GLOBULAR CLUSTER SYSTEMS. II. ON THE FORMATION OF OLD GLOBULAR CLUSTERS AND THEIR SITES OF FORMATION

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ABSTRACT

We studied the metal-poor globular cluster populations of a large variety of galaxies and compared their mean metallicity with the properties of the host galaxies. For this purpose, we constructed a comprehensive database of old metal-poor globular cluster populations, hosted by 47 galaxies, spanning about 10 mag in absolute brightness. The mean metallicities of the systems are found to be very similar and lie in the $-1.65 < [\text{Fe/H}] \leq -1.20$ range (74% of the population). Using only globular cluster systems with more than six objects detected, we find that 85% of the population are within $-1.65 < [\text{Fe/H}] \leq -1.20$. The relation between the mean metallicity of the metal-poor globular cluster systems and the absolute $V$ magnitude of their host galaxies presents a very low slope that includes zero. An analysis of the correlation of the mean metallicity of the populations with other galaxy properties (such as velocity dispersion, metallicity, and environment density) also leads to the conclusion that no strong correlation exists. The lack of correlation with galaxy properties suggests a formation of all metal-poor globular clusters in very similar gas fragments. A weak correlation (to be confirmed) might exist between the mean metallicity of the metal-poor clusters and the host galaxy metallicity. This would imply that at least some fragments in which metal-poor globular clusters formed were already embedded in the larger dark matter halo of the final galaxy (as opposed to being independent satellites that were accreted later). Our result suggests a homogeneous formation of metal-poor globular clusters in all galaxies in typical fragments of masses around $10^9$–$10^{10} \, M_\odot$ with very similar metallicities, compatible with hierarchical formation scenarios for galaxies. We further compare the mean metallicities of the metal-poor globular cluster populations with the typical metallicities of high-redshift objects. If we add the constraint that globular clusters need a high column density of gas to form, damped $Ly\alpha$ systems are the most likely sites among the known high-redshift objects for the formation of metal-poor globular cluster populations.

Key words: cosmology: observations — early universe — galaxies: formation — galaxies: halos — galaxies: star clusters

1. INTRODUCTION

Globular clusters contain the oldest known stellar populations of the Milky Way and probably of the observed universe. Consequently, they hold cosmologically significant information and are often used as fossil records of the formation of galaxies. At least two globular cluster subsystems were found to coexist in our Galaxy (Kinman 1959; Zinn 1985; Armandroff & Zinn 1988; Armandroff 1989): (1) a metal-poor, slowly rotating, spherically distributed system in the halo and (2) a metal-rich, rapidly rotating population concentrated in the disk (or the bulge; see, e.g., Minniti 1995). A similar situation was observed in M31 (Ashman & Bird 1993; Barmby et al. 2000). Subsequently, globular cluster subpopulations were also discovered in early-type galaxies (Zepf & Ashman 1993). This motivated comparisons between the globular cluster subpopulations and the host galaxies. Such studies were pioneered by Ashman & Bird (1993) and revived by Forbes, Brodie, & Grillmair (1997a). Our work is motivated by the recent increase in data identifying metal-poor globular cluster populations, especially in early-type galaxies, as well as by recent studies associating the metal-poor subpopulation in early-type galaxies with an extended, possibly halo-like component, similar to the ones observed in late-type galaxies (Geisler, Lee, & Kim 1996; Kissler-Patig et al. 1997; Lee, Kim, & Geisler 1998). This encouraged us not only to look into common properties of these subsystems and to investigate possible correlations between their properties and those of their host galaxies, but also to put them into a galaxy formation context and identify their possible sites of formation.

2. COMPILATION OF OLD GLOBULAR CLUSTER POPULATIONS

2.1. Focusing on Metal-poor Globular Clusters

We intend to select the oldest globular clusters around galaxies with the minimum pollution from younger globular clusters. Even if absolute ages are not well defined, halo globular clusters in the Milky Way were shown to be very old systems and at least older than 10 Gyr (see, e.g., Chaboyer et al. 1998; Jimenez & Padoan 1998). Globular clusters with $[\text{Fe/H}] \leq -1.2$ are essentially located in the halo, but more importantly, they are likely to be coeval to within less than 1 Gyr (see Rosenberg et al. 1999). This also seems
to be the case in other Local Group galaxies (Olszewski, Suntzeff, & Mateo 1996; Sarajedini et al. 1998). Furthermore, spectroscopic studies of giant elliptical galaxies show that the age of their metal-poor globular clusters appears to be indistinguishable within the errors (1 to a few Gyr) from that of the Milky Way halo clusters (Kissler-Patig, Forbes, & Minniti 1998b; Cohen, Blakeslee, & Ryshov 1998). Assuming that these globular clusters are among the first stellar populations formed in the galaxies, we expect them to reflect the local pre- or protogalactic conditions and especially the abundances more than 10 Gyr ago. This paper will focus on the metal-poor globular clusters, assumed to be the oldest ones.

It was proposed that, in some galaxies, the metal-poor and (at least part of) the metal-rich clusters were coeval within a few gigayears (see, e.g., Ortolani 1995; Feltzing & Gilmore 2000; Puzia et al. 1999). However, given the fact that this has not been generally demonstrated and that a number of scenarios predict the metal-rich clusters to be younger than the metal-poor ones, we do not discuss these in this paper.

2.2. On Colors and Metallicities and the Detection of Bimodality

Our goal is to identify properties that are commonly measured in all known metal-poor populations. The mean metallicity of the metal-poor subpopulation in a galaxy (noted as [Fe/H]_mp throughout the paper) is the only such property currently available for a majority of galaxies. The following analysis will focus on this property, and by mean metallicity we actually refer to the peak of the metallicity distribution of the metal-poor globular cluster sub-population in a galaxy.

The determination of the mean metallicity of metal-poor populations is complicated by two problems when derived from broadband colors, as for the majority of our sample: (1) a perfect separation of the metal-poor and metal-rich populations (and thus a determination of the mean color and/or metallicity for an unbiased sample of metal-poor clusters) is not possible from the broadband color distributions, and (2) the transformation of the broadband colors into metallicities suffers from systematic errors. The uncertainties associated with each point are discussed below.

In order to determine the mean metallicity of the metal-poor clusters from a color distribution of a whole system, the distribution is probed by a mixture-modeling test (KMM; see Ashman, Bird, & Zepf 1994) that, among other things, returns the most likely color peaks of the sub-populations. Typical errors for the peak determination in \( V - I \) (the most widely used color), induced by the KMM method alone range from 0.01 to 0.05 mag (sensitively dependent on the number of data points and the intrinsic width of the distributions), which translates into errors in the mean [Fe/H] values of up to 0.25 dex. These errors are typically added to the statistical errors present in the photometry and to potential systematic errors in the sampling of the metal-poor population. A large fraction of our metallicities are obtained from \( V - I \) colors derived from Hubble Space Telescope (HST) Wide Field and Planetary Camera 2 data. Median color values for the same system can vary from author to author by up to 0.06 in \( V - I \) (see, for instance, NGC 4472 in Neilsen & Tsvetanov 1999; Puzia et al. 1999). Moreover, in order to combine the studies in different bands and to combine the results derived from the colors and spectroscopy, the broadband colors need to be transformed into metallicities. The sensitivity of a color to metallicity transformation varies by almost a factor of 2 when going from \( V - I \) over \( B - I \) to \( C - T_i \), making a homogeneous compilation difficult. The different transformations for a given color into metallicity (often derived from the Milky Way clusters) can introduce errors of the order of \([\text{Fe/H}] \sim 0.3\) dex, depending on the exact method used to derive the relation (see, e.g., the comparison in Kissler-Patig et al. 1998a).

In summary, taking the quoted mean metallicities directly from the literature could result in a artificial scatter of up to 0.4 dex in [Fe/H]_mp in the extreme cases, given the different analyses of the various authors. Therefore, in addition to the [Fe/H]_mp values, we will use the \( V - I \) values of the blue peak in the globular cluster color distributions available for a subset of our sample. The latter avoids the possibility of introducing any error related to a different method of deriving metallicities or errors associated with the conversion of colors to metallicities.

2.3. Data Compilation

The mean metallicity of the metal-poor clusters, as well as their mean colors (when available), are given in Table 1 for all galaxies that are known, to date, to host a distinct metal-poor cluster population. We included the data published by A. Kundu in his Ph.D. thesis (Kundu 1999) for nine new galaxies (and additional data for eight galaxies already in our list).

New values for seven galaxies derived from data presented in Paper I (Gebhardt & Kissler-Patig 1999) are also added. The data and reduction are presented in the original paper. We selected all galaxies with clear bimodalities (see Paper I) and used the KMM code to derive the peak color of the blue globular clusters. These values, as well as the ones from Kundu (1999), were transformed into metallicities using the [Fe/H], \( V - I \) relation given in Kissler-Patig et al. (1998a), [Fe/H] = 3.27(V - I) - 4.50.

All other values in Table 1 are taken from the original references. We also added to the above sample a number of dwarf galaxies that present a unimodal metallicity distribution function with an average metallicity below the threshold defined in § 2.1. We have assigned global uncertainties to each color, \( \sigma_{V-I} \sim 0.25, \sigma_{g-b} \sim 0.20, \) and \( \sigma_{C-T_i} \sim 0.15 \) (following Forbes et al. 1997a), unless different values are given in the original papers.

The compilation includes galaxies of all types. However, spiral galaxies are underrepresented and bright elliptical galaxies dominate the sample. This observational bias is essentially due to the fact that (1) globular clusters are more easily identified on the smooth background of elliptical galaxies than in dusty spirals, and (2) bright ellipticals host a larger number of globular clusters than faint ellipticals or spirals.

The host galaxy properties with which we compare the globular cluster properties are compiled in Table 2. These are taken from the HYPERCAT database (Prugniel & Simien 1996; Golev & Prugniel 1998), except for the environment density taken from the Nearby Galaxy Catalog (Tully 1988). We chose the \( \text{Mg}_2 \) index as a metallicity indicator rather than, for example, the color of the galaxy because it is widely available and does not require dereddening or transformation to reflect the metal content of the galaxy. We keep in mind that \( \text{Mg}_2 \) is essentially
measured in the very inner regions of the galaxy and does not directly reflect the mean metallicity of the halo. Nevertheless, it appears to be a good indicator of the final global metallicity and correlates well with the velocity dispersion of the galaxy (see, e.g., Dressler et al. 1987).

The above-mentioned velocity dispersion is used as a size indicator for the galaxies rather than, e.g., the estimated absolute magnitude, since the former is distance-dependent, and the latter is not, and is therefore more difficult to bring onto a homogeneous scale. In order to get comparable values for all galaxies, we tried to select only seeing-limited, ground-based determinations for the central velocity dispersion, e.g., HST Space Telescope Imaging Spectrograph values are systematically higher because of the higher spatial resolution.

The data described above are used in the next section to...
investigate possible correlations between the mean metallicity of the globular clusters and the host galaxy properties.

3. GLOBULAR CLUSTER MEAN METALLICITIES AND GALAXY PROPERTIES

3.1. A "Universal" Mean Metallicity for Metal-poor Globular Clusters

Until the early 1990s, the mean metallicities of the globular cluster systems were thought to correlate with the galaxy luminosity (van den Bergh 1975; Brodie & Huchra 1991). Ashman & Bird (1993) first investigated the correlation between the mean metallicity of the metal-poor globular clusters only and the galaxy luminosity. They based their analysis on the data of four local dwarf galaxies, as well as the LMC, the Milky Way, and M31. They found that a mean value of \([\text{Fe/H}] \sim -1.6\) dex for all halo globular cluster systems appeared consistent with the data, and they claimed that genuine halo globular cluster systems have comparable mean metallicities, irrespective of the parent galaxy's luminosity. Furthermore, adding the data from the four early-type galaxies known at that time to have bimodal globular cluster metallicity distributions, they speculated that the earlier relations (see above) were primarily a result of the high fraction of metal-rich globular clusters in bright elliptical galaxies.

Forbes et al. (1997a) later confirmed this result, with a slightly larger sample of 11 galaxies, by looking at the correlation of mean metallicity with galaxy luminosity for the metal-poor and metal-rich clusters separately. For the metal-rich population, they found a positive correlation at the 3 \(\sigma\) level. For the metal-poor globular clusters, Forbes et al. (1997a) did not detect any correlation, but rather a random scattering. Their data set has a mean of \([\text{Fe/H}]_{mp} = -1.16\), with a dispersion of \(\sigma = 0.28\) (as determined by us using a maximum likelihood estimator on their 11 values).

The sample of globular cluster systems presented in this paper is the largest database to date, and greater than 4 times more numerous than Forbes et al.'s (1997a) initial data set. The mean of our data lies at \([\text{Fe/H}]_{mp} = -1.45\) with a dispersion of \(\sigma = 0.15\). Compared with the Forbes et al. data set, our sample is slightly more metal-poor on average and exhibits a smaller scatter. The mean absolute magnitude of the galaxies in our sample is \(<M_V> = -20.1\), with a dispersion of 2.4 mag. Figure 1 shows the distribution of mean metallicities, plotted as a percentage of globular cluster systems within each bin (\(\Delta[\text{Fe/H}]_{mp} = 0.15\)). The first apparent result is that the mean metallicities of the metal-poor globular clusters are not distributed homogeneously over the spanned range but rather peak around a characteristic value: 74% of the sample is concentrated around \(-1.65 < [\text{Fe/H}]_{mp} < -1.20\). The distribution is asymmetric and more extended toward lower metallicities (dominated by the dwarf galaxies), resembling in shape the halo field star metallicity distribution. When we exclude galaxies with a number of observed blue globular clusters, \(N_{GC} \leq 6\) (almost exclusively dwarf galaxies) from the sample, our statistics are slightly altered to \(\Delta[\text{Fe/H}]_{mp} \sim -1.37 \pm 0.2\), and for the 39 remaining galaxies \(<M_V> = -20.8 \pm 1.6\). The new histogram (Fig. 1) appears more peaked. Indeed, 85% of the globular cluster systems are found within \(-1.65 < [\text{Fe/H}]_{mp} < -1.20\) and 67% within the two central bins, i.e., \(-1.55 < [\text{Fe/H}]_{mp} < -1.25\). Thus, the data suggest an even higher concentration of the metal-poor globular clusters.

The peaked (roughly Gaussian) distribution of the mean metallicities would be expected on the basis of the central limit theorem, if all metal-poor globular clusters could be associated with a single sample (i.e., be considered to have a similar origin). The fact that the distribution looks peaked supports the latter hypothesis.

Figure 2 shows the metallicities of the globular cluster systems as a function of the absolute magnitude \(M_V\). The global trend is a decrease of the metallicity with \(M_V\). The statistical Spearman rank test seems to confirm this impression and gives a probability of 0.0005 that a correlation
Fig. 1.—Distribution of mean metallicities for the globular cluster systems. The left-hand panel presents the distribution of the mean metallicities of metal-poor clusters for the complete sample, and the right-hand panel shows only globular cluster systems with $N_{\text{GC}} > 6$ (see text).

is not present (Spearman’s $\rho = -0.521$). A linear fit gives $[\text{Fe/H}]_{\text{mp}} = -0.06(\pm0.01)M_V - 2.72(\pm0.22)$ for 46 values. However, removing the globular cluster systems with $N_{\text{GC}} \leq 6$ from the sample (but keeping Kundu’s), the same Spearman rank test gives a much lower probability of 0.0813 that a correlation is not present (Spearman’s $\rho = -0.283$ for 39 values). A linear fit gives $[\text{Fe/H}]_{\text{mp}} = -0.02(\pm0.02)M_V - 1.87(\pm0.31)$, with a low slope not significantly different from zero (at 1 $\sigma$).

Thus, the mean metallicity of the old metal-poor globular clusters seems to correlate with the absolute luminosity of their host galaxy. However, taking only the galaxies with $N_{\text{GC}} \geq 6$, this correlation is no longer statistically significant while we still have a large range in galaxy luminosity ($-23 < M_V < -16$). Thus, our findings confirm Ashman & Bird’s (1993) results for the metal-poor clusters. However, the globular cluster systems of dwarf galaxies seem to deserve a more complete discussion, and they will be discussed in a future paper.

3.2. Mean Metallicities against $\text{Mg}_2$, $\sigma$, and Environment Density

Next we investigate whether the mean metallicity of the metal-poor globular clusters correlates with other galaxy properties, such as metallicity, size, or environment. We used the derived mean metallicities, as well as the mean $V - I$ values (when available), to avoid possible systematic errors due to the different transformations from broadband colors to metallicities. Note that when several values for $V - I$ were available for a given system, we computed a simple mean, and averaged it with any other metallicity determination, if available for that system.

The correlation between $[\text{Fe/H}]_{\text{mp}}$ and the $\text{Mg}_2$ index of the host galaxy, as well as between $[\text{Fe/H}]_{\text{mp}}$ and the velocity dispersion $\sigma$ of the host galaxy, computed for the full sample, are significant at the >99% confidence level (with the Spearman test returning student-distributed $t$ values of 2.45 and 2.90 for 35 and 40 degrees of freedom, respectively). Since $\text{Mg}_2$ and $\sigma$ are strongly correlated (see Fig. 3 for our sample), the similarity of the relations is not surprising. Neglecting, however, the dwarf galaxies ($\text{Mg}_2 < 0.25$, $\sigma < 150$ km s$^{-1}$) that do not exhibit a separate metal-poor component reduces the significance of the correlations to the <92% confidence level ($t = 1.45$ and 1.30 for 33 and 35 degrees of freedom, respectively). Furthermore, the signifi-
F. 3. Clear correlation between and for the galaxies of our sample, as expected (see, e.g., Dressler et al. 1987).

The significance is reduced even further when selecting the clusters as in § 3.1 (i.e., only galaxies with more than six clusters are considered). The correlation disappears well below the 90% confidence level ( for 32 and 34 degrees of freedom, respectively).

A linear fit returns a relation of the form \([\text{Fe/H}]_{\text{mp}} = 1.07(\pm 0.44)\text{Mg}_2 - 1.68(\pm 0.13)\) for the full sample. The slope of this relation is 10 times shallower than a direct conversion of \(\text{Mg}_2\) into \([\text{Fe/H}]_{\text{mp}}\) (see Kissler-Patig et al. 1998a), indicating only a very weak dependence of globular cluster mean metallicity on galaxy metallicity, if present at all.

Again, a possible correlation for dwarf galaxies will be discussed in a future paper discussing metal-rich globular cluster subpopulations. We note that absolutely no correlation is detected with environment density ( for 35 degrees of freedom).

3.3. \(V - I\) against \(\text{Mg}_2\), \(\sigma\), and Environment Density

Similar test as in the section above were performed for \(V - I\) instead of metallicity in order to avoid any potential systematic effects arising from the conversion of color into metallicity.

The most significant correlations of the peak color with a galaxy property are again the correlation between \(V - I\) and \(\text{Mg}_2\), and \(V - I\) and \(\sigma\) for the full sample. The quantities are correlated at the \(\sim 97\%\) confidence level ( and for 27 degrees of freedom, respectively). These correlations are mostly driven by NGC 4458, the only galaxy with six or fewer clusters for which a \(V - I\) peak color is available. Note, however, that NGC 4458 is a rather uncertain detection: Neilsen & Tsvetanov (1999) had 17 clusters to detect a bimodality in the color distribution, of which six are associated with the metal-poor peak. Neither Kundu (1999) nor we could detect a bimodality and reproduce this result with 33 clusters detected in the Gebhardt & Kissler-Patig (1999) data set. Removing this galaxy from the sample, the significances of the correlations are reduced to the \(\sim 94\%\) and \(\sim 90\%\) confidence level ( and for 26 degrees of freedom, respectively), becoming marginal.

A linear fit returns a relation of the form \(V - I = 0.24(\pm 0.18)\text{Mg}_2 - 0.89(\pm 0.06)\) for the sample, excluding NGC 4458. The slope is compatible with zero within 1.3 \(\sigma\) errors (a similar result is obtained for the velocity dispersion). Figure 4 shows the relations. A correlation with environment density is completely absent ( for 26 degrees of freedom).

Fig. 3.—Clear correlation between \(\text{Mg}_2\) and \(\sigma\) for the galaxies of our sample, as expected (see, e.g., Dressler et al. 1987).

Fig. 4.—Peak \(V - I\) color of the metal-poor globular cluster systems plotted against the \(\text{Mg}_2\) index (left panel) and velocity dispersion (right panel) of their host galaxies. The dashed lines show a linear least-squares fit to the data (excluding the data point of NGC 4458). A weak (<2 \(\sigma\) confidence) correlation might exist between the plotted values.
We conclude that the mean metallicity of the metal-poor globular clusters is not significantly related to the size, metallicity, or environment of the host galaxy. A weak correlation might exist but remains to be confirmed. Interestingly, Larsen et al. (2001) find a similar trend for a very homogeneous sample of 12 galaxies. Tentative implications are discussed below.

4. SOME CONSTRAINTS ON THE FORMATION OF HALO GLOBULAR CLUSTERS

From the results of §3, we retain two important points:

1. The mean metallicity of our sample of metal-poor globular cluster systems is only weakly (if at all) dependent on the host galaxy's properties ($M_V$, type, environment, and metallicity). This suggests that the formation of metal-poor globular clusters was largely uncorrelated with the final host galaxy properties. The metal-poor globular clusters (often associated with the halo) could have formed either in the protogalactic phases of the host galaxies or in the earlier phases of the galaxy formation. The old age of the globular clusters also supports these latter ideas.

2. The mean value of our sample of metal-poor globular cluster systems seems almost "universal" at $[\text{Fe/H}]_{\text{mp}} \sim -1.4$, with a low dispersion of the metallicity distribution function of $\sigma_{[\text{Fe/H}]_{\text{mp}}} \sim 0.3$. This suggests a universal mode of formation for the metal-poor globular clusters, in the sense that their formation sites had very similar metallicities and/or properties.

4.1. Size of the Putative Fragments

With this formation hypothesis in mind, we can explore a noteworthy consequence for the fragment sizes. Ashman & Bird (1993) already addressed this problem comparing globular cluster subgroups within the M31 halo with expectations from cold dark matter models (predicting substructures of the order of $10^{-3} M_{\text{h}}$). They found the observations and predictions to be in good agreement, with typical mass scales for substructures within M31 of $2 \times 10^9 M_\odot$. The sizes can also be derived by combining (1) the mean metallicity of the metal-poor globular clusters around giant galaxies and (2) an assumed relation between the galaxy initial luminosity and the average globular cluster metallicity (Côté, Marzke, & West 1998). Relating the two, most metal-poor globular clusters must have formed in objects with luminosities around $M_V \sim -17$, i.e., masses of the order of $10^9 - 10^{10} M_\odot$ (i.e., in galaxies larger than the remaining dwarfs observed in the Milky Way neighborhood). This is in good agreement with Ashman & Bird's 1993 results.

4.2. Was the Formation of the Metal-poor Globular Cluster Independent of the Final Host Galaxy?

The current data favor a formation of most metal-poor globular clusters in very similar environments/substructures out of low-metallicity gas (as already speculated by Ashman & Bird 1993).

Whether these substructures were fragments à la Searle & Zinn (1978), i.e., entities within the dark matter halo of the final host galaxy, or satellites with similar properties but independent of the dark matter halo of the final galaxy, is unclear. However, it appears secure that they formed independently of the metal-rich component (bulge) of the host galaxy.

Thus, the properties cannot distinguish yet between a scenario in which the metal-poor globular clusters formed completely independently of the final galaxy and were later accreted (see, e.g., Richtler 1995; Côté et al. 1998; Hilker, Infante, & Richtler 1999) and a scenario in which they formed as part of the galaxy during the assembly of the halo (Searle & Zinn 1978). The latter would be favored if a correlation between the mean metallicity of the metal-poor clusters and the metallicity of the host galaxy existed. The former would be favored if no such correlation were present. Neither scenario would restrict any formation scenario of the final galaxy (e.g., major collapse, major merger, etc.), since all galaxy formation scenarios envision similar assemblies of the halos (be it as a first stage of further collapse or as the halos of progenitors of a subsequent major merging event).

If it exists, the correlation between the mean metallicity of the metal-poor population and the galaxy metallicity is about 10 times shallower than a one-to-one relation. Such a correlation would imply that a fraction of the metal-poor globular clusters formed in satellites (i.e., not related to the dark matter halo of the galaxy) but get accreted later, while the other part formed in fragments (i.e., already within the dark halo of the final galaxy). For our data set such a correlation is, however, still uncertain, and the fraction of metal-poor clusters from both origins in a system that contributes to it is also unknown and probably varies with galaxies.

Finally, we do know that in the Milky Way some halo globular clusters formed around other galaxies and were accreted later on. For example, such an accretion process can be witnessed today in the form of the Sagittarius dwarf galaxy (Ibata, Gilmore, & Irwin 1994). Although halo globular clusters of the Milky Way form a homogeneous population from their metallicity, it has been suggested from an analysis of their horizontal branch types (Zinn 1993) that it may contain two subsystems with similar average metallicities. This would complicate the interpretation of their origin. A review of pros and cons can be found in Ashman & Zepf (1998), Carney & Harris (2001),1 and Parmentier et al. (2000).

5. TIME AND SITE OF FORMATION OF THE METAL-POOR GLOBULAR CLUSTERS

5.1. DLA Systems as the Progenitors of Metal-poor Globular Clusters

Pettini et al. (1999) presented a diagram giving the rough location of different components of the early universe at $z \sim 3$ in a N(H i) metallicity plane. Among the objects whose metallicity can be estimated at high redshift are the damped Lyα (DLAs) systems, the Lyman break galaxies (LBGs), and the Lyα forest. DLA systems are neutral gas objects observed at all redshifts (Pettini et al. 1999; Prochaska & Wolfe 2000). Their dynamics are consistent with protogalactic clumps or progenitors of present-day galactic disks (Wolfe et al. 1995; Katz et al. 1996; Hahnelt, Steinmetz, & Rauch 1996). One interpretation of DLA systems is that they are gas clouds within protogalactic halos that could be associated with Searle-Zinn fragments. LBGs are star-forming objects similar to our local starbursting galaxies (Steidel et al. 1996). They appear as objects with

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1 See http://physun.mcmaster.ca/harris/WEHarris.html.
compact cores, some with multiple components, surrounded by diffuse and asymmetric halos (Steidel et al. 1996; Lowenthal et al. 1997). If the metallicity of the Lya forest is definitely too low, DLA systems and LBGs are found to lie in the same metallicity range as halo globular clusters. However, recent data from Kobulnicky & Koo (2000) show that the mean interstellar medium metallicity in their LBGs is consistent with the metal-rich globular cluster population in the Milky Way. Consequently, since metal-poor globular clusters are formed from metal-poor gas, DLA systems appear to be the best candidates for their site of formation.

Furthermore, globular clusters contain stars, and the column density of their progenitors must be above a threshold of \( N(H) \sim 10^{20} \) cm\(^{-2} \) for the star formation to occur (Kennicutt 1989). Simulations carried out by Nakasato, Mori, & Nomoto (2000) also suggest that self-enrichment in a cloud appears to exclude the formation of massive star clusters. However, this point is still controversial (Parmentier et al. 2000).

Bringing the above mentioned facts together confirms the allowed location of halo globular cluster progenitors in the \( N(H) \) versus [Fe/H] diagram and suggests that we should concentrate, as a working hypothesis, on DLA systems as the potential sites of formation of the (halo) metal-poor globular clusters.

### 5.2. Estimating the Metallicity Evolution of DLA Systems

With the previous hypothesis that DLA systems can be connected to the progenitors of the metal-poor globular clusters, we take advantage of the available database of DLA observations, normalized to Anders & Grevesse (1989) solar abundances, \( \log [\text{Fe/H}]_0 = -4.49 \) and \( [\text{Zn/H}]_0 = -7.35 \), to study the chemical evolution of these objects with redshift. However, [Fe/H] may not be a reliable estimate of the metallicity of DLA systems, since some Fe could be locked up in dust and result in biased [Fe/H] measurements. Pettini et al. (1997) showed that [Zn/H] is a more reliable estimator because it essentially measures the metallicity independently of dust depletion. The [Zn/H] and [Fe/H] variations as a function of the redshift (Table 3) are plotted in Figure 5. We use the column-density-weighted abundances \( \langle [M/H]_{\text{DLA}} \rangle = \log \langle [M/H]_{\text{DLA}} \rangle - \log [M/H]_0 \), where \( [M/H]_{\text{DLA}} \) (\( M = \text{Fe or Zn} \)), and the associated standard deviations as defined in Pettini et al. (1997).

The average values \( \langle [\text{Fe/H}]_{\text{DLA}} \rangle = -1.53 \pm 0.40 \) and \( \langle [\text{Zn/H}]_{\text{DLA}} \rangle = -1.13 \pm 0.38 \) for the two complete samples, give \( \langle [\text{Zn/Fe}]_{\text{DLA}} \rangle = 0.40 \pm 0.55 \) over the whole sample. We do not normalize the [Fe/H] to the [Zn/H] values, since it remains unclear whether \( \langle [\text{Zn/Fe}]_{\text{DLA}} \rangle \) is constant with redshift. A similar trend of decreasing metallicity with redshift appears for both [Fe/H]\(_{\text{DLA}}\) and [Zn/H]\(_{\text{DLA}}\). The possibility that part of this trend is caused by a fraction of high-redshift DLA systems missed because of dust is investigated and ruled out by Pei & Fall (1995; but see also Prochaska & Wolfe 2000). The steeper slope at \( z > 2.8 \) has been interpreted as the fast formation of metals after the dark age (Pettini et al. 1997; Lu et al. 1996).

In order to verify whether the above trend of decreasing metallicity with increasing redshift is supported by other evidence, we further compute the evolution of the metallicity of the universe with the redshift. We use the star formation evolution of Steidel et al. (1999) and also consider an

### TABLE 3

| \( z \) | \( dz \) | \( T_{\text{min}} \) | \( T_{\text{max}} \) | [Fe/H]\(_{\text{DLA}}\) | [Zn/H]\(_{\text{DLA}}\) | \( \sigma_{\text{Fe/H}} \) | \( \sigma_{\text{Zn/H}} \) | No. of DLA | [Zn/Fe] | \( \sigma_{\text{Zn/Fe}} \) |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.45 | 0.1 | 5.1 | 5.9 | 1 (1) | -1.30 | ... | ... | ... | ... | ... |
| 1.00 | 1.0 | 5.9 | 9.7 | 10 (1) | -1.54 | 0.42 | -0.98 | 0.33 | 4 (0) | 0.56 | 0.53 |
| 1.75 | 0.5 | 9.7 | 10.5 | 5 (0) | -1.32 | 0.57 | -0.96 | 0.44 | 8 (2) | 0.36 | 0.72 |
| 2.25 | 0.5 | 10.5 | 11.0 | 13 (0) | -1.61 | 0.50 | -1.23 | 0.38 | 12 (6) | 0.38 | 0.63 |
| 2.75 | 0.5 | 11.0 | 11.4 | 4 (0) | -1.29 | 0.64 | -1.11 | 0.27 | 7 (4) | 0.18 | 0.69 |
| 3.25 | 0.5 | 11.4 | 11.6 | 3 (0) | -1.75 | 0.10 | -1.39 | ... | 3 (3) | ... | ... |
| 3.75 | 0.5 | 11.6 | 11.8 | 2 (1) | -1.95 | 0.20 | ... | ... | ... | ... | ... |
| 4.25 | 0.5 | 11.8 | 12.0 | 3 (1) | -2.28 | 0.25 | ... | ... | ... | ... | ... |
| 2.45 | 4.1 | 5.1 | 12.0 | 47 (4) | -1.53 | 0.40 | -1.13 | 0.38 | 34 (15) | 0.40 | 0.55 |

Notes.—The [Zn/H]\(_{\text{DLA}}\) values are from Pettini et al. 1997, while the [Fe/H]\(_{\text{DLA}}\) values are compiled from Boissé et al. 1998, Lu et al. 1996, Pettini et al. 1999, and Prochaska & Wolfe 1999. Columns (5) and (10) give the number of DLA metallicities and of corresponding limits for [Fe/H] and [Zn/H], respectively.
alternative scenario between $z = 1$ and 3 from sub-millimeter data (Barger, Cowie, & Sanders 1999). The second scenario implies a higher metal production at $z < 3$ and a lower metal production at $z > 3$. The expected metallicity is computed following Pettini et al. (1997), except that the values are normalized to give a global metallicity in the present-day universe of $Z = \frac{1}{3} Z_\odot$ (Renzini 1999). As noticed by (Pettini et al. 1997), the metal production is deduced from the radiation essentially emitted by massive stars. To compare these values with direct DLA metallicities, we need to correct them using $\frac{[\alpha/Fe]}{[Fe/H]} = 0.25$ (Boesgaard et al. 1999). In our considered metallicity range $([Fe/H]_{\text{D}} < -1.0)$, this value is found to be approximately constant (Clementini et al. 1999). The resulting curves were added in Figure 5.

On the one hand, the comparison of DLA and globular cluster system metallicities is direct; both metallicities are observables. On the other hand, a number of assumptions have been used to estimate the metal production in the universe from the LBGs. Consequently, even if these latter curves can be used as an important check of the DLA metallicity trend, we need to rely on the latter to settle our conclusions.

5.3. Redshift Range for the Formation of the Oldest Globular Clusters

The chemical evolution of DLA systems is below the lower limit for our metal-poor globular clusters at $z \sim 4$. The conclusion suggested by these data is that the old globular cluster formation occurred at $z < 4$ for the adopted cosmology.

Steidel et al. (1999) found that the total integrated UV luminosity at $z \sim 3$ is of the same order as that at $z \sim 4$, suggesting a similar stellar formation in the two redshift ranges. However, an interesting point to stress is that a small number of star-forming galaxies are observed at redshifts $z > 4$ (see, e.g., Dey et al. 1998; Spinrad et al. 1998; Hu, McMahon, & Cowie 1999). The observed signal-to-noise ratio of these observations is low, and we have only very limited information on the galaxies. However, a preliminary conclusion is that those few galaxies may be in the very early stages of their formation. Nevertheless, observations of the bulk of high-redshift ellipticals are consistent with a formation at redshifts of the order of $z \sim 3$–4, while

formation at $z < 2$ and $z > 5$ appears to be ruled out (Treu & Stiavelli 1999; Menanteau et al. 1999; but see Jimenez et al. 1999 for an alternative). To date, the detection of $z > 4.5$ star-forming galaxies is still anecdotal, and most of the stellar formation is observed below this redshift. The results presented in this paper bring an additional argument to this hypothesis.

6. Conclusion

The mean metallicity of metal-poor globular clusters is approximately constant in all galaxies and environments, with no significant dependence on galaxy size for metallicity. This argues for the formation of all metal-poor globular clusters in very similar gas fragments. Furthermore, it suggests either a very homogeneous metallicity of the initial gas out of which old metal-poor globular clusters formed, or very similar self-enrichment processes in the clouds. Self-enrichment, however, is unlikely to play an important role during the formation of clusters, (see, e.g., Ashman & Zepf 1998; Nakasato et al. 2000), so a very homogeneous metallicity in the initial fragments is favored.

A weak correlation (to be confirmed) of the mean metallicity of metal-poor globular cluster systems with the host galaxy metallicity and/or size might exist. This would suggest that (at least some of) the fragments in which the metal-poor globular clusters formed were already embedded in the dark halo of the final galaxy, rather than belonging to independent satellites.

We found high-redshift DLA systems (having high column densities of neutral gas and metallicities similar to those of the metal-poor clusters and “Population II” objects) to be good candidates for the formation sites of metal-poor globular clusters. This would support a picture in which at least some DLA systems are gas clouds within protogalactic halos.

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