hk\) relative to \(b - y\) and Hβ are [Fe/H] = \(-0.643 \pm 0.018\) (s.e.m.) and \(-0.643 \pm 0.011\) (s.e.m.), respectively. It should be emphasized that the exact agreement between the two is purely fortuitous given the color sensitivity of the \(b - y\) calibration, as evidenced by the larger dispersion for the \((b - y)\)-based [Fe/H] determination. The dramatic decrease in the scatter with the Hβ relation is real and an indicator of the value of coupling the increased metallicity sensitivity of the \(hk\) index with the reddening- and metallicity-independent Hβ index and the minimal temperature dependence of the [Fe/H] calibration based on Hβ. If we repeat the adjustment derived above to ensure that the calibrations are zeroed to the same scale, the [Fe/H] from the \(hk\) index becomes \(-0.59\). Note that this is identical to the average we would have obtained from the calibrations used in the previous papers, although the individual \((b - y)\)-based and Hβ-based averages would not have been identical. The unweighted average of the four determinations is [Fe/H] = \(-0.56 \pm 0.03\), while inclusion of a weight based on the inverse of the standard error of the mean lowers the average to [Fe/H] = \(-0.57\).

Given that the photometric zero points for the \(m_1\) and \(hk\) photometry were derived independently of each other and that the reddening impacts \(m_1\) to a much larger degree than \(hk\), the...
agreement between the metallicities based upon the two indices is excellent.

4.4. Comparison with Previous Determinations

For the reddening determination, only one additional approach has become available since the discussion in Twarog et al. (1997), in which \( E(B-V) = 0.06 \) was adopted. This estimate was defined by a number of approximate attempts to derive reddening from UBV colors (Hawarden 1975; van den Bergh 1977) and crude constraints from isochrone fits (Bonifazi et al. 1990; Carraro et al. 1994), which led to a range between \( E(B-V) = 0.00 \) and 0.08. Kaluzny et al. (1996) used a field RR Lyrae variable to place an upper limit of 0.08 on the cluster. The reddening maps of Schlegel et al. (1998) indicate \( E(B-V) = 0.074 \) in the direction of NGC 2243, an upper limit along this line of sight but presumably close to the cluster value given the significant distance of the cluster above the Galactic plane. In summary, given the uncertainty inherent in all of these techniques, there appears to be no significant discrepancy with the value of \( E(B-V) = 0.055 \) derived from our uvbyH\beta photometry of the probable cluster members at the turnoff.

As with the reddening, the first attempts to derive a metallicity for NGC 2243 were coupled to reddening estimation through analysis of UBV photometry by Hawarden (1975) and van den Bergh (1977). The former derived \( E(B-V) = 0.06 \) and \( \delta(U-B) = +0.15 \) relative to the Hyades, while the latter found 0.03 and +0.06, respectively. Both indicated the cluster was metal deficient, but the [Fe/H]-values differed by 0.5 dex. The DDO data of Norris & Hawarden (1978) seemed to favor the unusually low [Fe/H] for an open cluster, a conclusion confirmed with the DDO recalibration (Twarog & Anthony-Twarog 1995) and cluster reanalysis by Twarog et al. (1997), where DDO data from five giants produced \([Fe/H] = -0.48 \pm 0.16 \) (s.d.). Of the five stars included in this average, 2410 lacks membership information, but 883 is assumed to be a nonmember on the basis of its anomalously high abundance (Friel et al. 2002). If this star is dropped from the DDO sample, where its metallicity is also high, the mean [Fe/H] for the remaining four stars becomes \(-0.53 \pm 0.14 \) (s.d.). The only additional photometric attempt to measure the cluster metallicity uses the Washington system and, using the revised calibration of Geisler et al. (1991), implies [Fe/H] = -0.75 from five giants. It must be emphasized that compared with the abundance scale of Twarog et al. (1997) and Friel et al. (2002), the Washington [Fe/H] estimates for moderately metal-poor open clusters are generally too low by between 0.1 and 0.3 dex.

On the spectroscopic front, only two sources of [Fe/H] exist. High-dispersion spectra of two giants analyzed by Gratton & Contarini (1994) give [Fe/H] = -0.48 \pm 0.15, where the error includes both internal and external uncertainties; the agreement between the two stars is much smaller. Friel et al. (2002) expanded the original spectroscopic sample of Friel & Janes (1993) and revised the metallicity calibration on the basis of their spectra of the giants. The revision compressed the scale by shifting the more metal-poor open clusters to higher [Fe/H], while lowering the metallicity of the clusters more metal-rich than the Hyades, exactly the trend delineated by comparison with the DDO data in Twarog et al. (1997). The result is that the earlier estimate for NGC 2243 of [Fe/H] = -0.56 from six stars (Friel & Janes 1993) has improved to [Fe/H] = -0.49 \pm 0.05 from nine stars. In summary, taking into consideration the differences among the techniques and the internal and external uncertainties in the calibrations and zero points, there is every indication that the metallicity determinations for NGC 2243, whether based on the evolved red giants or the turnoff stars, are converging toward a value of \([Fe/H] = -0.55 \pm 0.1\) and, more importantly, are systematically lower than the other well-studied anticenter open clusters, NGC 2204, 2420, 2506, and Mel 66.

5. FUNDAMENTAL PARAMETERS: DISTANCE AND AGE

5.1. Defining the Giant Branch

The traditional method for age and distance determination is via comparison of the cluster CMD to a well-matched set of theoretical isochrones, the approach we have consistently used in this series. In previous papers, the cluster CMD was either richly populated, the cluster was nearby, and/or there was membership information available that allowed one to isolate the evolved members of the cluster from the field. Comparison of Figures 3 and 5 reveals that reddward of \( b - y = 0.45 \) and brighter than \( V = 16.5 \), there is extensive contamination of the CMD by field stars along the line of sight, crossing the probable location of the subgiant branch between \( V = 15.5 \) and 16.5. One can minimize this issue by dealing solely with stars within the cluster core, a successful strategy for the easily identifiable turnoff and main sequence but a concern for an entire post-main-sequence track defined by fewer than two dozen stars, some of which are likely to be field stars. Past disagreement about potential contamination among the brighter stars (van den Bergh 1977; Bergbusch et al. 1991) can be tied to the limited coverage of earlier CCD surveys. Questions about the location of the red giant clump, as well as whether or not the cluster has more than one clump, require as reliable an isolation of the members from the field as the data will allow, along with CCD-based photometry for all potential giants, not just those in the core (Bonifazi et al. 1990).

To define our giant branch, we first limit our sample to all stars redder than \( b - y = 0.45 \) and brighter than \( V = 16.2 \); all stars in this portion of the CMD were transformed photometrically as giants, with indices that smoothly transition to the dwarf calibration at \( b - y = 0.45 \). From this sample of 77 stars we eliminate 11 that have errors in \( m_1 \) and/or \( h\kappa \) greater than 0.015 mag, while retaining only stars with errors in \( b - y \) below 0.010. One additional star that falls in the exclusionary range is retained for reasons explained below. The strict selection criteria are necessary because we use the \( m_1 \) and \( h\kappa \) versus \( b - y \) color-color diagrams to identify probable members. There is no proper-motion data for the cluster, and reliable radial velocities exist for approximately a dozen of the giants out of the 66 that remain. The sole advantage held by NGC 2243 is its almost uniquely low metallicity among the field stars in the disk. Since the cluster sits well above the Galactic plane, most contamination is expected from field stars within the disk, stars that are expected to populate the two-color diagrams in the zone between Hyades metallicity and NGC 2243. Few stars should be as metal-poor as NGC 2243.

To define the cluster relation in the two-color diagrams, we turn to the stars in the cluster core, defined here as less than 300 pixels (~1.5") from the cluster center. The boundary was chosen because it contains every star with a radial velocity consistent with cluster membership. The initial membership list is taken from the summary by Friel et al. (2002). Of the 14 stars studied, five are classified as probable nonmembers. Of these stars, three are excluded because of their deviant velocities, while two have velocities consistent with membership but spectroscopic abundances near solar. Two of the radial velocity members have been studied by Gratton & Contarini (1994) and
confirmed as members. A tenth member based on spectroscopic analysis (1654) has been added by Hill & Pasquini (2000). An additional source of radial velocity information is available from the moderate-dispersion spectroscopic survey of Collier Cameron & Reid (1987). Unfortunately, the derived cluster velocity is systematically off from the true value by 15 km s\(^{-1}\), and the typical uncertainty in the velocity measures is close to 10 km s\(^{-1}\). So, while stars near the cluster mean may or may not be members, we can use the data to exclude stars with exceptionally deviant velocities as probable nonmembers. To that list we add 2236 and 2704.

Armed with this information, one can now plot the \(hk\)\((b-y)\) diagram shown in Figure 8 for stars within 300 pixels of the cluster core. Filled circles are cluster members, while open circles are nonmembers. With the exception of one star (2135), the members form a tight sequence between \(b-y = 0.58\) and 0.9. The one exception is the star kept in the sample, despite having unusually large scatter in its indices, because it is a probable radial velocity member. It is found at the level of the cluster core. Filled circles are known cluster members, while open circles are nonmembers. Based on the position in the diagram, squares are stars tagged as probable nonmembers, while asterisks identify probable members.

Assuming that the majority of the stars within the core are members and that they follow a well-defined relation in the two-color diagram, we extended the pattern defined by the redder stars by identifying the starred points in Figure 8 as members. Any star that deviates from this pattern is classed as a nonmember (squares). A similar figure was constructed for \(m_1\) but is not shown; any star that deviated from the \(m_1\)\((b-y)\) relation was also classed as a nonmember. The agreement between the two diagrams for the core region is excellent. The members relation was then superposed on the diagram for all 66 stars within the CCD survey and the same criterion applied. The more extensive scatter caused by field stars contributed by the outer zone is readily apparent in Figure 9; the symbols have the same meaning as in Figure 8. Note that a few points classed as nonmembers appear to fall within the restricted range defined by the members; these stars were excluded because of deviations in the \(m_1\)\((b-y)\) plot. The result is that by extending the analysis to stars outside the core, we add six highly probable members to the giant region, bringing the total for the survey to 27.

The CMD for the stars in Figure 9 is shown in Figure 10, with the symbols having the same meaning. A number of points are apparent. First, a great deal of the scatter among the probable members in the CMD has been eliminated. The majority, although not all, of the stars that deviate from the first-ascent giant branch are classed as potential nonmembers, while some of the stars that appear within the range of the giant branch are tagged as such. This is not unexpected, given the photometric nature of the procedure and the likelihood that some of the remaining CMD deviants are composite members, especially with the rich binary population of the turnoff and the main sequence. As we have reiterated many times in this series, the exclusion of a few potential members from the sample is not a cause for concern as long as the stars that remain are highly probable cluster members.

Second, the identification of the red giant clump is now obvious. Seven probable members are found in the giant branch region between \(V = 13.63\) and 13.81. Of these, the five bluer stars have an average \(V\) of 13.70 \(\pm\) 0.04 (s.d.) and an average \(b-y\) of 0.589 \(\pm\) 0.007 (s.d.). In contrast, all the stars that populate the fainter clump between \(V = 14.0\) and 14.2 are classified as probable nonmembers. It should be noted, however, that two of these stars (883, 2619) have radial velocities

![Fig. 8.—Two-color diagram for giants within 300 pixels of the cluster center. Filled circles are known cluster members, while open circles are nonmembers. Based on the position in the diagram, squares are stars tagged as probable nonmembers, while asterisks identify probable members.](image1)

![Fig. 9.—Same as Fig. 8, but for the entire CCD field.](image2)

![Fig. 10.—CMD for the stars in Fig. 9. Symbols have the same meaning as in Fig. 8.](image3)
The Broadband CMD: Transforming the Data

As we have noted in past analyses, isochrones are invariably created for broadband systems, and a check of the most recent publications shows that theoretical isochrones are available on the UBVRI system, among others, but rarely for any other. This problem has been solved in past investigations by making use of the fact that \( b - y \) is well correlated with \( B - V \) at a given [Fe/H], with little dependence on evolutionary state. While reliable CCD \( BV \) data are available for the numerous main-sequence stars in the cluster core, the ability to transform from \( b - y \) to \( B - V \) is particularly important for the giants, for which more than half the identified probable members lie outside the published \( BV \) surveys.

The first step is to merge the \( BV \) photometry of BO and BE. For the \( V \) magnitudes, both surveys have been placed on the system of Table 1 using the offsets and color terms of Table 2. For \( B - V \), because of the more extensive tie-in of the CCD data of BE to the standard system, we adopted BE as the color system of choice, although, as noted below, choosing BO as the standard would have a negligible impact on our conclusions. Using only stars brighter than \( V = 17.5 \) with a difference in \( V \) between the two systems less than 0.075 mag, the difference in \( B - V \), in the sense BE - BO, has been calculated, producing a mean residual of 0.002 ± 0.029 in \( B - V \) from 190 stars. If we exclude three stars for which the residuals in \( B - V \) are larger than 0.10 mag, the average difference becomes 0.004 ± 0.022. Clearly the two-color systems are very similar. Finally, the residuals show a modest color term that can be removed by including a correction of \( \Delta\{B - V\} = 0.072\{B - V\} - 0.035 \); this reduces the residuals to 0.000 ± 0.019. After applying the small color term to the data of BO, the composite system is constructed by taking a straight average for the modified \( V \) and \( B - V \) data, generating a final listing of \( V, B - V \) data for over 900 stars.

To transform the giants, we selected the overlap between our sample of 66 stars with \( b - y > 0.45 \) and \( V < 16.2 \) and the composite \( BV \) data, resulting in 25 stars. Of these, three, 1804, 2410, and 3668, exhibit large deviations in the \( (b - y)(B - V) \) transformation. For the remaining 22 stars, the defined relation is \( B - V = 1.647(b - y) - 0.045 \); the scatter among the residuals about the mean relation is ±0.022 mag. Of the three deviants, only 2410 is a probable member included in the discussion of the CMD as a red giant clump star, so its correct colors are important. Star 2410 was only observed in \( B - V \) by BO. It has \( B - V = 1.03 \), in contrast with clump stars 910, 1271, and 1467 at \( B - V = 0.90, 0.91 \), and 0.94, respectively. In the \( VI \) survey of KA, the comparable colors are \( V - I = 1.00 \) for 2410 and 0.97, 0.99, 0.99 for 910, 1271, and 1467. The latter pattern agrees well with \( b - y \) for which the four stars have \( b - y = 0.598, 0.581, 0.583 \), and 0.593. It appears that the modified \( B - V \) color for 2410 from BO is systematically too large.

For the remainder of the CMD, from the \( V, B - V \) catalog we have selected stars from Table 1 located within 200 pixels of the cluster center with \( V < 18.5 \) for \( B - V \leq 0.8 \) and \( V \leq 16.2 \) for \( b - y \leq 0.45 \). If the differences in \( V \) and/or \( B - V \) between BE and BO were larger than 0.15 or 0.10 mag, respectively, the star was excluded. The resulting CMD is shown in Figure 11, in which the giant probable members from the complete survey as discussed above have been drawn as filled circles; the cross signifies the anomalous star 2135. The CMD for the turnoff exhibits the striking features noted in the past CCD studies, although with slightly better delineation due to the combination of the photometry. The unevolved main sequence is easily identified down to \( B - V = 0.65 \) and \( V = 18.5 \), as is the rich, parallel band of binaries starting near \( B - V = 0.8 \) and \( V = 18.5 \) that ultimately merges with the vertical turnoff near \( V = 16.2 \). The reality of the small gap in the main sequence, discussed in every past study of the CMD, is undeniable and is enhanced by the fact that there is a small but real color shift on either side of the break. The stars above the gap are typically 0.01–0.02 mag bluer than the stars below the break. As discussed below, this small but significant feature plays a critical role in constraining the age and metallicity of the cluster.

5.3. The CMD Fit: The Isochrones

A variety of isochrone sets are available for comparison with broadband photometry. For consistency with our previous discussions and because, when properly zeroed to the same color and absolute magnitude scale, most sets produce similar results for ages and distances, we use the sets of Girardi et al. (2002, hereafter PAD). Moreover, based on the many comparisons, including our own (Anthony-Twarog et al. 1991a, 1994; Daniel et al. 1994; Twarog et al. 1995) between open clusters and past and present generations of isochrones, we only make use of isochrones that include convective overshoot mixing. On a scale for which solar metallicity is \( Z = 0.019 \) and \( Y = 0.273 \), PAD isochrones were obtained for \( (Y, Z) = (0.25, 0.008) \) and \( (0.24, 0.004) \) or [Fe/H] = −0.38 and −0.68, respectively. Since isochrones with [Fe/H] = −0.57 are not available, it was decided to define the cluster parameters assuming each of the abundances was appropriate and interpolate the results for the derived [Fe/H].

For distance and age estimation, the next step in comparing the cluster CMD with a set of theoretical isochrones is ensuring that the color transformations and bolometric corrections between the theoretical and the observational plane reproduce the colors and absolute magnitudes of nearby stars with known temperatures and abundances. From an age standpoint, the critical test is whether or not a star of solar mass, composition, and age resembles the Sun. For open clusters of solar and subsolar abundance, the impact of this issue on cluster ages and distances has been emphasized on a variety of occasions (Twarog

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**Fig. 11.—Broadband CMD for NGC 2243 using stars from the cluster core (open circles) and the transformed \( b - y \) for the member stars in Fig. 9 (filled circles). The cross denotes star 2135.**
& Anthony-Twarog 1989; Twarog et al. 1993, 1995, 1999; Daniel et al. 1994). In past uses of the isochrones for clusters with approximately solar metallicity, we checked to ensure that the isochrones were on our adopted color and absolute magnitude scale of $M_V = 4.84$ and $B-V = 0.65$ for a solar mass star at 4.6 Gyr. One quickly finds that the solar metallicity isochrones of PAD are too red by 0.032 mag in $B-V$ and too bright by 0.02 mag in $V$; for the analyses of IC 4651 and NGC 3680, these adjustments were included.

Should these offsets be applied to isochrones that are metal-deficient by a factor of 5 compared with the Sun? There is some evidence that the correction for linking the metal-poor isochrones to the observational plane is not only smaller but may be zero for the PAD isochrones (Twarog et al. 1999). While this implies that the distance modulus derived by comparing the cluster CMD with the unevolved, uncorrected main sequence of the isochrones should be correct, there is no independent way of zeroing the age scale, as there is for solar metallicity. We use the metal-deficient isochrones without adjustment, keeping in mind that while relative comparisons among the isochrones should be reliable, the absolute age and distance scales are subject to potential systematic offsets.

The first comparison between theory and observation is for the $[\text{Fe/H}] = -0.38$ isochrones with ages 2.51, 2.82, and 3.16 Gyr, shown in Figure 12 with a shift of $E(B-V) = 0.055$ and an apparent distance modulus of $m - M = 13.40$. The color of the turnoff and the location of the subgiant branch are reasonably consistent with an age of about 2.7 Gyr, keeping in mind the nonlinear rate of evolution of both of these features. The isochrones, however, fail to match the cluster morphology in a number of ways. While the break in the turnoff due to hydrogen exhaustion has the correct approximate apparent magnitude, the predicted curvature of the turnoff below the break and the blueward extension of the hook above the break are too large. Such a small hook and break is predicted for a significantly older isochrone and is commonly associated with clusters similar in age to the Sun, such as M67. The more dramatic discrepancy is the location of the giant branch. The isochrone tracks are too red by 0.1 mag in $B-V$ and the predicted clump is too faint by 0.3 mag. Note that with this modulus, the observed clump has $M_V = +0.3$, making it anomalously bright compared with other clusters of similar age and metallicity (Twarog et al. 1997).

In Figure 13, we illustrate the second comparison with isochrones of $[\text{Fe/H}] = -0.68$; the reddening adjustment is the same, but the apparent modulus has been reduced to 13.05 to match the main sequence. The isochrones have ages of 3.16, 4, and 5 Gyr. On the basis of the color of the turnoff, the age of NGC 2243 rises to 5 Gyr, although the position of the subgiant branch implies a value between 4 and 4.5 Gyr. Morphologically, the isochrones do a better job with the hydrogen exhaustion phase, which is predicted to disappear between 4 and 5 Gyr, although the observed luminosity of the break is too high. The dramatic improvement occurs in the color of the giant branch and the red giant clump, where the isochrones are too blue by a few hundredths in $B-V$, and in the luminosity of the clump. The observed clump is too faint by 0.1 mag compared with the predicted position. With this distance modulus, the observed clump has $M_V = 0.65$, much more consistent with the typical range between 0.5 and 0.7 for clusters younger than 5 Gyr (Twarog et al. 1997).

The comparisons are exactly what one would expect for a cluster whose metallicity is intermediate between $[\text{Fe/H}] = -0.38$ and $-0.68$. Adopting $[\text{Fe/H}] = -0.57$, we find that NGC 2243 is approximately one-third of the way between the limiting models. Interpolating the disparities noted above, isochrones with an appropriate $[\text{Fe/H}]$ and adjusted for an apparent modulus of 13.15 should simultaneously match the color and luminosity of the giant branch and the clump, implying $M_V$ for the clump of +0.55. The age of the cluster is somewhat more of a challenge, since the subgiant branch and the turnoff do not supply identical ages for the lower metallicity comparison. Approximating 4.6 Gyr as the age from $[\text{Fe/H}] = -0.68$ and interpolating in log (age) to account for the nonlinear change in age with $[\text{Fe/H}]$ leads to $3.8 \pm 0.2$ Gyr as the approximate age of NGC 2243.

5.4. Comparisons with Previous Work

Past derivations of the cluster age and distance using CCD photometry are somewhat dated because of the combination of adopted isochrones and cluster parameters, but the analyses do illustrate the convergence that has occurred in defining cluster parameters over the last decade as the range of models and their transformation to the observational plane have improved.

BE used a comparison of NGC 2243 to 47 Tuc and theoretical isochrones without convective overshoot to conclude that NGC 2243 was likely to be more metal-rich than the globular cluster, in contradiction to some observational evidence at the time that NGC 2243 might be as metal-deficient as 47 Tuc, if not more so. Assuming similar abundances for the two clusters,
BE derived \( m - M = 13.05 \) for NGC 2243, with an age range of 4 to 6 Gyr for an \( [\text{Fe}/\text{H}] \) range of \(-0.47 \) to \(-0.78 \). It was concluded that convective overshoot was required to reproduce the main-sequence gap, a correct interpretation, while oxygen enhancement was needed to reproduce the color of the giant branch, a now questionable interpretation.

BO used cluster CMD morphology and synthetic CMDs based on a variety of theoretical stellar models in an attempt to constrain the cluster parameters. The models ranged from those with no convective overshoot, similar to what was adopted in BE, to extreme amounts of overshoot. With the exception of the extreme overshoot case in which the main-sequence gap could not be reproduced under any circumstances, BO were unable to decide which among the various evolutionary codes achieved a better match to the cluster CMD. Despite the ambiguity, BO concluded that the cluster must have \( Z \) between 0.003 and 0.006, \( E(B-V) \) between 0.06 and 0.08, an age between 3 and 5 Gyr, and a true modulus between 12.7 and 12.8 (\( m - M \) between 12.9 and 13.05), all values in surprisingly good agreement with what has been derived in the current investigation.

Finally, using the data of BO, \( E(B-V) = 0.06 \) and \( [\text{Fe}/\text{H}] = -0.44 \), Twarog et al. (1997) found \( m - M = 13.45 \), in good agreement with the result from the metal-rich isochrone match.

5.5. Comparison with Berkeley 29

With its slightly lower \( [\text{Fe}/\text{H}] \) determination and smaller distance modulus, NGC 2243 goes from being one of the three lowest-\( [\text{Fe}/\text{H}] \) clusters in the 76 cluster sample of Twarog et al. (1997) to the lowest in the list, although the exact abundance for its nearest competitor, Ber 21, remains much more uncertain. The smaller distance to the cluster moves it closer to both the Sun and the galactic center, reducing the galactocentric distance to 10.93 kpc, on a scale where the Sun is at 8.5 kpc, and just over 3 kpc from the cluster center as defined by Kaluzny (1994); for NGC 2243 we fortunately on the same system within a few millimagnitudes as the cluster center as defined by Kaluzny (1994), and \( \Delta V \) and \( \Delta V_2 \) (Kaluzny 1994), and \( \delta V \) (Salaris et al. 2004) is that Ber 29 is the same age as or slightly younger than NGC 2243. In the most recent determination by Salaris et al. (2004) the difference in age is close to 0.5 Gyr after adjusting the \( [\text{Fe}/\text{H}] \) of Ber 29 from their adopted value of \(-0.18 \) to a value near \(-0.5 \). This simple parametric approach is confirmed by the synthetic CMD work of Tosi et al. (2004). Although the isochrones have changed since the study of NGC 2243 by BO, Tosi et al. (2004) reach virtually identical conclusions regarding the age and metallicity of Ber 29. The latter cluster should have \( [\text{Fe}/\text{H}] = -0.5 \) or \(-0.7 \), an age of 3.4 or 3.8 Gyr, with derived reddening of \( E(B-V) = 0.13 \) or 0.10.

The last critical piece of information that could have resolved the question with the original study of Kaluzny (1994) is reddening. If one uses the reddening maps of Schlegel et al. (1998), the reddening for the Galactic field in the direction of Ber 29 is \( E(B-V) = 0.093 \), on the same scale on which the field of NGC 2243 has \( E(B-V) = 0.074 \). This value is almost certainly the correct value for Ber 29, given its location almost 2 kpc above the Galactic plane; if not, it should be an upper limit. Observational support for this claim comes from the spectroscopic analysis by Carraro et al. (2004), in which the temperature scale defined by minimizing the slope of abundances from the Fe lines with respect to the excitation potential in the curve of growth analysis yields \( E(B-V) = 0.08 \).

We assume that NGC 2243 and Ber 29 have identical abundances. We can then superpose the CMD for Ber 29 and then apply the reddening of NGC 2243 by lowering the colors of Ber 29 by 0.038 mag in \( B-V \) and shifting \( V \) to account for the differential apparent modulus until the main sequences superpose, in this case 3.00 mag, implying an apparent modulus for Ber 29 of 16.15 or a true modulus of \( (m - M)_0 = 15.85 \) (14.8 kpc), a little larger than the range of 15.6–15.8 predicted by Tosi et al. (2004). The data for Ber 29 have been taken from Kaluzny (1994), which is fortunately on the same system within a few millimagnitudes as the photometry of Tosi et al. (2004). To maximize the cluster membership, we will use only stars within 150 pixels of the cluster center as defined by Kaluzny (1994); for NGC 2243 we use the same stars found in Figure 13. The result is shown in Figure 14, where the points from NGC 2243 are drawn in red.

The agreement between the two clusters is impressive; the position of virtually every feature of the CMD is almost superposed for the two clusters, including the location of the main-sequence gap. What little differences there are in the color of the turnoff, the extent of the blue hook, and the relative location of the giants and the clump are easily reconciled by assuming that, morphologically, Ber 29 is slightly younger than

Fortunately, two recent studies have taken a more detailed look at the issue of the cluster age and abundance (Carraro et al. 2004 and Tosi et al. 2004). The former discusses the results from high-dispersion spectroscopy of two giants, while the latter uses CMD analysis and moderate dispersion data from 20 giants, not all of which are members. Carraro et al. (2004) find \( [\text{Fe}/\text{H}] = -0.44 \pm 0.18 \), while the spectroscopy of Bragaglia et al. (2004) produces \( [\text{Fe}/\text{H}] = -0.74 \pm 0.18 \). While statis-

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NGC 2243, as predicted by the parameters discussed above. For a color difference of 0.02 in $B$/$C_0$ for the turnoff, in the age range between 3.2 and 4 Gyr, the age differential implied is approximately 0.4 Gyr, in excellent agreement with the prediction of Salaris et al. (2004). What is important to emphasize is that this explanation can only work if Ber 29 is as metal-rich as NGC 2243. Any attempt to significantly lower the metallicity of Ber 29 relative to NGC 2243 will result in an age that must be greater than that of NGC 2243, unless the reddening for Ber 29 is increased above the limiting value. Taking the age differential from Salaris et al. (2004) as our limit, if NGC 2243 has an age of 3.8 Gyr, Ber 29 must be 3.3–3.4 Gyr old, confirming the analysis of Tosi et al. (2004). All things being equal, on the scale of $\frac{1}{2}$Fe = $H/C_{138}$ for NGC 2243 and the isochrones adopted above as zeroed to the observational plane, with the intrinsic color of the turnoff, $(B - V)_0$, implied by a reddening of $E(B - V) = 0.093$, $[\text{Fe/H}]$ for Ber 29 must be $-0.57$ or above.

Not surprisingly, all things are not equal. One of the conclusions of the spectroscopic work of Carraro et al. (2004) is that the giants of Ber 29 have nonsolar abundances for some of the light $\alpha$-elements, i.e., they have enhanced abundances, in contrast with NGC 2243 in which the elements appear to be scaled solar. What impact does this have on the analysis?

A simple test of the impact can be made by a comparison of the CMD for Ber 29 with a set of isochrones with the appropriate $[\text{Fe/H}]$ but other elements not scaled to the Sun. The lowest $[\text{Fe/H}]$-value for which the $\alpha$-enhanced isochrones are available from Girardi et al. (2002) is $-0.38$, slightly higher than required, but still indicative of the effect of the changes on the morphology and the age of the cluster; these are the same models adopted by Carraro et al. (2004). Figure 15 shows the photometry of Ber 29 superposed on isochrones shifted by $E(B - V) = 0.093$ and an apparent modulus of $m - M = 16.25$. The match of the data to the isochrones, as defined by the color of the turnoff and the luminosity of the subgiant branch, gives an age of 2.8 Gyr. Had we used the scaled solar abundance isochrones with $[\text{Fe/H}] = -0.38$, as we did for NGC 2243, the age for Ber 29 would be 2.5 Gyr, slightly younger than NGC 2243 when compared with the same set, as expected. The change from the earlier comparison of NGC 2243 is the exceptional agreement with the color and luminosity of the giant branch and red giant clump. If we assume that the age effect of boosting the $\alpha$-elements is approximately 10% in this age range, assuming that Ber 29 has the same $[\text{Fe/H}]$ as NGC 2243 raises its age to about 3.7 Gyr, the same value within the errors as NGC 2243. If we adopt $[\text{Fe/H}] = -0.44$, as measured by Carraro et al. (2004), the age must be lower; we estimate 3.1 Gyr. Carraro et al. (2004) claim an age of 4.5 Gyr for Ber 29 using the same isochrones but provide no details, so the source of the discrepancy remains unknown.

As an unrelated item, during the analysis of Ber 29 a check of the discussion by Kaluzny (1994) of the cluster Ber 54 identified a large error in the adopted distance modulus for this cluster.

![Fig. 14.—CMD for the core of Ber 29 (open circles) adjusted by $\Delta(B - V) = -0.038$ and $\Delta V = -3.00$ and superposed on the CMD for NGC 2243 (red crosses).](image1)

![Fig. 15.—Comparison of the CMD of Berk 29 to $\alpha$-enhanced isochrones with $[\text{Fe/H}] = -0.38$, adjusted for $E(B - V) = 0.093$ and $m - M = 16.25$. The isochrones have ages of 2.51, 2.82, and 3.16 Gyr.](image2)
cluster. Kaluzny (1994) finds, via differential comparison with M67, a cluster with the same morphological age, that Ber 54 is heavily reddened at $E(B - V) = 0.77$ but with a true distance modulus of $(m - M)_0 = 11.8$, or a distance of 2.3 kpc. Using these numbers, the apparent modulus is $m - M = 14.2$. Since the cluster turnoff point is fainter than $V = 19.5$, this makes no sense. The true distance modulus of 11.8 has propagated through the literature (Friel 1995; Salaris et al. 2004), placing the cluster at a galactocentric distance of 8.54 kpc on a scale on which the Sun is at 8.5 kpc.

An alternative approach is to assume that the red giant clump at $V \sim 17.3$ has an absolute magnitude typical of clusters with an age near M67, $M_V = +0.6$ (Twarog et al. 1997). Thus, the apparent modulus becomes $m - M = 16.7$ and the true modulus is $(m - M)_0 = 14.3$. The similarity of this number with the conclusion of Kaluzny (1994) supplies the likely explanation that the apparent and true moduli were transposed. On our scale, Ber 54 has a distance of 7.2 kpc from the Sun and a galactocentric distance of 10.5 kpc, well beyond the solar circle.

6. SUMMARY AND CONCLUSIONS

The specific goal of this investigation has been to derive the key cluster parameters of reddening, metallicity, distance, and age for the metal-poor anticenter cluster NGC 2243. We attempted to use the various photometric indices to optimize the sample of single-star cluster members near the turnoff with high-precision photometry in determining $E(B - V) = 0.055 \pm 0.004$ and $[\text{Fe}/\text{H}]= -0.57 \pm 0.03$, with excellent agreement among the various combinations of indices used to derive $[\text{Fe}/\text{H}]$. This point is crucial because $m_f$, $hk$, $b - y$, and $H\beta$ are tied to the standard system independently; i.e., each has its own transformation from instrumental to standard system. If there were significant errors in the zero points of the indices, the variation in the dependence of each color index on reddening and metallicity would conspire to generate much greater differences among the derived metallicities from the four techniques that are found in the analysis. In fact, the majority of the scatter among the derived $[\text{Fe}/\text{H}]$ values can be explained solely by the internal scatter within the photometry for the various indices.

Given the reddening and metallicity, one should be able to obtain the distance and age by comparison with appropriate isochrones. Using color-color diagrams coupled with the modest amount of membership information supplied by high-quality radial velocities, we were able to isolate highly probable members from the extended cluster area rather than just the core. This proved valuable in that it excluded a large number of field giants that confused the location of the subgiant branch and eliminated the controversial second clump from the discussion as a random projection of field stars. The note of caution that underlies this claim is that two of these stars have radial velocities consistent with membership but are excluded because their abundances are inconsistent with those of the cluster. If some form of anomalous evolution has the ability to make normal cluster stars appear metal-rich because of mass transfer, mixing, or some unknown phenomenon, these stars should be revisited. However, for our purposes, their exclusion is reasonable.

Comparison of the cluster CMD to isochrones that bracket the derived $[\text{Fe}/\text{H}]$ produces a set of parameters and discrepancies indicating that neither $[\text{Fe}/\text{H}]$ is ideal but that NGC 2243 lies at an intermediate to that of the sets tested. The final, best-fit parameters are $m - M = 13.15 \pm 0.10$ at an age of 3.8 $\pm$ 0.2 Gyr. As always, it cannot be overemphasized that these estimates are tied to a specific set of isochrones generated using a specific conversion between the theoretical and observational plane. In a relative sense, the data confirm past analyses using cluster morphology that NGC 2243 is approximately the same age as M67 but younger than Mel 66. The data should be on the same scale as the clusters analyzed in previous papers in this series.

Given our results for NGC 2243, the cluster is located at a galactocentric distance interior to 11 kpc but at the edge of the galactic discontinuity. A differential comparison between NGC 2243 and Ber 29 has been undertaken because the latter cluster now represents the most distant open cluster with a supposedly reliable $[\text{Fe}/\text{H}]$ based on spectroscopy. Unfortunately, the spectroscopic abundances differ by 0.3 dex, despite having overlapping 1 $\sigma$ error bars, making the interpretation of the distant galactic gradient an exercise in personal bias. If one believes in a uniform gradient over a distance of 17 kpc, the high $[\text{Fe}/\text{H}]$, when coupled with Saurer 1, forces the beholder to dismiss the clusters as anomalies unrepresentative of the real disk (Carraro et al. 2004). Adoption of the low metallicity is consistent with the claim of a linear galactic gradient (Tosi et al. 2004) but leaves no explanation for Saurer 1. An even simpler solution that is consistent with the higher metallicity for Ber 29 and Saurer 1 is that there is no significant gradient beyond 10.5 kpc, as found by Twarog et al. (1997). The current reality is that if these two cluster have abundances typical of clusters near 11 kpc, it is intriguing, but hardly definitive evidence for any claim regarding the nature of the disk at galactocentric distances near 20 kpc. More and better data are needed both at large distance and in the key region bracketing 10 kpc.

Given the similar morphology of NGC 2243 and Ber 29, we can place some constraints on the differential properties of the two clusters because of the significant improvement in reddening estimation for Ber 29. The reddening maps of Schlegel et al. (1998) coupled with the spectroscopic data of Carraro et al. (2004) imply that Ber 29 has $E(B - V)$ below 0.094. If we adopt this limit as the true value for the cluster and assume that Ber 29 has $[\text{Fe}/\text{H}]$ identical to NGC 2243, a differential comparison of the two clusters’ CMDs implies $m - M = 16.15$ for Ber 29 and an age slightly younger than NGC 2243. Any attempt to make Ber 29 significantly more metal-poor than NGC 2243 would require that Ber 29 be older than NGC 2243 and/or that the reddening estimate for Ber 29 be raised above the limit. The derived parameters for Ber 29 are in surprisingly good agreement with those of Tosi et al. (2004) and, when coupled to the success of the early analysis of NGC 2243 by Bonifazi et al. (1990) in comparison with the current investigation, the convergence of the results is growing evidence of the power of the technique of CMD synthesis in generating reliable results in the absence of more direct observational data. Adjusting the age estimate for Ber 29 if $[\text{Fe}/\text{H}] = -0.44$ leads to 2.8 Gyr.

However, spectroscopic data (Carraro et al. 2004) indicate that Ber 29 does not have scaled-solar abundances and, unlike NGC 2243, has some light-$\alpha$–enhanced abundances. If we choose to compare the cluster with the available isochrones with the closest match to this effect, the age estimates increase by approximately 10% but, more importantly, the agreement between the location and luminosity of the giant branch and clump for $[\text{Fe}/\text{H}] = -0.38$ is excellent, in sharp contrast with the results for NGC 2243. The apparent modulus for Ber 29 rises slightly to $m - M = 16.25$. On the basis of the internal consistency of the comparisons made above, it would be difficult to assign an $[\text{Fe}/\text{H}]$ as low as $-0.8$ to Ber 29; all of our results indicate that the value of $-0.5 \pm 0.1$ is the most probable.
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