AGE GRADIENT AND THE SECOND PARAMETER PROBLEM IN THE GALACTIC HALO[1]

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ABSTRACT

We establish a framework for determining absolute ages of Galactic globular clusters and then use these ages to investigate the age-metallicity and age–Galactocentric distance relations for the 36 clusters with the most reliable age data. The clusters span Galactocentric distances from 4 through 100 kpc and cover a metallicity range from [Fe/H] = −0.6 to −2.3. Adopting currently plausible choices for the relation between cluster metallicity and horizontal-branch luminosity, and α-enhancement ratios, we find that the majority of the globular clusters form an age distribution with a dispersion $\sigma(t)$ of $\sim 10^9$ yr, and a total age spread smaller than 4 Gyr. Clusters in the lowest metallicity group ([Fe/H] < −1.8) appear to be the same age to well within 1 Gyr at all locations in the Milky Way halo, suggesting that star formation began throughout the halo nearly simultaneously in its earliest stages. We find no statistically significant correlation between mean cluster age and Galactocentric distance (no age gradient) from 4 to 100 kpc. The correlation between cluster age and horizontal-branch type suggests that causes in addition to metallicity and age are required to understand the distribution of stars along the horizontal branches in globular cluster color-magnitude diagrams.

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

1. INTRODUCTION

It is not yet clear how, and in which order, the oldest constituents of the Galaxy formed. The current debate is bounded by two well-known extreme scenarios: one is the ELS rapid-collapse model (Eggen, Lynden-Bell, & Sandage 1962; Sandage 1990) in which the bulk of star formation in the halo occurred over not much more than a rotation period. In the simplest form of the ELS picture, all the globular clusters might have a rather small range in ages, and cluster age and metallicity are not expected to be strongly correlated with Galactocentric distance. Alternatively, Searle & Zinn (1978, hereafter SZ) proposed that both the halo clusters and the halo field stars formed in fragments (possibly originally located outside the Milky Way) that had their own individual histories of star formation and chemical enrichment. In addition, another possible consequence of this picture is that the accretion of major fragments could have continued for several gigayears following the initial collapse.

The original motivation for the SZ picture was to explain in a natural way the wide range of globular cluster metallicities that we observe at all locations in the halo, as well as the progressive emergence of the enigmatic "second parameter" (see below) with increasing Galactocentric distance. Thus, in the SZ scenario, the halo cluster system might exhibit a significant age spread, especially in its outermost regions where the various second-parameter anomalies are strongest. In this connection, Lin & Richer (1992) have noted that some surprisingly young outer halo clusters could have been captured more recently from satellites of the Milky Way, rather than having formed within the environs of the Milky Way halo. This view has been reinforced by the recent observations of the Sagittarius dwarf and its clusters (Ibata, Gilmore, & Irwin 1994; Da Costa & Armandroff 1995), which appear to be actively undergoing accretion into the Milky Way halo at the present time. Therefore, the existence of a few such young clusters need not necessarily be a signature of an extended phase of star formation within the Galactic halo itself. On the theoretical side, a quantitative model of globular cluster formation has been developed by Harris & Pudritz (1994) and McLaughlin & Pudritz (1996) that identifies the SZ gaseous "fragments" as supergiant molecular clouds (SGMC): essentially 10^8–$10^9 M_\odot$ versions of the smaller GMCs that reside in the Galactic disk today. A specific consequence of this model (in which protoclusters are postulated to build up by the collisional accretion of small cloudlets within the host GMC) is that the growth time should increase outward in the halo, where the ambient gas pressure and density are smaller. Thus, we should expect to see a larger range of cluster ages in the outermost halo and (conversely) a very small range (less than 1 Gyr; see McLaughlin & Pudritz for quantitative predictions) in the inner bulge where the col-

lisional growth times are fastest. When this picture is added to the possibility of late infall and accretion as mentioned above, we might expect the total age distribution of the globular clusters in a large galaxy such as the Milky Way to be a complex story indeed.

On the observational side, the "second parameter" problem in the color-magnitude diagrams of globular clusters remains a keystone to understanding the cluster age distribution. Among globular cluster horizontal branches (HB), the general trend is for them to be redder than the RR Lyrae instability strip in clusters with $[Fe/H] > -1$, and for the color distribution to become increasingly bluer with decreasing $[Fe/H]$. Almost all clusters with $[Fe/H] < -2$ have HBs dominated by stars bluer than the instability strip. There are, however, exceptions to this rule with a number of clusters possessing HB morphologies too red or too blue for their $[Fe/H]$ values. Hence there must be some additional parameter(s) that influence HB morphology. This is the "second-parameter" problem. Thorough recent reviews of this problem are given by Carney, Fullton, & Trammell (1991), van den Bergh (1993), Lee, Demarque, & Zinn (1994, hereafter LDZ) and Chaboyer, Demarque, & Sarajedini (1995, hereafter CDS). The current standard solution of this problem is cluster age. With all other parameters held constant, the HB of a cluster becomes bluer with increasing age due to decreasing envelope mass. Observationally it is known that the second-parameter effect becomes more evident at large Galactocentric distances R_{gc}, where many clusters possess HBs that are redder than the mean for their $[Fe/H]$ values. Hence if the second parameter is indeed age, the average age of the outer halo clusters should be smaller than that of the nearby ones, and the outer halo clusters should simultaneously exhibit a larger age spread. It is important to stress that this is one of the main underpinnings of the SZ scenario for the chaotic formation of the halo and for Zinn's (1993) recent revision of this model.

Evidence in favor of the view that age is the second parameter has been developed through the detailed simulations of cluster HBs by LDZ. They argue that the age of the halo must decrease monotonically from the center of the Milky Way outward. Other parameters, such as the CNO-group abundances, helium abundance, mass loss in pre-HB stages, core rotation, or possibly even cluster density (Fusi-Pecci et al. 1993; but see van den Bergh & Morris 1993), may all have effects on the temperature distribution of stars along the HB. However, the model simulations of LDZ show that most of these others are unlikely to be the "global" second parameter, with age remaining as the main contender.

Unfortunately, these conclusions remain at least partly circumstantial since the morphologies of the HB and red giant branches by themselves do not directly measure cluster age. The most direct approach to establishing cluster ages is to obtain deep color-magnitude photometry of the main-sequence stars. Although many data of this type are available for the nearby globular clusters (see, e.g., Vanden-Berg, Bolte, & Stetson 1990, hereafter VBS), sufficiently accurate photometry of the turnoff and unevolved main sequence for the most remote halo clusters (and thus the most extreme second-parameter anomalies) has proved beyond the reach of current ground-based telescopes.

Recently, Stetson et al. (1996) have used the *Hubble Space Telescope* to obtain highly accurate deep CMDs for three of the outermost halo clusters, representing the extremes of the metallicity range found there. The purpose of our paper is to show that the new results of Stetson et al., together with the most reliable age calibrations for globular clusters elsewhere in the halo, indicate that there exist very distant halo clusters that are as old as clusters in the inner halo. Furthermore, we show that, with entirely plausible assumptions concerning the cluster abundances and distance scale, there is no net age gradient in the Galactic halo, and the cluster-to-cluster age dispersion, particularly for clusters at the same metallicity, is remarkably small. The notable exceptions to these results comprise a handful of strongly anomalous clusters at intermediate R_{gc} that may be late-accretion objects and that form a diverse lot even among themselves (see § 3.3 below). In its entirety, this view is different from that suggested by LDZ but similar to CDS, and it remains to be seen how it can be accommodated in detail by Galactic formation models.

2. DATA

VBS have examined the best existing CMDs for globular clusters in considerable detail and have also determined a homogeneous set of relative ages for clusters within several metallicity subgroups. VBS adopt the position that, because of uncertainties in the relevant physics (e.g., detailed chemical abundance ratios, convection, opacities), it is dangerous to use theoretical models to compare absolute ages across different metallicity regimes by their color-based technique. On the other hand, relative ages can be determined differentially with high precision (as small as 0.5 Gyr for the best-studied objects) with respect to fiducial clusters within narrowly defined metallicity subgroups.

To form a list of clusters with the most accurately estimated ages, we begin with objects in the VBS compilation. To these we add several other clusters with more recently published high-quality, main-sequence photometry: NGC 7078 (Durrell & Harris 1993), NGC 6101 (Sarajedini & da Costa 1991), NGC 5053 (Fahlman, Richer, & Nemec 1991), NGC 1904 (Chaboyer, Sarajedini, & Demarque 1992), Ruprecht 106 (Buonanno et al. 1990), Arp 2 (Buonanno et al. 1994), NGC 1851 (Walker 1992b), NGC 6229 (Buonanno 1994), NGC 6352 (Fullton et al. 1995), and our recent *HST* study of NGC 2419, Pal 3, and Pal 4 (Stetson et al. 1996). For NGC 6352 the differential age measurement is made from the difference in magnitude between the horizontal branch and the cluster turnoff (Buonanno, Corsi, & Fusi-Pecci 1989), rather than from the VBS color-differential technique.

Our primary goal is to use this material to investigate the correlations between cluster age and several other parameters including metallicity, HB type, and (perhaps most interesting) Galactocentric distance. The key distinction between our results and those of (for example) LDZ is that the ages are deduced directly from the main sequences, rather than indirectly from HB and RGB morphology. However, to intercompare clusters with very different metallicities and convert our differential ages into absolute ones, we must make some further assumption about the age zero points in each metallicity group. To set the scale for absolute ages, we extract from the literature the age estimates derived from full-scale isochrone fitting for selected clusters in each metallicity group, and then use the differential (VBS) results to deduce ages for the remaining clusters in that metallicity group. To ensure that the data are homo-

geneous (i.e., similar input physics for the isochrones), we have, wherever possible, used clusters whose absolute ages were determined from detailed isochrone fits with the Bergbusch & VandenBerg (1992) oxygen-enhanced isochrones and with helium abundances in the range $Y = 0.23-0.25$. Although we do not use the HB to establish either the distance or age, it turns out that the distance scale for our selected fiducial clusters (see below) is essentially equivalent to an HB luminosity calibration,

$$M_V(RR) = M_V(HB) = 0.15[Fe/H] + 1.0 , \qquad (1)$$

which is in accord with the great majority of current evidence (see LDZ; CDS; Carney, Storm, & Jones 1992, hereafter CSJ; Skillen et al. 1993). (Note, however, that RR Lyrae observations in the LMC [Walker 1992a], in conjunction with Cepheid distances to the Large Cloud, yield significantly brighter HB luminosities for the old component of the LMC; if a similarly bright level were to hold for the outer globular clusters in the Milky Way, their ages would be correspondingly reduced.) Following VBS, we employ four metallicity subgroups, for which the age zero points are set as follows.

1. $[Fe/H] < -1.8$.—Fiducial clusters in this especially well defined group are NGC 4590 (McClure et al. 1987), NGC 6341 (Stetson & Harris 1988) and NGC 7099 (Bolte 1987b). The *relative* age determinations for all three of these clusters (see VBS) imply that they have the same age to within 0.5 Gyr. However, even though the papers listed all used O-enhanced isochrones ([O/Fe] = 0.7) and have similar precision, the derived absolute ages range from 14 to 17 Gyr. This illustrates clearly the difficulty in establishing absolute ages for globular clusters. Averaging the results, we adopt an absolute age of 16 ($\pm$1.6) Gyr for NGC 7099, from which we derive the values for all of the other clusters in the group differentially.

2. $-1.8 < [Fe/H] < -1.5$.—Our single fiducial cluster is NGC 7492, with an age of 15 ($\pm$2) Gyr from the same O-enhanced isochrones (Côté, Richer, & Fahlman 1991).

3. $-1.5 < [Fe/H] < -1.00$.—In this group, there are, unfortunately, no totally reliable CMDs that have been well fitted to the O-enhanced isochrones. We therefore chose to go a bit further back in the literature and selected age determinations from the VandenBerg & Bell (1985) scaled-solar isochrones. These are available in a consistent way for NGC 362 (Bolte 1987a) and NGC 5904 (Richer & Fahlman 1987). From each of these, we subtract 2 Gyr to bring them back to the equivalent age for [O/Fe] = +0.7 as used in the previous two groups (see, e.g., Durrell & Harris 1993). This procedure yields an average absolute age of 14 ($\pm$1.4) Gyr for these two clusters. NGC 288, with its fainter turnoff point and extremely blue HB, is also in this group, and is ~2 Gyr older, according to the differential age calculation (VBS).

4. $-1.0 < [Fe/H]$.—Absolute age determinations for 47 Tuc (Hesser et al. 1987) and NGC 6838 (Hodder et al. 1992) give a mean age of 14 ($\pm$1) Gyr for these two metal-rich objects. The isochrones here use [O/Fe] = 0.3-0.4, in accord with the available data for halo field star abundances.

Data for a total of 36 globular clusters with Galactocentric distances ranging from 4 to 100 kpc are included in the sample and are listed in Table 1. Unfortunately, no clusters within 3 kpc of the Galactic nucleus yet have CMDs that

TABLE 1
GALACTIC GLOBULAR CLUSTER DATA

Cluster	[Fe/H]	R_{gc} (kpc)	HB Index	ΔAge (Gyr)
NGC 2298......	-1.86	15.4	0.93	0.0
NGC 2419......	-2.12	95.2	0.86	0.0
NGC 4147......	-1.83	20.5	0.55	-1.0
NGC 4590......	-2.06	9.9	0.44	0.0
NGC 5053......	-2.38	16.9	0.50	0.0
NGC 6101......	-1.80	10.6	0.84	0.0
NGC 6341......	-2.33	9.4	0.91	0.0
NGC 6397......	-1.91	6.1	0.98	0.0
NGC 6809......	-1.81	4.0	0.87	$+0.5$
NGC 7078......	-2.22	10.1	0.67	$+0.8$
NGC 7099......	-2.12	6.9	0.89	0.0
NGC 1904......	-1.54	18.1	0.89	-1.7
NGC 5272......	-1.57	11.7	0.08	-1.7
NGC 6205......	-1.56	8.2	0.97	-0.2
NGC 6218......	-1.61	4.3	0.96	-1.7
NGC 6752......	-1.61	5.3	1.00	-1.7
NGC 7492......	-1.51	23.5	0.81	0.0
Rup 106	-1.69	16.9	-0.82	-5.7
Arp 2...........	-1.6	18.8	0.86	-4.7
Pal 3	-1.66	90.0	-0.50	-1.7
NGC 288	-1.24	11.4	0.98	$+2.5$
NGC 362	-1.16	9.0	-0.87	0.0
NGC 1261......	-1.35	17.3	-0.71	$+0.5$
NGC 1851......	-1.26	16.3	-0.36	0.0
NGC 2808......	-1.37	10.7	-0.49	0.0
NGC 3201......	-1.45	8.8	0.08	$+1.0$
NGC 5904......	-1.33	6.1	0.38	0.0
NGC 6229......	-1.44	27.7	0.25	0.0
NGC 6254......	-1.52	4.7	0.98	2.0
Pal 4	-1.3	100.9	-1.00	0.0
Pal 5	-1.38	17.2	-0.40	1.0
Pal 12	-1.07	14.9	-1.00	-3.5
NGC 104	-0.76	7.3	-0.99	0.0
NGC 6352......	-0.63	3.6	-1.00	0.0
NGC 6838......	-0.71	6.7	-1.00	0.0
Ter 7	-0.7	14.3	-1.00	-4.0

NOTE.—Absolute cluster ages can be obtained by adding the fiducial cluster age to each Δage. The fiducial cluster for the metal-poorest group is NGC 6341 with an age of 16.0 Gyr. For the next group it is NGC 7492 with an age of 15.0 Gyr. For the group with [Fe/H] = -1.2 the standard cluster is NGC 362 at an age of 14.0 Gyr while for the most metal rich clusters it is NGC 104 at 14.0 Gyr.

are good enough to allow accurate ages to be determined. Metallicities, distances, and HB morphology indices are taken from the recent compilation of Harris (1995).

The pitfalls of estimating absolute ages for clusters are well known and have been emphasized in the literature many times (see VBS or Bolte & Hogan 1995 for particularly extensive discussions). Even small uncertainties in the adopted cluster reddening, distance, or composition can lead to uncertainties in the deduced absolute age that are typically 2 Gyr for clusters with well-defined main-sequence photometry, such as those included here. By averaging over as many clusters as possible, and by using a uniform distance scale with the same set of isochrones, we may then reasonably attempt to reduce the uncertainty in the zero point for each subgroup (relative to the other subgroups) to $\simeq$1–2 Gyr. The differential age measurements within a subgroup have internal uncertainties (precisions) of typically 0.5 Gyr for the clusters included here, all of which have high-quality photometry (see VBS; Durrell & Harris;

Stetson et al. 1996). The discussion in the following sections demonstrates that this expectation is achievable.

3. AGES, METALLICITIES, AND THE SECOND PARAMETER

The discussion of LDZ, which establishes relative cluster ages by careful interpretation of HB morphology, suggests that there is a net age gradient through the Milky Way halo amounting to 2 Gyr over 40 kpc and 4 Gyr over 100 kpc. We wish to investigate this same question, relying instead on ages determined from the main-sequence turnoff region of the CMD. However, we must address two questions first: (1) is there an age-metallicity relation for globular clusters, and (2) to what extent does (turnoff-calibrated) age correlate with HB morphology?

3.1. The Age-Metallicity Relation

The age-metallicity correlation for the present data is shown in Figure 1. Since the data points at a given metallicity are not independent, as they were determined differentially with respect to one of the clusters, we took an average of the ages and metallicities in each bin using the same weights for the metallicities as for the ages. This resulted in four uncorrelated points, one for each metallicity bin, with the ± 1 σ error bars in the ages corresponding to two sources of error. These are the uncertainty of the absolute zero point for each bin and the uncertainty in the differential age for each cluster (estimated from the uncertainty in measuring the shift in the position of the red giant branch from the reference cluster to the cluster in question that was taken to be 0.5 Gyr for all the globular clusters in our sample). The errors from these sources were then added as follows to produce a final error in each of the four points,

$$\sigma^2(\text{total}) = \sigma^2(\text{absolute}) + \sigma^2(\text{differential})/N , \quad (2)$$

where N is the number of clusters in a metallicity bin. These points (*filled circles*), together with their error bars are
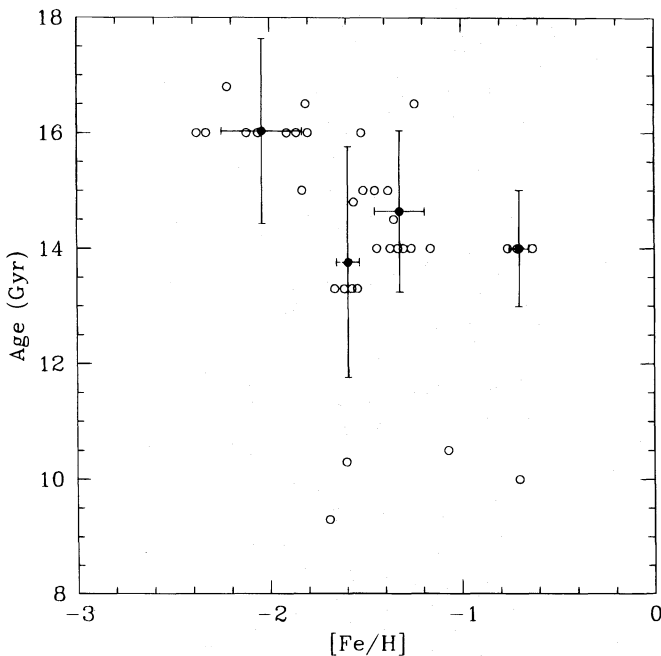

Age (Gyr) vs [Fe/H]

FIG. 1.—The plot of absolute age vs. metallicity for the globular clusters in our sample. Data for the individual clusters are plotted with open circles with the error bars suppressed to avoid cluttering the diagram. Mean points for each metallicity group with the ± 1 σ error bars included are plotted as filled circles.

plotted on top of the individual cluster points (*open circles*) in Figure 1. These four data points should be effectively uncorrelated, so simple propagation of error should do to estimate the error in the slope.

Excluding the four "young" clusters with ages of less than 12 Gyr that may have been accreted from other systems (see § 3.3), we find a slope in the age-[Fe/H] plane that is different from zero, but it is significant at less than the 1 σ level (68% confidence). Formally, a linear least-squares fit to the data, excluding the young systems, yields

$$\text{age(Gyr)} = -1.21(\pm 1.33)[\text{Fe/H}] + 13.04(\pm 1.74) . \quad (3)$$

This slope should be compared with that of -4.0 derived by CDS. To check our result, we carried out Monte Carlo simulations of the data, allowing the individual cluster differential ages to vary randomly by ± 0.5 Gyr and the absolute age to vary by ± 1 σ where σ is the absolute age error for the metallicity group. We then reconstructed the four data points and carried out least-squares fits to them. A total of 10^4 trials were done in this manner, and they yielded a mean slope of $-1.22(\pm 1.35)$, completely consistent with our initial results.

The 11 clusters with [Fe/H] < -1.8 have a standard deviation in age of only 0.4 Gyr, which is to be compared to an age dispersion of 0.9 Gyr for the 21 clusters with [Fe/H] > -1.8. Taken at face value, our data are then consistent with a scenario in which the most metal poor clusters formed initially, over a length of time consistent with the rotation period of the Galaxy. The more metal rich clusters formed somewhat later over a more extended period of time. The confidence in such a scenario is low, however, due to the low statistical significance of the slope in the age-[Fe/H] relation. Our data are not strongly inconsistent with a picture in which all clusters of all metallicities formed simultaneously.

However, the results in the preceding paragraph are the least secure of the several presented in this paper because they depend on the variation of oxygen and the other α-elements with [Fe/H]. The Bergbusch & VandenBerg (1992) calculations do not, in fact, allow for the observed enhancements in metal-poor stars (cf. Wheeler, Sneden, & Truran 1988) of any of the α-elements except oxygen (for reasons mentioned in their paper). Moreover, their adopted [O/Fe] values now appear to be somewhat too high when compared with the latest determinations of this quantity in field subdwarfs and subgiants. For instance, whereas Bergbusch & VandenBerg adopted [O/Fe] = 0.7 at [Fe/H] = -2, current indications are that field stars with this iron content have [O/Fe] somewhere in the range of 0.4 to 0.6 (see, e.g., Spite & Spite 1991; Bessell, Sutherland, & Ruan 1991). However, the high [O/Fe] values assumed by Bergbusch & VandenBerg compensate to some extent for their neglect of enhancements in the abundances of other α-elements. New computations by VandenBerg et al. (1996), which use the latest Livermore opacities, indicate that (for [Fe/H] = -2) the turnoff luminosity versus age relations for [O/Fe] = 0.7, with scaled solar number abundance ratios for all other elements, correspond closely to those for [α/Fe] = 0.5, where α = O, Ne, Mg, Si, etc. Consequently, there is some basis for confidence in the ages that we have inferred for the globulars using the Bergbusch and Vanden-Berg isochrones.

Among recent similar discussions of the age-metallicity relation for globular clusters, the most nearly comparable

ones to ours are probably that of CSJ (compare their Figs. 20–21 with our Fig. 1) and CDS (compare their Fig. 1 with our Fig. 1). Aside from a small zero-point difference in the age scale due to their particular choices of [α/Fe] and the isochrones, CSJ find substantially similar results compared with ours: no clear trend of age with metallicity for [Fe/H] > −1.8, and a higher age dispersion for the intermediate-metallicity group. Notably, however, both CSJ and CDS also find significantly larger ages than we do for the most metal poor group ([Fe/H] < −1.8) and thus conclude that a clear overall age-metallicity relation exists. We do find such a relation, but it is certainly not a very robust result, as shown in Figure 1. CSJ find that an increased [O/Fe] ratio for these metal-poorest clusters would reduce, although not eliminate, the relation, leaving the metal-poor group ∼2 Gyr older than the mean of the other clusters. CDS, however, claim to detect a very significant age-metallicity relation for the clusters with the most metal poor systems again being the oldest. The difference between these results and ours appears to be due to a combination of small effects, since our approach differs in several details. Both CSJ and CDS first adopt a distance to each cluster from the HB level. From this CSJ calculate the bolometric magnitude of the turnoff point, then finally the cluster age from $M_{bol}(TO)$ and the adopted stellar models. Similarly, CDS derive the cluster age from model calibrations of $M_V(TO)$ as a function of metallicity, where $M_V(TO)$ is determined from the difference between the level of the HB and the TO, ΔV_{TO}^{HB}. By contrast, the ages we use are deduced from full best-fit isochrone comparisons to the main-sequence, turnoff, and subgiant regions of the fiducial clusters in each metallicity group, followed by differential age determinations of the other clusters in the group with the method of VBS. Although our results are, within the observational errors, *consistent* with the CSJ and CDS distance scales (eq. [1]), we do not use the HB level to set either the distance or the age.

Discussions by Sandage & Cacciari (1990) and Sandage (1993) demonstrate how the age-metallicity relation changes as a function of the adopted $M_V(HB)$ distance scale, when the HB (or RR Lyrae) stars are used to set the cluster distance. The turnoff luminosity and finally the cluster age are derived through the model dependence of $M_{bol}(TO)$ on age. Although they favor a notably steeper slope on $M_V(HB)$ versus [Fe/H] (see CSJ for an exhaustive discussion of the HB luminosity calibrations), they find mean age differences of ∼2 Gyr across the full metallicity range. Interestingly, the closest analog of their study to ours is through their alternate derivation of the cluster distances by direct main-sequence fitting to the stellar models, from which they find no trend of age with metallicity and a mean age of 15.5 Gyr with [O/Fe] = 0.6 (see Fig. 14 of Sandage & Cacciari).

3.2. *The HB Type–Age Relation*

As another way of exhibiting the age dispersion and mean age of our cluster sample, we show in Figure 2 a plot of cluster age versus population gradient along the HB. Let us first concentrate on the central part of this distribution, excluding the clusters with extreme blue or red HBs. The nine objects with $-0.8 < (B-R)/(B+V+R) < +0.4$ are seen to have an rms age dispersion of just 0.6 Gyr. [B, V, and R are defined as the number of HB stars to the blue (B), red (R), and in the variable (V) region of the HB of the cluster. More details can be found in LDZ.] Such a cluster-
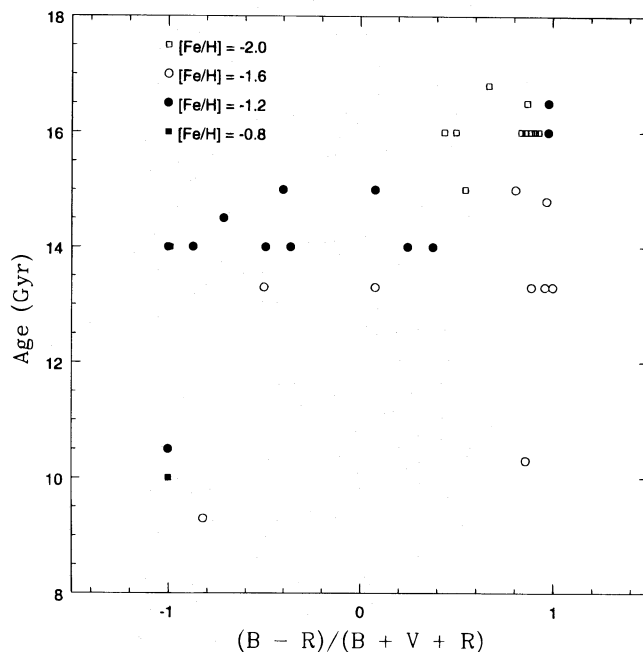

Fig. 2.—The relation between age and HB parameter for the globular clusters. The symbols correspond to clusters with different metal abundances: *filled squares* [Fe/H] = −0.8, *filled circles* [Fe/H] = −1.2, *open circles* [Fe/H] = −1.6, *open squares* [Fe/H] = −2.0. In the HB parameterization, pure blue HBs will have an index of +1 and pure red HBs will have an index of −1. Over a broad range in HB types and metallicities the cluster ages are essentially constant. This shows that causes other than metal abundance and age are important in determining the HB type.

to-cluster dispersion is the smallest it could be when the differential age measurement uncertainties are taken into account.

A complementary way to view the distribution in Figure 2 is that seven of these same nine clusters have metallicities in the narrow range $-1.45 < [Fe/H] < -1.26$, have an extremely small dispersion in age of 0.48 Gyr and yet span 60% of the entire range in HB type. From the LDZ simulations, at [Fe/H] = −1.2 the rate of change of the HB parameter with age is $\Delta(HB)/\Delta(t) = 0.3/Gyr$ while at an age of 13 Gyr $\Delta(HB)/\Delta([Fe/H]) = 2.46/dex$. The observed dispersion in the HB parameter for these seven clusters is 0.41, the age dispersion is 0.48 Gyr, while the dispersion in [Fe/H] is a mere 0.07. Hence, it appears that the dispersion in the HB parameter caused solely by age (0.14), caused solely by the metallicity dispersion (0.17), or due to both effects (0.22) is too small to explain the observed spread. This suggests that *variations in HB morphology for these objects are not primarily due to differences in age and metallicity.*

It is only at the extremes of the distribution in HB type that a larger dispersion in age is seen. Red HB clusters span an ∼5 Gyr range in ages, although considering the objects at $(B-R)/(B+V+R) \sim -1$ as a single group is probably ill advised, since it includes both the normal metal-rich bulge clusters, such as NGC 6352 and M71, and outer halo objects, such as Rup 106 and Pal 4, which must be generically very different (see below). The blue-HB clusters for which $(B-R)/(B+V+R) \sim +1$ tend to have somewhat older ages, with the important exception that Arp 2, a pure blue HB cluster, appears to be very young. These results clearly indicate that, even at a single metallicity, there is no

one-to-one correspondence between the ages of globular clusters and their HB types that can be applied globally.

3.3. *Is There an Age Gradient in the Galactic Halo?*

To examine evidence for or against an age gradient in the Galactic halo, we plot in Figure 3 the derived absolute ages versus Galactocentric distances for the clusters listed in Table 1. Two features of this diagram immediately stand out: (1) The great majority of the clusters, over all metallicity groups, fall within a single band with a mean age at 14.9 Gyr, an rms dispersion of 1.2 Gyr, and a total range of 3.7 Gyr. (2) Four clusters (Pal 12, Rup 106, Arp 2, and Ter 7) stand distinctly off this main band, with ages that are younger by ~5 Gyr than the main group. In addition, the latter handful of objects is already somewhat overrepresented, because a much larger fraction of the outer halo clusters have now been investigated than the inner halo ones. Thus these "young" objects can arguably be viewed as having anomalously low ages.

We comment first on the age dispersions. Within the main cluster population as defined by Figure 3, the overall dispersion is already small, but it is strikingly lower among clusters within the same metallicity group. For the most metal poor group, the dispersion is 0.4 Gyr, while in the worst case (for the clusters at $[Fe/H] \sim -1.2$), the dispersion is still only 0.9 Gyr. This larger dispersion is due mainly to NGC 288 and NGC 6254, which appear to be 2.0 and 1.5 Gyr older than the mean of the other clusters at this metal abundance. As implied in the preceding sections, this narrow age spread is the direct result of our particular approach to fitting the adopted isochrones, along with the chemical composition parameters. However, the main point we wish to stress is that, using a highly plausible set of assumptions and model fitting methodology along with the

best available cluster data, we find that it is possible to argue that the cluster-to-cluster differences in age, particularly at a given metallicity, are as small as they could possibly be expected to be, given the internal precisions (0.5 Gyr at least) in the age determinations themselves.

Next we address the question of an overall age gradient. Using the entire sample of clusters with R_{gc} from 4 to 100 kpc (and excluding the clearly anomalous young objects, which are discussed below), there is no evidence for a radial age gradient. A linear least-squares fit to the data for these clusters yields a slope of -0.001 ± 0.011 Gyr kpc^{-1}. The three outermost clusters in our sample (NGC 2419, Pal 3, and Pal 4) have extended the data to $R_{gc} = 100$ kpc, whereas the CDS compilation contained no systems beyond 40 kpc. The existence of these clusters in the far outer halo of the Galaxy at ages identical to those in the inner regions, demonstrates that star formation, even in this remotest part of the Galactic halo, began just as early as in the considerably denser inner halo. The outermost halo remains a region of considerable interest, and there remain several globular clusters beyond 30 kpc from the Galactic center for which no accurate ages are yet available. We are currently obtaining new age determinations for some of these other very remote clusters.

Inspection of Figure 3 also suggests that the main era of globular cluster formation may have ended rather abruptly ~13.3 Gyr ago. The actual numerical value for the time at which cluster formation ended of course depends on the zero point from the particular set of isochrones and abundance ratios that we have adopted. The important feature is the surprisingly sharp lower edge to the distribution. It is highly unlikely that this feature can have been generated accidentally or as a by-product of large random errors in the age determinations, which would be expected to blur out a true physical cutoff. This provides additional evidence that the differential age determinations are indeed at the claimed level of 0.5–1 Gyr for clusters with high-quality photometry.

In the preceding discussion, the four anomalously young clusters with intermediate Galactocentric distances ($R_{gc} \sim 20$ kpc) have been neglected. These clusters share several properties that appear to set them apart from both the main group of clusters in Figure 3 and the outermost-halo ones, such as Pal 4. (1) Buonanno et al. (1994) and Da Costa & Armandroff (1995) argue that three of these clusters, along with NGC 6715, are associated with the Sagittarius dwarf galaxy (Ibata et al. 1994). This suggests that most of these small, younger clusters may have been captured long after their formation elsewhere. (2) Possibly confirming evidence of this is that they have much lower luminosities than the typical cluster in the Galaxy; their mean M_V is -5.8 (Webbink 1985), whereas it is -7.4 for the globular cluster system of the Galaxy as a whole. As Harris & Pudritz (1994) note, they might therefore have formed within parent SGMCs that were an order of magnitude smaller than those making up the original protohalo. (3) Further support for their formation elsewhere is that more than 65% of the globular clusters in the Galaxy have core radii less than 2 pc, whereas all the "young" clusters have larger cores, with Arp 2 possessing one of the largest known cores at 16 pc radius (Webbink 1985).

These bits of evidence, although clearly circumstantial, suggest to us that these four clusters should not be considered when discussing the early formation history of the
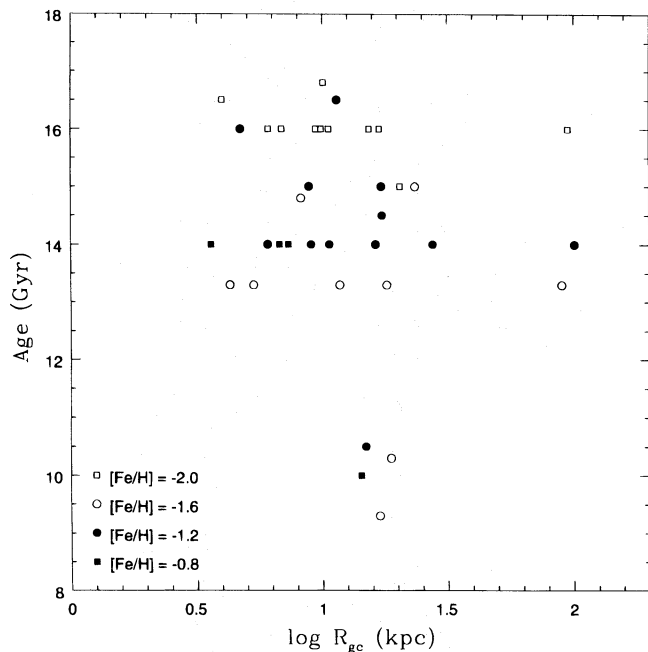

FIG. 3.—Globular cluster ages plotted against Galactocentric distance. The different symbols are as in Fig. 2. Four clearly young clusters in the mid-to-outer halo region at ages near 10 Gyr stand well off the main band of objects. Neglecting these (see text), there is no evidence of any strong age gradient among the main body of the cluster system from 4 to 100 kpc from the Galactic center.

Milky Way. What they certainly do indicate is that the history of the Galactic halo is an ongoing process with satellite galaxies occasionally being absorbed into the Milky Way up to the present time.

4. SUMMARY AND CONCLUSIONS

The absolute age distribution of globular clusters points to a number of conclusions that are likely to bear on the manner in which the Milky Way Galaxy formed.

1. The most metal poor clusters may be slightly older than clusters at higher metallicities. These metal-poor systems formed on a short timescale that was similar to the free-fall collapse time of the proto-Galaxy. It appears that these clusters formed throughout the entire halo of the Galaxy at very nearly the same time.

2. There is no evidence for a gradient in globular cluster ages for those systems lying between ~ 4 and 100 kpc from the Galactic center. It thus appears that when clusters formed in the Galaxy, they did so throughout its entire extent. This is quite a remarkable result implying that the physical conditions capable of supporting cluster formation existed over a huge distance and hence presumably over a wide range in physical properties.

3. The HB morphology of clusters must, at least in part, be due to causes other than metallicity and age. Furthermore, interpreting the systematic trend toward redder HB morphology at increased R_{gc} as being primarily due to age (LDZ) appears to be too simplistic.

Finally, we note, that accurate ages for the innermost (bulge-type, high-metallicity) clusters are not yet available in large numbers and may still change the overall conclusions once they can be added to the correlations that we have discussed above.

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