NGC 2419, M92, and the Age Gradient in the Galactic Halo

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ABSTRACT

The WFPC2 camera on HST has been used to obtain photometry of the low-metallicity ([Fe/H] = −2.14), outer-halo globular cluster NGC 2419. Our color-magnitude diagram in (V, V − I) reaches \( V_{\text{lim}} \approx 27.8 \), clearly delineating the subgiant and turnoff region and about three magnitudes of the unevolved main sequence. A differential fit of the NGC 2419 CMD to that of the similarly metal-poor ‘standard’ cluster M92 shows that they have virtually identical principal sequences and thus the same age to within 1 Gyr. Previously published studies of many other low-metallicity globular clusters throughout the Milky Way halo show that they possess this same age to within the \( \sim 1 \) Gyr precision of measurement. The addition of the remote-halo object NGC 2419 to this list leads us to conclude that the earliest star (or globular cluster) formation began at essentially the same time everywhere in the Galactic halo throughout a region now almost 200 kpc in diameter. Thus for the metal-poorest clusters in the halo there is no detectable age gradient with Galactocentric distance. To estimate the absolute age of NGC 2419 and M92, we fit newly computed isochrones transformed through model-atmosphere calculations to the \((M_V, V - I)\) plane, with assumed distance scales that represent the range currently debated in the literature. Unconstrained isochrone fits give \( M_V(RR) \approx 0.55 \pm 0.06 \) for both clusters, and a resulting age of 14 to 15 Gyr. Incorporating the full effects of helium diffusion would further reduce this estimate by \( \sim 1 \) Gyr. The first reports of Hipparcos parallax measurements for the lowest-metallicity subdwarfs suggest that the distance scale could be as bright as \( M_V(RR) = 0.15 \) for [Fe/H] \( \approx -2 \), which would require the cluster ages to be less than 10 Gyr; however, the isochrone fits for a distance scale this extreme leave several serious problems which have no obvious solution in the context of current stellar models.

Subject headings: Stellar Systems: Globular clusters
1. Introduction

When did the halo of the Milky Way begin to form, and how long did it take? The possible models for halo formation are still bounded by the two classic extremes of Eggen et al. (1962 = “ELS”, in which the halo stars and globular clusters condense out of a rapid, monolithic collapse of the protogalaxy) and Searle & Zinn (1978, in which the Galaxy assembles piecemeal over a much longer period from small, initially independent gas clouds).

The best-explored route to answering these questions has been through the age calibration of the Galactic globular clusters (GGCs). Obtaining accurate and precise measures of their absolute ages, and their dispersion in ages, is well known to be a challenging problem which strongly couples both observation and theory. Some discussions assert that the age dispersion is several Gyr, which would argue strongly against any pure fast-collapse model of formation (e.g. Chaboyer et al. 1996a; Sarajedini & King 1989; Salaris et al. 1993; Lee et al. 1994). Other studies employing a more selected set of the best available observations (e.g. Stetson et al. 1996 [hereafter SVB]; VandenBerg et al. 1990, 1996 [hereafter VBS90, VBS96]; Durrell & Harris 1993; Richer et al. 1996; Salaris & Weiss 1997), favor the interpretation of an age distribution with a narrow (< 1 Gyr) peak and a long, sparsely populated tail to younger ages, which would be more consistent with an ELS-style collapse. An important recent development has been the refinement of methods for precise measurement of age differences among clusters independently of distance and reddening (VBS90; VBS96; Sarajedini & Demarque 1990; Chaboyer et al. 1996a). With high-precision photometry at its current limits, it is now possible to determine relative cluster ages to within ±0.5 Gyr, and even narrower limits ultimately lie within reach (see SVB).

The interpretive models continue to evolve with the data. Sandage (1990) has reformulated the original ELS picture to allow for a spectrum of density fluctuations within the protohalo. Conversely, other authors including Zinn (1993), Lee (1993), and van den Bergh (1993) have extended the basic Searle-Zinn view to raise the possibility that much of the halo might have accreted later in the form of comparatively few, large dwarf galaxies. In addition, it has become increasingly apparent that the Milky Way halo clusters define clumpy regions within phase space (e.g. Rodgers & Paltoglou 1984; Zinn 1993; Majewski 1994; van den Bergh 1994; Johnson et al. 1996; Lynden-Bell & Lynden-Bell 1995; Fusi Pecci et al. 1993) which may be the relics of major accretion events. The Sagittarius system that we now see being disrupted along with its small retinue of clusters (e.g. Ibata et al. 1997, Da Costa & Armandroff 1993) would then be only the most recent such infall event. More direct evidence for several possibly distinct epochs of cluster formation can be found in the convincing demonstrations (e.g., Gratton & Ortolani 1988; Stetson et al. 1989; Bolte 1989;
Green & Norris 1990; Buonanno et al. 1990, 1993; Sarajedini 1997) that at least a few clusters in the mid-halo region are substantially younger — sometimes by as much as 30% — than the mean age of the GGCs.

A key question capable of strongly influencing the competing models is the existence or absence of any age gradient in the Galactic halo: does cluster age depend clearly and systematically on Galactocentric distance? Searle & Zinn (1978), Zinn (1993), and Lee et al. (1994) build a case based on horizontal-branch morphology and cluster kinematics that the clusters formed over a progressively longer spread of times at larger Galactocentric distance, and thus that the mean cluster age should decrease with increasing $R_{gc}$. However, truly direct age measurements must be obtained through photometry of deeper levels in the color-magnitude diagram (CMD), i.e. the turnoff and unevolved main-sequence regions. With the HST cameras, age measurements from main-sequence photometry are now possible for even the most remote known Milky Way halo clusters. The very oldest systems in the halo are, by most available evidence, most likely to be the globular clusters of lowest metallicity (e.g., VBS96). Thus by a careful study of these clusters, which are found everywhere in the halo, we may obtain a strong lower limit to the true age of the Galaxy. Similarly, the age range among these same low-metallicity clusters gives us an excellent way to estimate when the different parts of the halo began star formation.

This paper is the first in a series of HST color-magnitude studies for the globular clusters in the outermost halo of the Milky Way. In this paper, we present an age analysis of the outermost-halo, low-metallicity cluster NGC 2419 (= C0734+390; $\alpha_{2000} = 7^h38^m05^s5$, $\delta_{2000} = +38^\circ52'55''.7$; $\ell = 180^\circ4$, $b = +25^\circ2$; $R_{gc} \sim 90$ kpc; see Harris 1996). In subsequent papers, we will present CMD analyses for the other five clusters at $R_{gc} > 80$ kpc (Palomar 3, 4, 14, Eridanus, and AM-1). Since most of these clusters exhibit the “second-parameter” horizontal-branch anomaly in its most extreme form, in their totality they will provide a stringent test of the formation scenarios mentioned above.

In certain respects, NGC 2419 is arguably the most unusual cluster in the outer Milky Way halo. It is much more luminous than the other outer-halo clusters, with an absolute visual magnitude $M_V^i \simeq -9.5$ (Harris 1996) that places it among the five most luminous clusters in the Galaxy. Its metallicity of $[Fe/H] \simeq -2.14$ (Zinn 1985, Suntzeff et al. 1988) puts it clearly in the most metal-poor group of known GGCs. But in contrast to the other outer-halo globulars and most of the dwarf spheroidal galaxies that inhabit the same region of space, NGC 2419 has a horizontal branch which is rather uniformly populated from blue to red like other classic low-metallicity objects such as M15, M92, and M68. Thus its HB morphology is not strikingly unusual for its metal abundance. However, NGC 2419 cannot simply be interpreted as (for example) a metal-poor cluster that might have formed initially
deep in the inner halo and then migrated out on a highly elliptical orbit. Its very large core radius and half-mass radius \((r_c \sim 9 \text{ pc}, r_h \sim 19 \text{ pc})\) are entirely characteristic of the most remote clusters and unlike any inner-halo object (typically \(r_c \sim 1 \text{ pc}, r_h \sim 3 \text{ pc}\) for clusters at \(R_{gc} \sim R_{\odot}\)). These features along with the well known systematic increase of \(r_h\) with Galactocentric distance (e.g. van den Bergh et al. 1991; van den Bergh 1995a) demonstrate that it belongs to the outermost-halo group as much as any of the other outer-halo clusters. Since it is at a very different place in the halo from all the other lowest-metallicity clusters, NGC 2419 holds considerable interest for the Galactic age gradient question.

The first color-magnitude study of NGC 2419, by Racine & Harris (1975) from photographic plates, was barely sufficient to reveal the nature of the brighter parts of the CMD (the giant branch and horizontal branch), but fainter features such as the turnoff and subgiant stars were hopelessly beyond reach of the technology of the time. The first CCD-based photometry of the cluster (Christian & Heasley 1988) reached three magnitudes deeper and thus just barely resolved the turnoff stars. Their data were sufficient at least to indicate that NGC 2419 was similar in age to the “normal”, inner-halo globular clusters to within a few Gyr. Our new HST photometry, as will be seen below, reaches considerably deeper still, and now allows us to carry out an age comparison that is as precise as for any other cluster in the Milky Way.1

In brief, the main purpose of this paper is to estimate the relative age of NGC 2419 in comparison with normal nearby clusters of similar metal abundance. In §2, we briefly describe the CMD; in §3, we estimate its age relative to M92; in §4, we present sample isochrone fits to both NGC 2419 and M92 for a new set of stellar models and theoretical transformations, under different assumptions for the Population II distance scale; and in §5, we discuss briefly the significance of these results for the early history of the Galaxy.

2. Color-Magnitude Diagrams

In Figure 1, we show the composite color-magnitude array (CMD) for NGC 2419 as derived from our Cycle 4 HST imaging with the WFPC2 camera. The complete data reduction and calibration are described in Stetson et al. (1997). To isolate a sample of stars which most narrowly defines the cluster sequences that we are particularly interested in (the lower giant branch, subgiant branch, and main sequence), we have selected from the Stetson et al. (1997) dataset all the measured stars farther than a projected radius of 1

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1Our study employs data from Cycle 4 programs 5481 and 5672. Preliminary discussions of this work are given in Harris et al. (1995), Hesser (1995), Hesser et al. (1996a,b), and Richer et al. (1996).
From cluster center; inside this radius, the photometric scatter increases noticeably because of crowding and higher background. We further eliminated individual stars with especially uncertain photometry ($\sigma(V)$, $\sigma(V-I)$, or $\chi$ which stand off by more than three standard deviations from the mean values at any $V$ magnitude). This culling procedure left a final sample of 17275 stars.

To define the principal sequences of the CMD, we took mean magnitudes and colors in 0.1– or 0.2–mag bins, with three iterations of outlier rejection. For the sparsely populated bright end ($V < 21$) of the red-giant branch (RGB) we added the stars from within $R < 50''$ (not shown in Fig. 1) to help define the RGB locus more accurately. The mean lines from the inner region, for the bright stars that are least affected by crowding ($V \lesssim 24$), are identical with those from the outer region shown here to well within $\pm 0.01$ mag in color at every point; however, for the fainter main-sequence stars, the data from the inner region become severely incomplete for $V \gtrsim 25$ and we rely on only the mean points from the outer region to define the faint end of the CMD. The mean points are displayed in Figure 2 and listed in Table 1: in the Table, the first group of entries gives the mean points for the HB and the remainder give the giant branch and main sequence. The number of stars in each bin is listed in the last column. Clearly, the accuracy and depth of the HST photometry, combined with the very large sample of stars, permit the cluster sequences to be defined to a level of precision that is fully comparable with other, much nearer, clusters that have been well studied from the ground. We note in passing that the zeropoints of the magnitude and color scales are tied to the HST ($V, I$) photometric system, but rely on a preliminary tie-in to ground-based photometry of the same fields and may therefore contain a residual offset of up to $\pm 0.02$ mag. This point should be kept in mind for the later discussion on the absolute reddening and distance of NGC 2419 (§4.3 below). However, this will not affect the differential analysis of NGC 2419 relative to other, “standard,” metal-poor clusters, to which we will pin its age measurement (§4).

Our new CMD confirms the basic conclusions of the previous studies (Racine & Harris 1975; Christian & Heasley 1988) that NGC 2419 strongly resembles other very metal-poor objects like M92 and M15, with its steep giant branch and predominantly blue horizontal branch that extends, with obvious gaps, to very high temperature. Further detailed discussion of the CMD morphology is given by Stetson et al. (1997). Here, we concentrate on its age analysis.
3. Relative Age Estimation

A well known method for precise determination of relative ages of globular clusters is to compare the positions of age-sensitive features in the CMD, such as the color difference between the main-sequence turnoff (MSTO) and the base of the red-giant branch, or the magnitude difference $\Delta V(MSTO - HB)$ between the MSTO and horizontal branch (HB). The color-difference approach was first fully employed by VBS90 (also see Sarajedini & Demarque 1990); since the color differences being looked for in the CMD are at the level of a few hundredths of a magnitude, precise definitions of the CMDs are necessary for this method to give reliable results. A principal conclusion from most of these studies was to show that the most metal-poor clusters in the halo (those with $[\text{Fe/H}] \sim -2$) have ages that were indistinguishable at the level of $\pm 1$ Gyr or less. Although Chaboyer et al. (1996b) have argued on the basis of $\Delta V(MSTO - HB)$ that M68 is distinctly younger than M92, others such as Carney et al. (1992a) and VandenBerg (1997) have used the same approach to suggest these two clusters are nearly coeval. Rather than relying on a single age-sensitive parameter which may in practice be hard to define accurately for a given dataset, we believe it is important to employ all relevant parts of the CMD in an age comparison. Our new data allow us to define the fiducial sequences in the critical turnoff and subgiant regions narrowly enough to perform similar tests on NGC 2419.

We can compare NGC 2419 directly only with clusters that also have well defined CMD’s in the $(V - I)$ plane, whereas most previous photometry is in $(B - V)$ (cf. VBS90; SVB). Fortunately, new data in $(V - I)$ are rapidly becoming available for many clusters including M92, which we will use as our fiducial near-halo, low-metallicity cluster. M92 has been the point of comparison for several differential-age studies of the low-metallicity clusters with excellent photometry, including M15, NGC 4590, NGC 7099, and NGC 6397 (VBS90; SVB; Salaris et al. 1997). The metallicity of M92, from a mean of several recent measurements (e.g. Zinn 1985; Beers et al. 1990; Peterson et al. 1990; Sneden et al. 1991; Shetrone 1996), is $[\text{Fe/H}] = -2.25$. The uncertainty (precision) of the mean metallicity quoted in each of these studies is typically $\pm 0.06$ dex, but this value in most cases represents only the internal precision of the particular method for measuring line strengths. A better estimate of the true external uncertainty (accuracy) of the metallicity can be obtained from the mutual agreement among different studies, which for the five M92 analyses listed above is $\sigma[\text{Fe/H}] = \pm 0.15$ dex (rms scatter). Thus for M92 we estimate the uncertainty in the mean metallicity to be near $\pm 0.07$ dex. By contrast, for NGC 2419 the metallicity measurement relies principally on one study (Suntzeff et al. 1988), which gives $[\text{Fe/H}] = -2.14$ from low-dispersion measurements of Ca and Mg line strengths for eight stars. We adopt an uncertainty of $\pm 0.15$ dex, assuming it to be comparable to any of the single studies quoted above. The difference between the two clusters, $\Delta[\text{Fe/H}](N2419-M92) =$
0.11 ± 0.17, is small enough that we can safely treat them as similar.

In Figure 3, we show the direct CMD comparison between M92 and NGC 2419, using the new ground-based \((V, V-I)\) photometry of M92 by Johnson & Bolte (1997). The mean points for M92 are listed in Table 2 (where the first 8 entries give the points for the HB, and the remaining entries the giant branch and main sequence). In Fig. 3, the mean points defining NGC 2419 were shifted by the amounts \(\Delta V, \Delta(V-I)\) shown in the figure so that the main sequences of the two clusters coincide at a point 0.05 mag redder than the turnoff, following the prescription of VBS90.

By hypothesis, the horizontal shift \(\Delta(V-I)\) represents the reddening difference between the two clusters; thus, \(E(V-I)_{N2419} = E(V-I)_{M92} + 0.14\). Similarly, the vertical shift \(\Delta V\) should represent their difference in distance moduli. The value \(\Delta V = 5.28 ± 0.04\) that we obtain by matching their main sequences at the fiducial point just below the MSTO is, notably, quite similar to what we would have found by matching only their horizontal-branch levels: for M92, four high-quality photometric studies of the RR Lyraes and the HB give \(V(HB) = 15.15 ± 0.03\) (Carney et al. 1992b; Cohen & Matthews 1992; Sandage 1969; Buonanno et al. 1983), whereas for NGC 2419, our new data give \(V(HB) = 20.45 ± 0.03\) from the HB stars nearest the RR Lyrae region. The difference between the two is then \(\Delta V(HB) = 5.30 ± 0.04\), in close agreement with the offset employed in Fig. 3.

The isochrones (described in more detail in §4 below) used for calibrating the differential ages are shown in Figure 4. The color difference between the turnoff and lower giant branch, for the metallicity of M92 or NGC 2419, changes at the rate \(\Delta(V-I)/\Delta \tau = 0.013\) mag/Gyr over the 12- to 18-Gyr age range shown; this ratio is quite insensitive to the chosen luminosity level on the giant branch, since the isochrone lines are nearly parallel there. The age sensitivity in the \((V-I)\) plane is similar to \((B-V)\), for which \(\Delta(B-V)/\Delta \tau ≃ 0.012\) mag/Gyr at the same metallicity (VBS90). From Fig. 3, we find that the observed color difference between M92 and NGC 2419 is indistinguishable from zero at any level from the base of the RGB up to the HB \(\sim 2\) mag higher. We therefore adopt \(\Delta(V-I) = 0.00 ± 0.006\) mag, where the quoted error is simply the precision in color with which we can perform the sliding fit between the two colors. In terms of age, this gives us \(\Delta \tau = 0.0 ± 0.5\) Gyr.

A highly complementary way to use the differential CMD fit is to employ the magnitude difference \(\Delta V\) between the main-sequence turnoff and the horizontal branch. Since \(\Delta V\) is a monotonically increasing function of cluster age, any age difference between the two clusters in Fig. 3 would be revealed as a vertical offset between the HB levels, once the MSTO regions are superimposed. That is, from the CMD fit between the two clusters, we estimate the doubly differential quantity \(\Delta(\Delta V)\); if the fiducial sequences of the two clusters are as
well established as they are here, this quantity can readily be measured to within a vertical uncertainty of \( \pm 0.05 \) mag. It is apparent from Fig. 3 and also from the \( \Delta V (HB) \) value calculated above that, to within this uncertainty, the offset \( \Delta (\Delta V) \) between NGC 2419 and M92 is also zero. The age sensitivity of \( \Delta V \) is \( \simeq 0.073 \) mag/Gyr for \( \tau \sim 15 \) Gyr (VBS96; see their Figure 4), which then translates into \( \Delta \tau = 0.0 \pm 0.7 \) Gyr, in close agreement with the color-shift estimate.

In short, NGC 2419 \textit{has essentially the same age as M92} if their compositions are as similar as they appear to be. By inference, NGC 2419 has the same age as the other low-metallicity-age clusters in the Galactic halo to within the typical \( \sim 1 \) Gyr precision of the differential-age method. These same objects are highly likely to be the oldest globular clusters (VBS90; VBS96; Chaboyer \textit{et al.} 1996a) as well as the oldest visible objects in the Galaxy for which we can accurately measure ages. The implication is clear: we are immediately forced to the conclusion that \textit{globular cluster formation began in the outermost halo of the Galaxy at just as early a stage as it did in the inner parts of the halo.}

The only alternative we can suggest for this conclusion is that the two clusters being compared here (NGC 2419 and M92) have \textit{large, selective abundances differences} ([Fe/H], helium, or \( \alpha \)--elements) which are working in conspiracy with an age difference to produce the identical CMD morphologies that we see. If the abundance difference is in metallicity, a 0.4-dex offset in [Fe/H] would be required to mask a 1-Gyr age difference in the \((V - I)\) plane. Such a difference is too large to be accommodated by the [Fe/H] measurements summarized above. A 1-Gyr age decrease could also be produced by a helium abundance increase of \( \Delta Y \simeq 0.05 \); again, existing data of several kinds (see VBS96 for extensive discussion) make this option highly unlikely for an object this metal-poor. The most plausible route to achieve an age difference may be in the \([\alpha/Fe]\) ratio, for which a 0.3-dex change in \( \alpha \) would shift the deduced age by \( \simeq 1 \) Gyr. If NGC 2419 is to be younger than M92, then it would need to have \([\alpha/Fe] \gtrsim 0.6\) if M92 has \([\alpha/Fe]\) at the ‘normal’ level of +0.3. Additional comments on this possibility will be made below.

4. \textbf{Isochrone Fitting and Absolute Age Estimation}

Determining the \textit{absolute} age of NGC 2419 is then equivalent to asking: What is the age of M92? As will be seen below, this latter cluster provides the most incisive comparison between the observations and the theoretical stellar models because the foreground reddening, which is nearly negligible for M92, is essentially eliminated as a free parameter for isochrone matching and other comparisons with theoretical modelling.
Given the well known uncertainty over RR Lyrae luminosities and the Population II distance scale – a controversy which has been heightened by the recently published Hipparcos parallaxes for subdwarfs and Cepheids (e.g. Reid 1997; Feast & Catchpole 1997) – we will defer a full analysis of absolute ages. In this paper, we will present only sample isochrone fits which illustrate how the current stellar models match up with the actual clusters under different assumed distance scales. Since these stellar models, and their transformations into the observational \((M_V, V - I)\) plane, will be used in our subsequent papers on the outer-halo clusters, we first briefly describe their construction.

4.1. Model Calculations

VandenBerg et al. (1997) have recently computed a large grid of evolutionary sequences for low-mass, metal-poor stars that extend from the Hayashi line through the main-sequence and red-giant phases to the zero-age horizontal branch (ZAHB). For each of the adopted \([\text{Fe/H}]\) values between \(-2.3\) and \(-0.3\), tracks were generated for \(\alpha/\text{Fe} = 0.0, 0.3, \) and \(0.6\), where the “\(\alpha\)” elements include O, Ne, Mg, Si, S, Ar, Ca, and Ti. Based on the Zhao & Magain (1990) and Dufour (1984) investigations, the abundances of Na and Cl were assumed to obey the relations \([\text{Na}/\text{Fe}] = [\text{Cl}/\text{Fe}] = [\alpha/\text{Fe}]\). Aluminum and manganese were assumed to follow \([\text{Al}/\text{Fe}] = -[\alpha/\text{Fe}]\) and \([\text{Mn}/\text{Fe}] = -0.5 [\alpha/\text{Fe}]\) to approximate roughly the available data (e.g. Wheeler et al. 1989; Magain 1989). Finally, solar number abundance element-to-iron ratios were adopted for C, N, Cr, and Ni (cf. Wheeler et al. 1989), and the initial helium contents were chosen to be consistent with \(Y = 0.235 + 1.936 Z\); for the \([\text{Fe/H}]\) values of concern here (NGC 2419 and M92), this assumption produces a negligible increase in \(Y\) over the cosmological value.

Opacities similar to those reported by Rogers & Iglesias (1992) for temperatures \(\geq 6000\) K and to those given by Alexander & Ferguson (1994) for lower temperatures were computed for the adopted element mixes (see VandenBerg et al. 1997 for details). The relatively minor improvements to the H-burning nuclear reaction rates favored by Bahcall & Pinsonneault (1992) and a treatment of Coulomb interactions in the equation of state represent the only substantive changes to the stellar evolution code, compared with that described by VandenBerg (1992, and references therein). All calculations assumed a value of \(\alpha_{\text{MLT}} = 1.89\) for the usual mixing-length parameter, to be consistent with the requirements of a Standard Solar Model, and the surface pressures were derived by integration of the hydrostatic equation in conjunction with the Krishna Swamy (1966) \(T - \tau\) relation. Using model atmospheres to derive the boundary pressures would clearly have been the preferred approach, but such calculations for the required wide range in gravity, effective temperature,
[Fe/H], and [$\alpha$/Fe] are not yet available. In spite of this deficiency, Vandenberg et al. (1997) demonstrate that the predicted $T_{\text{eff}}$ scale of their models appears to agree quite well with existing observational constraints. Isochrones on the theoretical plane were obtained by interpolation in these tracks with the methods described by Bergbusch & Vandenberg (1992).

### 4.2. Model Transformations to the Observational Plane

The approach we adopt to convert the theoretical isochrones ($M_{\text{bol}}, T_{\text{eff}}$) to the observational plane ($M_V, V - I$) is slightly different from that used in other recent discussions, such as VBS96, where the transformation to observed quantities was accomplished with semi-empirical bolometric corrections and color-$T_{\text{eff}}$ relations. Here, we take the more classical route of transforming the isochrones as strictly as possible through stellar-atmosphere models; i.e., we carry both the observations and the theory as far as they can go on their own ground, and only then do we compare them directly.

Values of $\log g$ were found at 50 K increments in $T_{\text{eff}}$ for $T_{\text{eff}} > 5000$ K, at 100 K increments for $T_{\text{eff}} < 5000$ K, and at the turnoff (hottest) temperature, for each of the sets of isochrones through cubic spline interpolation. The opacity distribution functions (ODFs) were found for the isochrone abundances by interpolation in ODFs with abundances of $-3.0, -2.0, -1.0$ and $-0.5$. The Marcs program (Gustafsson et al. 1975) was then used to calculate model atmospheres for each of these ($T_{\text{eff}}, \log g$) points. The H/He/metals ratios used in the model atmosphere and synthetic spectrum calculations were the same as those employed in the stellar interior work. The models calculated for enhanced alpha-element abundances, i.e. [$\alpha$/Fe] = +0.6 and +0.3, used the same ODFs as those with [$\alpha$/Fe] = 0.0. However, the $P_g - P_e - T$ relationships were calculated in the models allowing for the different [$\alpha$/Fe] values.

The model atmospheres were then used for synthetic spectrum calculations, again allowing for the different alpha-element abundances. The microturbulent contribution to the Doppler broadening velocity was chosen to vary with $\log g$ by interpolating in the values 1.0 km/sec at $\log g = 4.5$; 1.7 km/sec at $\log g = 1.5$; and 2.5 km/sec at $\log g = 0.5$. The line list was an improved version of that used by Bell et al. (1994) and Tripicco & Bell (1995), who give examples of fits to the spectra of the Sun and Arcturus.

The synthetic spectra were multiplied by the pass band sensitivity functions and were converted to magnitudes to give the surface brightness magnitudes of the models. The sensitivity functions were the Bessell (1990) ones for $UBVRI$ and the WFPC2 filters.
F555W and F814W. The magnitude zero points were found by requiring the magnitudes of the Dreiling & Bell (1981) Vega model to match the fluxes given by Hayes (1985), then finally by matching them to Bessell’s (1983) \((V, V - I)\) observational data for Vega. Normalizing the Dreiling-Bell model to the Hayes fluxes required a \(-0.004\) magnitude adjustment to the model \((V - I)\) colors. The Bessell data have also been used for WFPC2 zero points by Holtzman et al. (1995).

The Bessell \(V\) magnitude results are very similar to those calculated for the F555W pass band: the difference in absolute visual magnitude for virtually all the models is \(< 0.01\) mag. This is in agreement with earlier WF/PC calculations for these pass bands by Edvardsson & Bell (1989). The \(I\) band and the F814 magnitudes also agree very well, again following the results of Edvardsson & Bell. This agreement is somewhat surprising, in view of the difference in sensitivity function profiles, in the detectors, and in the effect of \(H_2O\) and \(O_2\) telluric lines on ground-based data in this spectral region.

The isochrones are based upon a solar apparent visual magnitude of \(V = -26.73\), which gives \(M_V = 4.84\), and an adopted solar bolometric correction of \(-0.12\). The \(T_{\text{eff}}\) and visual surface brightness of a solar model and this bolometric correction were used to find the bolometric corrections of the cluster models from their \(T_{\text{eff}}\) and visual surface brightnesses. The zero point of the bolometric correction scale consequently rests on the visual surface brightness of this solar model. We note that Bell & Tripicco (1996) use the angular diameters of the Sun and Vega, the visual surface brightnesses of their models and the apparent magnitude of Vega to derive \(V = -26.77\) for the Sun. This value is consistent with that derived from solar fluxes and from direct observation of the Sun \((V = -26.75 \pm 0.06; \textit{cf.} \) Hayes 1985\). However, uncertainties in the angular diameter of Vega, the solar model and solar observations must translate into an uncertainty of perhaps \(\pm 0.05\) mag in the bolometric corrections of field subdwarfs and consequently into comparisons of isochrones and cluster main sequences. The visual surface brightness magnitudes of the metal-poor giant models are brighter than those of Population I models of the same \(T_{\text{eff}}\). This brightening is due in part to the smaller line blocking and in part to the differences in model structure, which cause the continuous flux of the metal-poor models to be greater. This effect in turn causes the bolometric corrections for the metal-poor models to be smaller than those of the Population I models. These changes also cause the \((V - I)\) colors of the metal-poorer models to be slightly redder than those of the metal-richer models of the same \(T_{\text{eff}}\).

The properties of the solar model \((T_{\text{eff}} = 5760 \text{ K}, \log g = 4.44)\) that was used to set the zero point of the bolometric correction are discussed by Bell & Tripicco (1996). This model is fainter in \(V\) than that used by VandenBerg & Bell (1985, hereafter VB85), owing
to the addition of further line and continuous opacity sources which are dependent on metal abundance. These opacity sources have less effect at lower metallicity and so the $V$ magnitudes of the present metal-poor models agree more closely with the VB85 ones than do the solar models. Consequently the bolometric corrections of the metal-poor models are $\sim 0.1$ mag larger in an absolute sense than those of VB85, causing a decrease of $\sim 1.5$ Gyr at a fixed turnoff luminosity. Further discussion of this point can be found in VandenBerg (1997).

The $(V - I)$ colors of the giant branch models are slightly bluer than those of the dwarfs at the same $T_{\text{eff}}$, by an amount which increases with decreasing $T_{\text{eff}}$. The cooler $\alpha = +0.6$ models have somewhat bluer colors than those with $\alpha = 0.0$. The $(V - I)$ colors for the [Fe/H] = −2.14 isochrones are very similar to those published by VB85 for dwarfs for [Fe/H] = −2.0 and by Bell & Gustafsson (1989) for giants of the same abundance. The surface abundances of some metals, particularly C (Bell et al. 1979), alter as stars evolve along the giant branches of some metal-poor globulars. However, we have not allowed for this, since the effect on broadband colors is expected to be small.

4.3. The Age of M92 and NGC 2419: Old or Young?

The transformed isochrones can now be superimposed on the CMD for each cluster. The models shown here have a composition [Fe/H] = −2.14, $Y = 0.235$, and $[\alpha/H] = 0.3$. The moderate $\alpha$-enhancement is supported by direct spectroscopic measurement of oxygen abundances in M92 and the great majority of other metal-poor clusters (Carney 1996; Sneden et al. 1991), though in a few other objects (notably M13; see Pilachowski & Armandroff 1990; Kraft et al. 1997) an $[\alpha/Fe]$ ratio closer to the solar value is observed.

In Figure 3, we show the match between the transformed isochrones and the M92 CMD, where the distance scale is set essentially by fitting the model ZAHB at the level of the M92 horizontal branch. The cluster CMD is then shifted horizontally until the unevolved main sequence matches the models. If the model colors are correct, the color shift subtracted from the cluster mean points should then represent the reddening. Our deduced shift of $\delta(V - I) = 0.013 \pm 0.01$ (estimated uncertainty of fit) corresponds to $E(B - V) = 0.01 \pm 0.01$, which is in close agreement with the normally used value for M92 of $E(B - V) = 0.02$ (Sandage 1969; Harris 1996) and is consistent with the idea that the model colors do not need further arbitrary zero-point adjustment.

The resulting distance modulus, $(m - M)_V = 14.60 \pm 0.06$, corresponds to a horizontal-branch luminosity at the level of the RR Lyraes of $M_V(HB) = 0.55$. This level
agrees to within 0.1 magnitude with: (a) previous calibrations from subdwarf parallaxes (e.g. VBS96; Sandquist et al. 1996); (b) ZAHB models (Lee et al. 1990; Dorman 1992); (c) Cepheid distances to the RR Lyrae populations in Local Group dwarf galaxies including the LMC, SMC, and IC 1613 (van den Bergh 1995b; Walker 1992; Saha et al. 1992); and (d) the distance modulus to the moderately metal-poor cluster NGC 6752 (at [Fe/H] = −1.6) calibrated through its white-dwarf sequence and nearby field white dwarfs (Renzini et al. 1996). It is, however, 0.1 − 0.2 magnitudes brighter than HB luminosities measured from (a) the Baade-Wesselink method (e.g. Carney et al. 1992a); (b) Cepheid-calibrated distances to the RR Lyrae in M31 (Fusi Pecci et al. 1996); and (c) statistical parallax of field RR Lyraes (Layden et al. 1996). Recent Hipparcos parallaxes of a few blue-HB field stars (de Boer et al. 1997) give $M_V(\text{HB}) \sim 0.7 \pm 0.2$, a value which is consistent with any of the other methods listed above.

In Figure 6, the same isochrone fit is shown for NGC 2419. The resulting reddening estimate (again, under the assumption that the model colors along the main sequence are systematically accurate) is $E(V - I) = 0.145 \pm 0.01$ and thus $E(B - V) = 0.11 \pm 0.01$. To within its quoted uncertainty, this estimate agrees with the differential color shift from Fig. 3 added to the (small) reddening of M92. It is also consistent with the value of $E(B - V) = 0.10 \pm 0.05$ obtained by Christian & Heasley (1988) by CMD fitting to both M15 and M92 in the $(V, B - V)$ plane. The distance modulus of $(m - M)_V = 19.88 \pm 0.06$ gives $M_V(\text{HB}) = 0.57$, and a true distance for NGC 2419 of 81 kpc from the Sun or $\simeq 90$ kpc from the Galactic center.

For both clusters, the best-fitting age read off the isochrones is $(15 \pm 1)$ Gyr. VBS96 and VandenBerg (1997) obtained similar results from isochrone fitting in the $(B - V)$ plane, by using a semi-empirical color transformation procedure somewhat different from the model-atmosphere transformations that we employ here. A further reduction of $\lesssim 1$ Gyr might be obtained by incorporating a realistic amount of helium diffusion into the stellar models, as discussed by Proffitt & VandenBerg (1991), VandenBerg (1997), and Castellani et al. (1997). More drastic changes than this now seem very hard to achieve in a natural way within the context of the most recent models; see VBS96 and VandenBerg (1997) for more detailed discussion of the input physics.

The overall quality of fit of the isochrones to the cluster data, in both Figs. 5 and 6, is virtually identical with what we would have obtained under various other assumptions.

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2We note that the Layden et al. mean value of $M_V = 0.71 \pm 0.12$ at [Fe/H] = −1.6 would rise to $M_V \sim 0.61$ if the Sturch (1966) prescription for calculating the RR Lyrae reddenings were adopted. Normalizing this value to [Fe/H] = −2.2 using $\partial M_V/\partial [\text{Fe/H}] = 0.15$ (Carney et al. 1992a), we would obtain $M_V \simeq 0.52$ at the metallicity of M92, in good agreement with the present estimate.
For example, instead of setting the distance by matching the ZAHB to the cluster HB, we could have subtracted the (observationally known) reddening from the cluster mean points and then shifted it vertically until the main sequence fell in line with the models. Within the quoted uncertainties, the same answers emerge for the distance modulus and reddening. Still another approach that relies even more heavily on the correctness of the models would be to perform an unconstrained fit of the CMD to the models independently of other observational input: that is, we could find the distance modulus and reddening that give the best ‘global’ match of all features in the CMD to the isochrones (main sequence, subgiants, horizontal branch, and giant branch). The results are again the same as before to within the internal uncertainties of the method.

The concordance between the model isochrones and the real clusters continue to improve with advances in both the theory and the data, but residual discrepancies show up in three areas (Figs. 5 and 6): (a) the ZAHB model line should, ideally, lie $\sim 0.05 - 0.1$ mag fainter than the mean HB points at the RR Lyrae region to take account of post-ZAHB luminosity evolution (e.g. [Lee et al. 1990, Dorman 1992, Salaris et al. 1997]); (b) the theoretical RGB line runs nicely parallel to the observed giant branch but is consistently redder by $\Delta(V-I) \simeq 0.02 - 0.03$ mag; and (c) along the turnoff and subgiant region, the mean data points cross over two isochrone lines, starting approximately on the 16-Gyr line at the MSTO and finishing on the 14-Gyr line at the base of the giant branch. All of these discrepancies are at such a low level that we speculate that very small uncertainties in the photometric zeropoints, the reddening, the abundances, the isochrones themselves, and the model transformations (at the level of $0.01 - 0.02$ mag in each) may have conspired to leave the various offsets that we see.

Many other choices of parameters – distance modulus, reddening, $\alpha$–abundance, etc. – which differ only slightly from the ones shown above can be made, with quite plausible results. An exhaustive exploration of this parameter space will not be presented here, but as an illustration of the possibilities, we show another sample isochrone fit in Figure 7 for NGC 2419: here, the reddening and distance modulus have been deliberately chosen to produce the theoretically expected ‘ideal’ match strictly for both the horizontal branch (where the ZAHB is placed $\simeq 0.07$ mag fainter than the observed mean HB) and the unevolved main sequence (where the isochrone line runs exactly through the mean main-sequence points for the entire range $M_V > 4$). The best-fitting age is now 14 Gyr, and the remaining discrepancy in the fit has now been put entirely on the theoretical RGB, which stands redward of the real cluster by $\simeq 0.05$ mag. This solution requires a cluster reddening of $E(B-V) = 0.12$ and an RR Lyrae luminosity of $M_V(HB) = 0.50$. Overall, reasonable fits to the data can be found for isochrone shifts that differ from one solution to the next by $\pm 0.02$ mag in color and $\pm 0.1$ mag in luminosity. The corresponding (external) uncertainty
in the cluster age is then $\pm 2$ Gyr.

Salaris et al. (1997) provide another recent analysis of the ages of the most metal-poor clusters (M15, M68, M92), using isochrones from their independently calculated set of stellar models. By using the ZAHB to set the distance moduli, they employ only the deduced MSTO luminosity to estimate the cluster ages, and find all three clusters to lie in the range $(12 \pm 2)$ Gyr. Aside from details of the codes and opacity prescriptions, the principal differences between their models and those of VandenBerg et al. (1997) appear to be in the adopted abundances (Salaris et al. use a value $[\alpha/Fe] = +0.5$ which is on the upper end of the plausible range) and in the luminosities of the ZAHB models (the Salaris et al. HB models are brighter by $\sim 0.10 - 0.15$ mag). These effects generate most of the $\sim 2$ Gyr difference in ages that we find for the same clusters. Neither set of models includes diffusion (Proffitt & VandenBerg 1991; Castellani et al. 1997). Nevertheless, the comparison suggests that the true internal uncertainties in the models, given identical input parameters, are at the $\pm 1$ Gyr level (see Gratton et al. 1997 for a similar conclusion).

However, changes to the distance scale have recently been proposed that go well beyond the range discussed above. Reid (1997) has used new parallaxes of 15 low-metallicity subdwarfs from the Hipparcos database to fit the main sequences of five metal-poor globular clusters, thus calibrating their HB luminosities. For M5 and M13 (at [Fe/H] $\simeq -1.5$), he obtains $M_V(HB) \simeq 0.55$, quite similar to the levels obtained from the unconstrained isochrone fits that we discussed above. However, for M92, M15, and M68 (at [Fe/H] $\simeq -2.1$), he obtains $M_V(HB) = 0.15$, about 0.4 mag brighter. In Figures 8 and 9, we show the implications of a ZAHB luminosity this high. The best-fitting age would now be near 10 Gyr, extrapolating from the four isochrones plotted (or $\sim 9$ Gyr after accounting for helium diffusion). But the overall isochrone fit is obviously seriously discrepant in three ways: (a) This solution would require the models to have an arbitrary color adjustment of $\delta(V-I) \simeq 0.07$ mag on the main sequence even after the true cluster reddening is accounted for, in the sense that the predicted model colors are too blue by that amount. (b) The ZAHB model line is too faint by $\sim 0.4$ mag. (c) The RGB line stands off the cluster points by almost 0.1 mag. Curiously, this means that the model colors for the giants would be nearly correct as they stand, and that the main-sequence model colors would be the ones that require a large arbitrary redward correction. Normally, the model RGB colors are taken as the more easily adjustable because of their strong dependence on the modelling of convection.

Gratton et al. (1997) have also used Hipparcos parallax data for 7 low-metallicity subdwarfs to calibrate the distances and ages of several clusters; for the lowest-metallicity clusters, they find $M_V(HB) \simeq 0.2 - 0.3$, a level about halfway between our estimates.
and those of Reid (1997). Again using only the MSTO luminosity to calibrate the age, they derive \( t \sim (14 \pm 1) \) Gyr for the oldest clusters in their sample (M92, NGC 288, and NGC 6752, with the results somewhat dependent on which of several conversion models is adopted; see their Table 2).

These high estimated HB luminosities for M92 and the other low-metallicity clusters may turn out to be an artifact of the small number of stars in subdwarf samples, along with a variety of other biases such as the presence of binaries and the \([Fe/H] \) measurements themselves. These issues are discussed in a more recent analysis of the Hipparcos subdwarf parallaxes by Pont et al. (1997), based on a considerably larger sample of metal-poor stars and a more extensive analysis of biases including radial velocity data to detect binaries. Pont et al. (1997) derive \((m - M)_V = 14.67 \) and thus \( M_V(HB) = 0.48 \) for M92, a value quite similar to what we find purely from the isochrone fits (Fig. 3). In summary, the full impact of the new Hipparcos data, and the continuing improvements to the stellar models, has yet to be felt; nevertheless, we believe that an age in the generous range of 12 to 15 Gyr for the most metal-poor clusters in the Galaxy is well supported by the current mix of theory and observation.

5. Discussion and Summary

Our WFPC2 photometry for NGC 2419 allows us to define the CMD loci for this remote-halo, low-metallicity cluster to a level three magnitudes below the main-sequence turnoff. Our analysis of the CMD shows that it has the same age, to within \( \sim 1 \) Gyr, as M92 and other mid-halo clusters which have similarly low metallicity and color-magnitude morphology. For this low-[Fe/H] subgroup of clusters at least, we therefore find no detectable age gradient through the Galactic halo from \( R_{gc} \approx 7 \) kpc to 90 kpc (cf. Richer et al. 1996 and Salaris & Weiss 1997 for additional discussion). The clear implication is that all parts of the Milky Way protogalaxy began their earliest star formation at very much the same time.

The differential-age determinations that we have employed here may be vitiated by large differences in composition between NGC 2419 and M92, most notably in the \( \alpha \)-element ratios. No evidence for such differences was found by Suntzeff et al. (1988) from 7.4 Å-resolution blue spectra of nine giants in NGC 2419; nor did Carney (1996) find large differences between clusters, from his review of the bulk of the available evidence for halo and globular cluster stars. Nonetheless, until high-dispersion spectroscopic abundance analyses can be carried out for NGC 2419, abundance differences in the \( \alpha \)-elements cannot be ruled out definitively. If NGC 2419 is indeed younger than the inner-halo objects of
similar metallicity, quite a high \([\alpha/Fe]\) level \((\gtrsim 0.6)\) will be required.

In addition, we have still not obtained high-quality age determinations for any low-metallicity clusters in the innermost \(\sim 5\) kpc of the Galaxy, which is the one remaining region where significantly older clusters might still lurk undetected. But in this respect it should also be noted that there are only a handful of clusters known with \([Fe/H] \lesssim -1.7\) and \(R_{gc} < 5\) kpc (see, e.g. Stetson & West 1994 and the more recent data from the catalog of Harris 1996). In addition, all of these few have high radial velocities which rule out the possibility that they spend most of their time within the bulge. These bits of evidence, though not definitive, suggest that there are very few extremely low-metallicity clusters that genuinely belong to this innermost region. Nevertheless, it is not out of the question that older objects could exist even if their metallicities are not extremely low. Either way, the age distribution of the inner-halo clusters needs to be explored more fully.

We have also shown sample fits of the CMDs for M92 and NGC 2419 to up-to-date isochrones incorporating well calibrated transformations to the observational \((M_V, V - I)\) plane. Using the distance scale that most naturally fits the ZAHB model luminosity and the main-sequence colors, we find that the best-fitting age for the most metal-poor globular clusters in the Milky Way is near 14 Gyr.

Our picture of the earliest epoch of the Galaxy is one in which clusters began to appear at very much the same time everywhere across a vast protogalactic region, spanning perhaps 200 kpc diameter in present-day dimensions. We do not, however, necessarily conclude that the near-simultaneous formation of all these widely spread ‘first’ clusters was therefore coordinated globally by some ELS-style monolithic collapse. Considerable evidence based on both the metallicities (Searle & Zinn 1978) and masses (Harris & Pudritz 1994) of the halo globular clusters supports the view that they were born as protoclusters embedded within host \(\sim 10^8 - 10^9M_\odot\) gas clouds (the “supergiant molecular clouds” or SGMCs of Harris & Pudritz 1994) and not just as isolated condensations within the greater proto-Galactic halo.

If clusters form within these primeval dwarf-galaxy-like gaseous fragments, then (see Harris & Pudritz 1994; McLaughlin & Pudritz 1996) their formation timescale is determined by the time needed to build up \(10^5 - 10^6M_\odot\) dense gas clouds within these SGMCs, and not (as in ELS) the free-fall time of the whole protoGalactic region. This timescale for protocluster growth is typically a few \(10^8\) y or less, depending on the density and external pressure of the SGMC, but even in the larger, lower-density clouds the growth time is typically \(\lesssim 1\) Gyr.

In this picture, the observation that the most metal-poor globular clusters have essentially the same age everywhere in the halo has a different interpretation from the classic ELS scenario, but an equally simple one: it requires that all of the various primordial SGMCs that would eventually merge to build the larger Galaxy must have begun building
the first generation of stars and clusters in the same $\sim 1$–Gyr time period. We suggest that this requirement can be automatically satisfied by cosmological boundary conditions. The first discrete gaseous structures would have emerged everywhere at redshifts $z \gtrsim 5$, and current models (e.g., Kauffmann et al. 1993; Silk & Wyse 1993) predict that the mass spectrum of the emergent clouds should peak in the dwarf-size region ($10^8 - 10^9 M_\odot$). In other words, these clouds would have been set in place, scattered throughout the potential wells of larger protogalaxies, within about a Gyr of the recombination epoch. Inside the SGMCs, formation of massive, protoglobular clusters could then have immediately begun no matter where they found themselves, yielding fully formed clusters within a few $10^8$ years later, Protocluster buildup would necessarily have proceeded faster in the higher-density, higher-pressure SGMCs in the centermost regions of large protogalaxies, but within a $\pm 1$–Gyr age spread the differences would now be indistinguishable.

These initial conditions would, in short, allow globular cluster formation to begin in all parts of the larger protogalaxy at very much the same time and, even without a rapid global collapse of the protohalo, we might expect the first generation of clusters to have formed within the narrow age spread that we now observe. As is noted by Harris & Pudritz, this same model of cluster formation within SGMCs (whose sizes are constrained by external pressure) also predicts the systematic increase of cluster half-mass radius with Galactocentric distance in just the proportions that we see ($r_h \sim R_{gc}/2$).

If such a description of these early events were true, we could scarcely claim that the Milky Way is in any way unique. We would therefore expect that the oldest globular clusters in any large galaxy, spiral or elliptical alike, should possess very much the same age as we have found for the Milky Way.

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Table 1. Fiducial Points for NGC 2419 CMD

| V     | ±    | V - I  | ± | n |
|-------|------|--------|---|---|
| 18.816 | .043 | 1.111  | .005 | 10 |
| 19.228 | .027 | 1.070  | .005 | 17 |
| 19.614 | .028 | 1.016  | .006 | 19 |
| 19.969 | .031 | .932   | .015 | 11 |
| 20.337 | .057 | .916   | .009 | 7  |
| 20.431 | .090 | .783   | .005 | 5  |
| 20.381 | .049 | .757   | .007 | 3  |
| 20.378 | .052 | .705   | .004 | 3  |
| 20.507 | .049 | .393   | .007 | 4  |
| 20.618 | .048 | .224   | .006 | 4  |
| 20.645 | .016 | .192   | .003 | 12 |
| 20.687 | .013 | .151   | .002 | 38 |
| 20.788 | .019 | .114   | .003 | 16 |
| 20.922 | .030 | .073   | .004 | 16 |
| 20.993 | .067 | .034   | .004 | 3  |
| 21.369 | .026 | -.002  | .009 | 11 |
| 21.713 | .039 | -.025  | .010 | 11 |
| 22.572 | .014 | -.034  | .010 | 12 |
| 24.211 | .074 | -.236  | .024 | 10 |
| 24.938 | .028 | -.211  | .042 | 16 |
| 17.499 | .023 | 1.372  | .016 | 7  |
| 17.710 | .016 | 1.304  | .012 | 7  |
| 17.918 | .025 | 1.288  | .013 | 8  |
| 18.085 | .018 | 1.255  | .009 | 10 |
| 18.293 | .023 | 1.212  | .004 | 9  |
| 18.516 | .019 | 1.211  | .007 | 12 |
| 18.719 | .015 | 1.194  | .005 | 16 |
| 18.891 | .012 | 1.166  | .006 | 19 |
| 19.103 | .013 | 1.161  | .008 | 21 |
| 19.310 | .010 | 1.132  | .005 | 25 |
| 19.504 | .011 | 1.106  | .004 | 36 |
| 19.726 | .009 | 1.094  | .003 | 37 |
| 19.905 | .008 | 1.088  | .003 | 59 |
| $V$   | ±   | $V-I$ | ±   | n  |
|-------|-----|-------|-----|----|
| 20.102 | .008 | 1.073 | .006 | 41 |
| 20.309 | .008 | 1.049 | .002 | 60 |
| 20.489 | .007 | 1.042 | .003 | 61 |
| 20.705 | .007 | 1.026 | .003 | 74 |
| 20.908 | .007 | 1.021 | .003 | 81 |
| 21.066 | .013 | .974  | .017 | 7  |
| 21.146 | .011 | .982  | .023 | 9  |
| 21.248 | .009 | .991  | .006 | 10 |
| 21.371 | .008 | .998  | .013 | 8  |
| 21.455 | .010 | .979  | .008 | 15 |
| 21.549 | .012 | .971  | .011 | 8  |
| 21.661 | .007 | .965  | .010 | 12 |
| 21.749 | .009 | .973  | .008 | 12 |
| 21.865 | .007 | .980  | .005 | 16 |
| 21.951 | .006 | .959  | .007 | 21 |
| 22.041 | .008 | .937  | .017 | 14 |
| 22.142 | .007 | .946  | .008 | 16 |
| 22.239 | .006 | .943  | .007 | 18 |
| 22.357 | .007 | .936  | .006 | 19 |
| 22.448 | .006 | .936  | .007 | 27 |
| 22.559 | .007 | .917  | .010 | 20 |
| 22.647 | .005 | .928  | .007 | 29 |
| 22.759 | .004 | .905  | .006 | 31 |
| 22.846 | .005 | .916  | .005 | 29 |
| 22.949 | .005 | .885  | .008 | 37 |
| 23.045 | .005 | .866  | .007 | 36 |
| 23.149 | .004 | .842  | .004 | 58 |
| 23.248 | .003 | .798  | .005 | 71 |
| 23.352 | .004 | .754  | .005 | 78 |
| 23.447 | .003 | .729  | .004 | 77 |
| 23.550 | .003 | .705  | .004 | 101|
| 23.651 | .003 | .694  | .003 | 119|
| 23.750 | .003 | .688  | .003 | 127|
| 23.853 | .002 | .684  | .003 | 174|
Table 1—Continued

| V   | ±   | V − I | ±   | n  |
|-----|-----|-------|-----|----|
| 23.951 | .002 | .678  | .002 | 185 |
| 24.051 | .002 | .677  | .003 | 208 |
| 24.148 | .002 | .691  | .003 | 211 |
| 24.252 | .002 | .692  | .003 | 209 |
| 24.350 | .002 | .694  | .003 | 242 |
| 24.452 | .002 | .701  | .003 | 235 |
| 24.553 | .002 | .715  | .003 | 264 |
| 24.650 | .002 | .722  | .003 | 295 |
| 24.754 | .002 | .730  | .003 | 307 |
| 24.850 | .002 | .736  | .004 | 305 |
| 24.949 | .001 | .747  | .003 | 356 |
| 25.050 | .001 | .764  | .004 | 322 |
| 25.152 | .001 | .774  | .004 | 362 |
| 25.250 | .001 | .781  | .004 | 406 |
| 25.349 | .002 | .802  | .004 | 409 |
| 25.451 | .001 | .803  | .004 | 400 |
| 25.551 | .002 | .828  | .004 | 480 |
| 25.650 | .001 | .838  | .004 | 443 |
| 25.748 | .001 | .854  | .004 | 466 |
| 25.850 | .003 | .871  | .005 | 460 |
| 25.949 | .001 | .889  | .005 | 522 |
| 26.050 | .001 | .908  | .005 | 466 |
| 26.150 | .002 | .929  | .006 | 465 |
| 26.251 | .001 | .935  | .006 | 492 |
| 26.348 | .001 | .972  | .006 | 507 |
| 26.451 | .001 | .992  | .007 | 477 |
| 26.549 | .001 | 1.000 | .007 | 478 |
| 26.653 | .001 | 1.010 | .007 | 455 |
| 26.751 | .001 | 1.061 | .008 | 481 |
| 26.850 | .002 | 1.063 | .009 | 444 |
| 26.950 | .001 | 1.111 | .009 | 412 |
| 27.049 | .003 | 1.077 | .012 | 370 |
| 27.151 | .001 | 1.118 | .013 | 352 |
| 27.250 | .002 | 1.115 | .013 | 329 |
| V    | ±   | V - I  | ±   | n  |
|------|-----|--------|-----|----|
| 27.349 | .002 | 1.192  | .014 | 252 |
| 27.451 | .001 | 1.156  | .015 | 241 |
| 27.550 | .002 | 1.202  | .015 | 209 |
| 27.647 | .002 | 1.206  | .016 | 157 |
| 27.748 | .003 | 1.243  | .023 | 99  |
Table 2. Fiducial Points for M92 CMD

| $V$   | $V - I$ | $V$   | $V - I$ |
|-------|---------|-------|---------|
| 16.62 | -0.120  | 17.81 | 0.735   |
| 16.12 | -0.084  | 17.90 | 0.689   |
| 15.83 | -0.052  | 17.96 | 0.649   |
| 15.57 | -0.019  | 18.09 | 0.613   |
| 15.40 | 0.017   | 18.17 | 0.592   |
| 15.33 | 0.070   | 18.26 | 0.576   |
| 15.24 | 0.143   | 18.39 | 0.561   |
| 15.17 | 0.228   | 18.54 | 0.557   |
|       |         | 18.69 | 0.555   |
| 12.75 | 1.143   | 18.89 | 0.558   |
| 13.90 | 1.022   | 19.06 | 0.568   |
| 14.67 | 0.972   | 19.37 | 0.589   |
| 15.91 | 0.867   | 19.67 | 0.617   |
| 16.61 | 0.828   | 19.95 | 0.648   |
| 17.09 | 0.810   | 20.65 | 0.740   |
| 17.39 | 0.781   | 21.11 | 0.816   |
| 17.60 | 0.766   | 21.58 | 0.913   |
| 17.74 | 0.754   | 22.13 | 1.036   |
Figure Captions

Fig. 1.— Composite color-magnitude diagram for NGC 2419, from HST/WFPC2 images and ALLFRAME data reduction; see Stetson et al. (1997). Stars further than 50″ from cluster center are plotted, selected as described in §2 of the text. This CMD is employed for definition of the fiducial sequences.

Fig. 2.— Fiducial mean points for the color-magnitude diagram, constructed as described in the text. For most of the points, the internal error bars are smaller than the plotted symbol size.

Fig. 3.— Differential CMD fit between NGC 2419 (from the present work) and the similarly metal-poor cluster M92 (from Johnson & Bolte 1997). The CMD for NGC 2419 has been shifted brightward and blueward by the amounts ΔV, Δ(V − I) shown in the figure. Quantitative analysis (see text) shows that the two clusters have the same age to less than 1 Gyr. The absolute scales (MV, (V − I)0) on the graph have been set by adopting the reddening and distance modulus for M92 derived later in the text (see Figures 5 and 6), though these absolute calibrations do not affect the differential fit itself.

Fig. 4.— Model isochrones in (MV, V − I), derived as described in §4 of the text. The chemical composition of the models is Y = 0.235, [Fe/H] = −2.14, and [α/Fe] = 0.3. Isochrone lines are plotted for four different ages (12, 14, 16, 18 Gyr), shifted arbitrarily so that their main sequence lines coincide at a point Δ(V − I) = 0.05 mag redder than the turnoff point. The color difference between the MSTO and the giant branch then changes with age at the rate shown on the figure.

Fig. 5.— Isochrone fit and absolute age estimation for M92. The adopted isochrones, as in Fig. 4 above, have abundances Y = 0.235, [Fe/H] = −2.14, and [α/Fe] = 0.3, and ages of 12, 14, 16, and 18 Gyr. The fiducial sequences for the cluster have been shifted by the amounts δ(V − I), (m − M)V listed in order to superimpose them on the isochrones. The resulting RR Lyrae luminosity is MV(HB) = 0.55, and the best-fit age is 15 ± 1 Gyr.

Fig. 6.— Isochrone fit to NGC 2419, with the same stellar models as in the previous figure. The resulting RR Lyrae luminosity is MV(HB) = 0.57; the best-fit age is 15 Gyr. As in Fig. 5, the fit in this graph optimizes the fit of the isochrones to all parts of the cluster CMD.

Fig. 7.— Isochrone fit to NGC 2419, for a distance modulus and reddening that optimize the fit strictly to the ZAHB and unevolved main sequence. Here the horizontal-branch stars are plotted individually (small crosses) to show the location of the ZAHB line along the lower
envelope of the observed HB. Open circles represent the mean points for the other parts of the CMD. See §4.3 for discussion.

Fig. 8.— Isochrone fit to M92. The isochrone lines are the same as in the previous figures, but the assumed distance scale is $M_V(HB) = 0.15$, following the Reid (1997) analysis of the Hipparcos subdwarf parallaxes. The cluster HB is placed at $M_V = 0.15$, and the fiducial sequences are then shifted horizontally until the main sequence points fall in line with the isochrone ZAMS. The deduced age is 10 Gyr or less. The deduced ‘reddening’ of M92 in this case would be $\delta(V - I) = 0.08$ mag. See §4.3 of the text for discussion.

Fig. 9.— Isochrone fit to NGC 2419, assuming $M_V(HB) = 0.15$ as in the previous figure.
NGC 2419 WFPC2 Photometry

$R > 50''$
Differential Fit

Δ(V-I)=0.140, ΔV=5.28

-2

0

2

4

6

8

M_v

0

0.5

1

(V-I)_0

M92

NGC 2419
Relative Age Calibration

$(-2.14, +0.3)$

$12(2)18$ Gyr

$\Delta(V-I)/\Delta\tau = 0.013 \text{ mag/Gy}$
\[(m-M)_v=14.60, \delta(V-I)=0.013\]

\[\alpha=0.3 \quad 12(2)\text{18 Gyr}\]
\[(m-M)_v = 19.88, \delta(V-I) = 0.145\]

\[\alpha = 0.3 \quad 12(2)18 \text{ Gyr}\]

NGC 2419
\[(m-M)_{v}=19.95, \delta(V-I)=0.165\]
\[\alpha=0.3 \quad 12(2)18 \text{ Gyr}\]

NGC 2419
(m−M)\text{v} = 15.00, \quad \delta(V-I) = 0.08

\alpha = 0.3 \quad 12(2)18 \text{ Gyr}
$(m-M)_v = 20.30$, $\delta(V-I) = 0.23$

$\alpha = 0.3$  $12(2)18$ Gyr

NGC 2419