

EXTREMELY α -ENRICHED GLOBULAR CLUSTERS IN EARLY-TYPE GALAXIES: A STEP TOWARD THE DAWN OF STELLAR POPULATIONS?

THOMAS H. PUZIA,^{1,2} MARKUS KISSLER-PATIG,³ AND PAUL GOUDFROOIJ¹

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ABSTRACT

We compare $[\alpha/\text{Fe}]$, metallicity, and age distributions of globular clusters in elliptical, lenticular, and spiral galaxies, which we derive from Lick line index measurements. We find a large number of globular clusters in elliptical galaxies that reach significantly higher $[\alpha/\text{Fe}]$ values ($[\alpha/\text{Fe}] > 0.5$) than any clusters in lenticular and spiral galaxies. Most of these extremely α -enriched globular clusters are old ($t > 8$ Gyr), and cover the metallicity range $-1 \lesssim [Z/H] \lesssim 0$. A comparison with supernova yield models suggests that the progenitor gas clouds of these globular clusters must have been predominantly enriched by massive stars ($\gtrsim 20 M_{\odot}$), with little contribution from lower mass stars. The measured $[\alpha/\text{Fe}]$ ratios are also consistent with yields of very massive pair-instability supernovae ($\sim 130\text{--}190 M_{\odot}$). Both scenarios imply that the chemical enrichment of the progenitor gas was completed on extremely short timescales of the order of a few Myr. Given the lower $[\alpha/\text{Fe}]$ average ratios of the diffuse stellar population in early-type galaxies, our results suggest that these extremely α -enhanced globular clusters could be members of the very first generation of star clusters formed, and that their formation epochs would predate the formation of the majority of stars in giant early-type galaxies.

Subject headings: galaxies: evolution — galaxies: formation — galaxies: star clusters —
globular clusters: general

Online material: color figures

1. INTRODUCTION

The field of globular cluster system research has contributed countless important insights to astronomy (e.g., Shapley 1918; Searle & Zinn 1978; Zinn 1985; Harris 1991; Ashman & Zepf 1998, and references therein). Because they survive a Hubble time, globular cluster systems (GCSs) provide important information on the assembly history of their parent galaxy and the physical conditions in the star-formation episodes during which they formed. With the advent of the *Hubble Space Telescope*, extragalactic GCSs in a variety of host galaxies outside the Local Group became accessible to accurate photometric studies (e.g., Whitmore et al. 1993; Whitmore & Schweizer 1995; Gebhardt & Kissler-Patig 1999; Puzia et al. 1999; Kundu & Whitmore 2001a, 2001b; Côté et al. 2004). In the last few years, progress in GCS research experienced a boost through the availability of efficient multiobject spectrographs, which facilitate spectroscopy of large samples of extragalactic globular clusters out to large distances (~ 20 Mpc; see e.g., Kissler-Patig et al. 1998; Cohen et al. 1998; Puzia et al. 2004). Spectroscopy provides the best constraints on the ages and chemical compositions of globular clusters.

The chemical composition of individual extragalactic globular clusters provides insight on the enrichment histories and timescales of their parent massive gas clouds. Because of the different progenitor lifetimes of Type II and Type Ia supernovae (SNe) (e.g., Tornambé & Matteucci 1986), and the different chemical composition of their ejecta (e.g., Nomoto et al. 1997a), the progenitor gas clouds will undergo different chemical evolution depending on whether they were enriched on short timescales predominantly by Type II SNe, or on extended timescales by both Type II

and Ia SNe. Ages and chemical compositions of globular clusters can be used to reconstruct the early assembly histories of globular cluster systems and their host galaxies, since self-enrichment is excluded for all but the most massive globular clusters (Recchi & Danziger 2005). Together with accurate ages and metallicities, the chemical composition of globular clusters can be used to reconstruct the early assembly histories of globular cluster systems.

In this paper, we investigate $[\alpha/\text{Fe}]$, metallicity, and age distributions of individual globular cluster systems as a function of environment (in elliptical, lenticular and spiral galaxies), based on high-quality spectroscopy data from the literature. We identify and discuss extremely α -enriched clusters that are (almost) exclusively found in ellipticals.

2. DATA

The majority of our analysis is based on the spectroscopic data set of Puzia et al. (2004), who obtained high-S/N spectra for globular clusters in seven early-type galaxies (NGC 1380, 2434, 3115, 3379, 3585, 5846, and 7192) with the FORS multiobject spectrograph at ESO's Very Large Telescope (VLT). We augment this sample with high-quality index measurements from the literature, which are explained in the last section in Puzia et al. (2004). We refer the reader to this paper for further details. In summary, we add to the sample of globular clusters in elliptical galaxies data from NGC 3610 (Strader et al. 2004) and NGC 4365 (Larsen et al. 2003; Brodie et al. 2005). To the sample of globular clusters in lenticular galaxies, we add spectra from NGC 3115 (Kuntschner et al. 2002), NGC 4594 (Larsen et al. 2002), and NGC 5128 (Peng et al. 2004). The sample of globular clusters in spiral galaxies is assembled of clusters in the Milky Way (Puzia et al. 2002), M31 (Trager et al. 1998; Beasley et al. 2004; Puzia et al. 2005b), M81 (Schroder et al. 2002), and the Sculptor spirals NGC 55, 247, 253, and 300 (Olsen et al. 2004).

All index measurements were uniformly performed with the passband definitions of Worthey et al. (1994) and Worthey &

¹ Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218.

² ESA Research Fellow, Space Telescope Division of ESA.

³ European Southern Observatory, Karl-Schwarzschild-Strasse 2, 85748 Garching bei München, Germany.

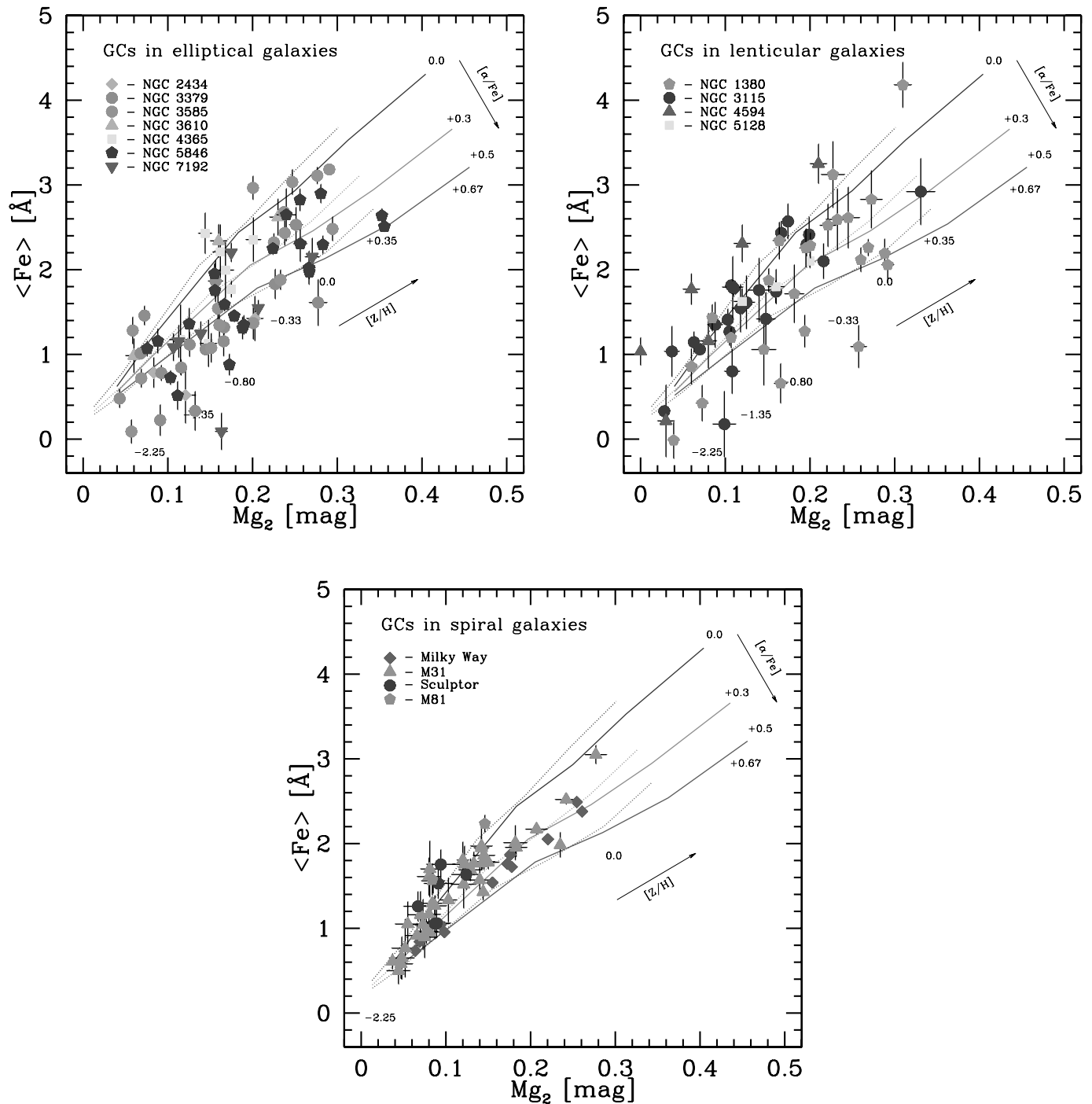


FIG. 1.— $[\alpha/\text{Fe}]$ diagnostic plots for globular clusters in spiral (*top left*), lenticular (*top right*), and elliptical galaxies (*bottom*). Different symbols show different globular clusters in individual host galaxies, which are described in the legend of each panel. Solid lines show iso- $[\alpha/\text{Fe}]$ tracks for 0.0, 0.3, and 0.5 dex for a 13 Gyr old stellar population with metallicities from $[Z/\text{H}] = -2.25$ to $+0.67$. To illustrate the systematics due to age, we show the same tracks for a 3 Gyr stellar population, indicated by dotted lines. Note that the models' tracks are virtually independent of age up to solar metallicities. The model predictions were taken from Thomas et al. (2003, 2004). [See the electronic edition of the *Journal* for a color version of this figure.]

Ottaviani (1997), and are calibrated on the Lick standard system using Lick index standards. In the following analysis we consider only globular clusters that have high-quality measurements in the indices $H\beta$, $H\gamma_A$, $H\delta_A$, $\langle \text{Fe} \rangle$, $\text{Mg } b$, and Mg_2 , since these enter our age, metallicity, $[\alpha/\text{Fe}]$ fitting routine. To guarantee a robust comparison of the three samples, we select data with measurement uncertainties $\Delta H\beta \leq 0.5$, $\Delta H\gamma_A \leq 0.7$, $\Delta H\delta_A \leq 0.7$, and $\Delta [\text{MgFe}]' \leq 0.4 \text{ \AA}$ (see Puzia et al. 2005a). The final data set contains 87, 47, and 59 globular clusters with high-quality index measurements in elliptical, lenticular, and spiral galaxies, respec-

tively, and samples the brightest $\sim 10\%$ of the globular cluster luminosity function. In terms of calibration quality and signal-to-noise ratio, it is, to our knowledge, the best-quality spectroscopic data set of extragalactic globular clusters currently available.

3. ANALYSIS

We use the technique described in Puzia et al. (2005a) to derive ages, metallicities, and $[\alpha/\text{Fe}]$ ratios for all sample globular clusters. In summary, we compare the age-sensitive Balmer line indices $H\beta$, $H\gamma_A$, and $H\delta_A$, and the metallicity-sensitive indices

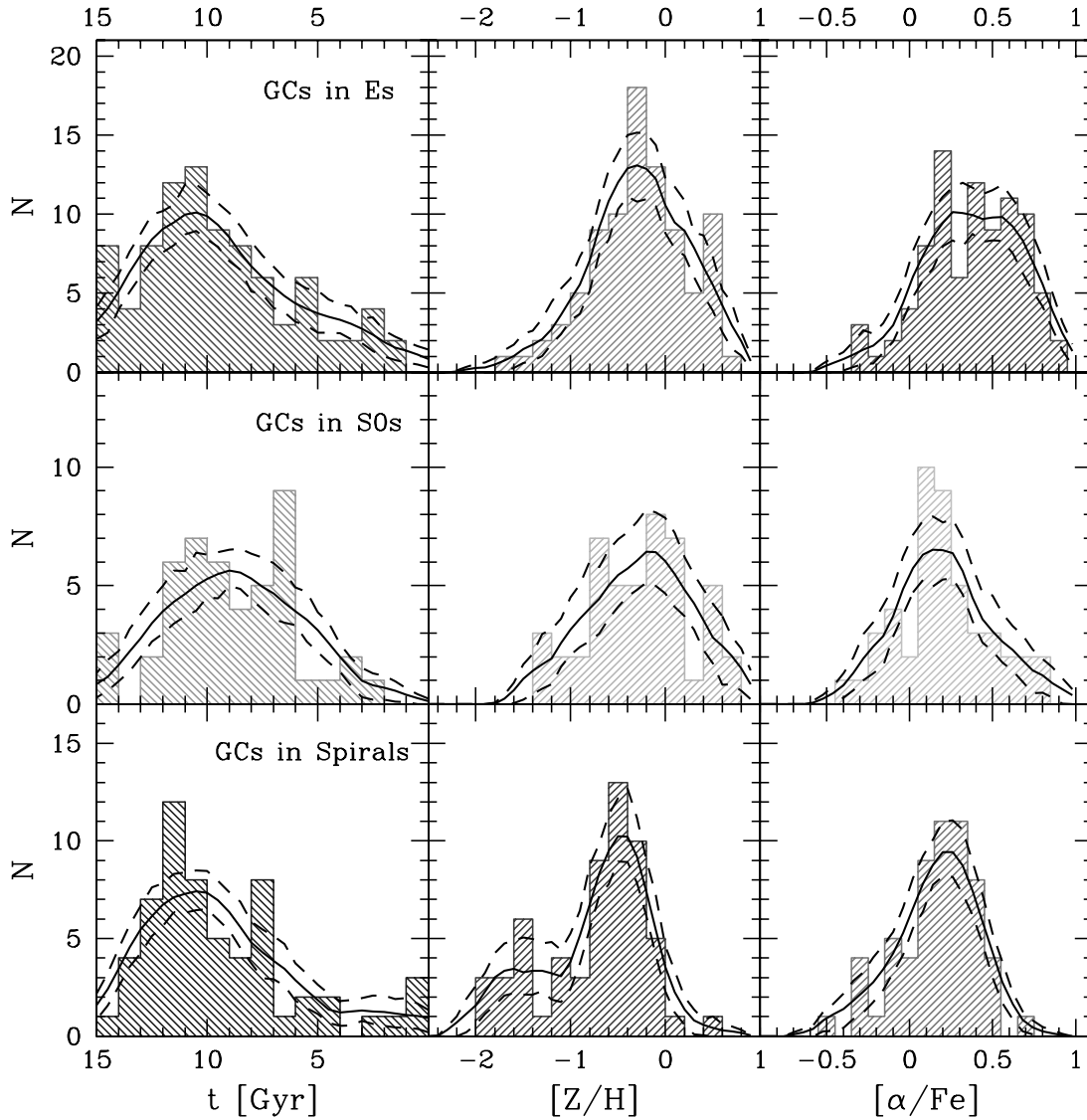


FIG. 2.—Age, metallicity, and $[\alpha/\text{Fe}]$ distributions of globular clusters in elliptical (*top row*), lenticular (*middle row*), and spiral galaxies (*bottom row*). Solid curves are nonparametric probability density estimates, with 90% confidence limits indicated by dashed lines. [See the electronic edition of the *Journal* for a color version of this figure.]

$\langle \text{Fe} \rangle$, Mg_2 , and $[\text{MgFe}]'$ to the population synthesis models of Thomas et al. (2003, 2004), which provide predictions for stellar populations with well-defined abundance patterns, in particular those with varying $[\alpha/\text{Fe}]$ ratios. These models were previously calibrated on Galactic globular clusters (Puzia et al. 2002; Maraston et al. 2003) for which accurate abundance ratios, including Fe peak and α elements, were known from high-resolution spectroscopy. Ages, metallicities, and $[\alpha/\text{Fe}]$ ratios are derived in an iterative χ^2 -minimization approach of diagnostic grids, taking into account index measurement errors and systematic uncertainties of the Lick index system. Since the error distributions are similar for all indices that enter the analysis, a comparison of all three globular cluster samples with the same simple stellar population (SSP) model predictions guarantees a robust differential analysis. Absolute globular cluster ages have to be interpreted cautiously, since the absolute age scale is prone to systematic uncertainties in the model calibration and an unknown contribution from hot horizontal-branch stars. However, our analysis allows the distinction between old ($t > 8$ Gyr), intermediate-age ($2 < t < 8$ Gyr), and young ($t < 2$ Gyr) globular clusters. The internal metallicity and $[\alpha/\text{Fe}]$ calibrations are more robust, and have systematic un-

certainties $\lesssim 0.15$ dex. It is important to realize that these internal systematics do not affect our *differential* analysis.

We present $[\alpha/\text{Fe}]$ diagnostic plots for globular clusters in spiral, lenticular, and elliptical galaxies in Figure 1. Figure 2 shows the derived distributions of globular cluster ages, metallicities, and $[\alpha/\text{Fe}]$ ratios in elliptical, lenticular, and spiral galaxies. The most unbiased representation of these data is realized via nonparametric probability density estimates using an Epanechnikov kernel (see Silverman 1986 for details), which are indicated by solid lines. Dashed lines show bootstrapped 90% confidence limits. The median ages for the elliptical, lenticular, and spiral samples are 10.2 ± 2.1 , 9.4 ± 2.2 , and 10.5 ± 2.0 Gyr,⁴ respectively. The sampling of all three subsamples is somewhat biased toward the central regions of galaxies, and therefore toward more metal-rich globular clusters. In fact, in the elliptical and lenticular samples, there are only a few clusters more metal poor than $[Z/\text{H}] \approx -1.5$, which correspond to the metal-poor subpopulation of Galactic-halo globular clusters (e.g., Zinn 1985). For both the elliptical and lenticular subsample we find a slightly subsolar

⁴ The errors give the semi-interquartile ranges.

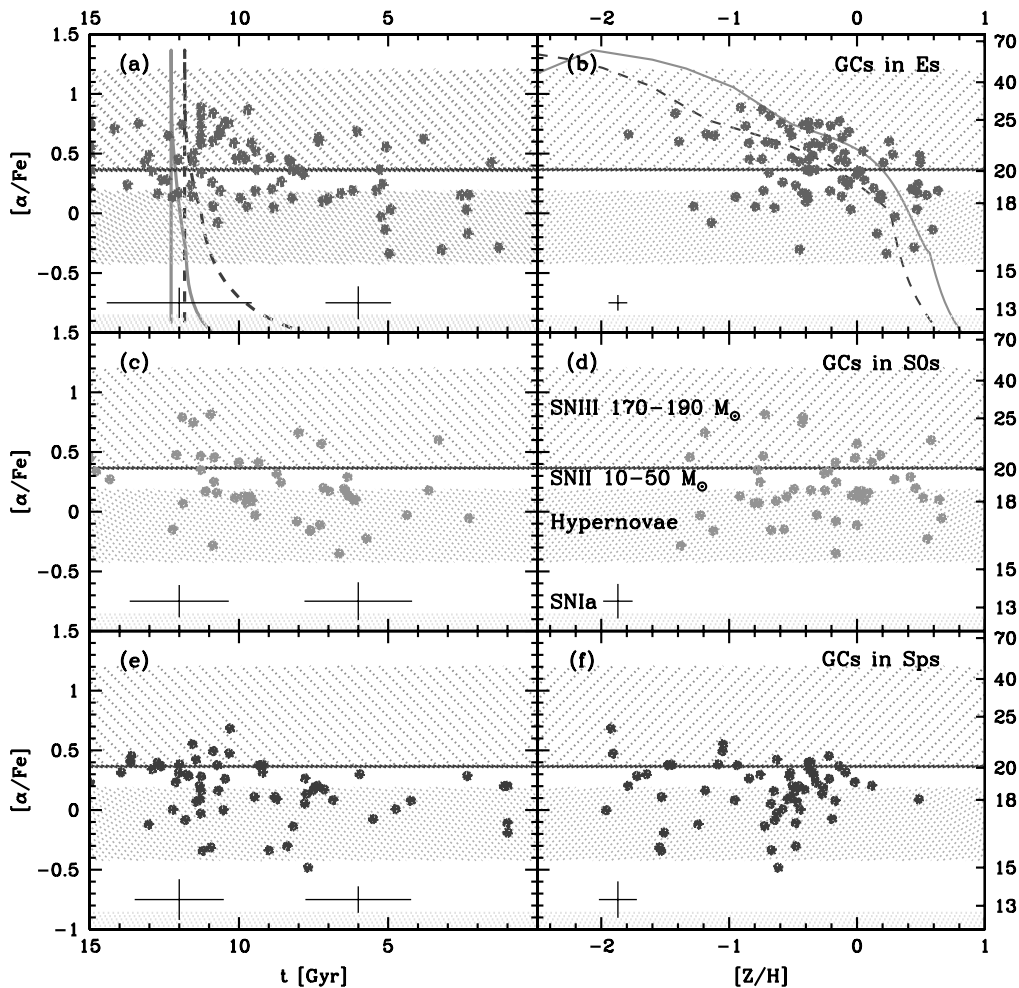


FIG. 3.—Correlation plots of $[\alpha/\text{Fe}]$ ratios with ages (left panels) and metallicities (right panels) for globular clusters in elliptical (top row), lenticular (middle row), and spiral galaxies (bottom row). To illustrate the enrichment by supernovae of different types, mean $[\alpha/\text{Fe}]$ ratios of the ejecta of type Ia SNe (yellow shading), cumulative Type II SNe ejecta with progenitor masses in the range $10\text{--}50 M_{\odot}$ (thick horizontal line) integrated over a Salpeter IMF, hypernovae with very large explosion energies $\geq 10^{52}$ ergs (cyan shading), and Type III pair-instability SNe with progenitor masses $170\text{--}190 M_{\odot}$ (magenta hatched region) were overplotted (see § 4.1 for details). The right ordinate indicates progenitor masses of Type II SNe that produce the $[\alpha/\text{Fe}]$ indicated by the left ordinate. In the upper panels (a and b), we plot two enrichment models for an elliptical galaxy with $10^{10} M_{\odot}$ (dashed line) and $10^{12} M_{\odot}$ initial baryonic mass (solid line), taken from Pipino & Matteucci (2004). Small crosses indicate average statistical errors. Because of the changing $\Delta t/t$, the statistical age uncertainties were calculated for the young and old subsamples split at 8 Gyr. [See the electronic edition of the Journal for a color version of this figure.]

mean metallicity, while the spiral sample is much less affected by this bias and probes significantly lower globular cluster metallicities, down to $[Z/H] \approx -2.0$. The corresponding median metallicities are $[Z/H] = -0.32, -0.23,$ and -0.58 dex, for the elliptical, lenticular, and spiral sample, respectively.

Perhaps the most striking feature in Figure 2 is the very broad and possibly bimodal $[\alpha/\text{Fe}]$ distribution for globular clusters in elliptical galaxies (upper right panel), with a high- $[\alpha/\text{Fe}]$ “shoulder” reaching values up to ~ 1.0 dex. This shoulder is significantly less developed in the sample of lenticular galaxies and entirely absent for the sample of spiral galaxies. Both spiral and lenticular samples have a median value of $[\alpha/\text{Fe}] \sim 0.2$ dex, twice as low as for the sample of ellipticals. We emphasize that, although NGC 1380 GCS may slightly dominate the high- $[\alpha/\text{Fe}]$ values in the lenticular sample, no single globular cluster system dominates any of the distributions. Instead, globular clusters from all galaxies populate the derived distributions rather homogeneously (see Fig. 1).

Although there is some evidence for multiple components in the probability density estimate of the $[\alpha/\text{Fe}]$ distribution of globular clusters in ellipticals, the KMM algorithm (Ashman et al.

1994) rejects the hypothesis that the distribution is different from the bimodal at a $\sim 2 \sigma$ level. The test does not strongly support bimodality, but does provide additional evidence that the $[\alpha/\text{Fe}]$ distribution for globular clusters in ellipticals is significantly broader and reaches much higher $[\alpha/\text{Fe}]$ values than those for globular clusters in lenticular and spiral galaxies.

4. DISCUSSION

While the average properties of the samples were already addressed in Puzia et al. (2005a), we focus here on the globular clusters showing extreme $[\alpha/\text{Fe}]$ values. Figure 3 shows $[\alpha/\text{Fe}]$ plotted against age (left panels) and metallicity (right panels) for globular clusters in elliptical, lenticular, and spiral galaxies (from top to bottom). The direct comparison of GCSs shows important differences: globular clusters tend to have higher $[\alpha/\text{Fe}]$ ratios and reach higher metallicities in hosts with earlier morphological type. Most of the extremely α -enhanced clusters ($[\alpha/\text{Fe}] > 0.5$) are old ($t \geq 8$ Gyr), and are mainly found in elliptical galaxies. Very few counterparts are found in lenticular and spiral galaxies. The metallicities of these extreme $[\alpha/\text{Fe}]$ clusters span a wide range from metal poor ($[Z/H] \approx -2$ dex) to solar, concentrating

around values between $-1 \lesssim [Z/H] \lesssim 0$ dex in ellipticals and lenticulars, while the few candidates in spirals have metallicities $[Z/H] \lesssim -1$ dex. There is tentative evidence for an age- $[\alpha/\text{Fe}]$ correlation for globular clusters in elliptical galaxies (correlation coefficient 0.5; see Fig. 3a), in the sense that younger globular clusters have, on average, lower $[\alpha/\text{Fe}]$ ratios. For metal-rich globular clusters ($[Z/H] > -1.0$) in elliptical galaxies, we find an anticorrelation of $[\alpha/\text{Fe}]$ and metallicity, which becomes weaker toward later type hosts. At face value, these results suggest that a first generation of globular clusters in elliptical galaxies was enriched to much higher $[\alpha/\text{Fe}]$ values (i.e., faster) than in lenticular and spiral galaxies.

4.1. Chemical Enrichment with Different SN Types

We explore in the following whether the $[\alpha/\text{Fe}]$ ratios of the extremely α -enriched clusters can be reproduced by state-of-the-art supernova yield models. For this purpose, we compute $[\alpha/\text{Fe}]$ ratios of the ejecta of Type II SNe in the mass range $13\text{--}70 M_{\odot}$ (Nomoto et al. 1997a), Type Ia SNe (Nomoto et al. 1997b), hypernovae with very large explosion energies $\gtrsim 10^{52}$ ergs (Nakamura et al. 2001), and pair-instability SNe with progenitor masses $>160 M_{\odot}$ (Heger & Woosley 2002). To stay consistent with the definitions of the SSP models, we compute $[\alpha/\text{Fe}]$ ratios of the SN yields as the mass of the α -elements N, O, Mg, Ca, Na, Ne, S, Si, and Ti relative to the mass of the Fe-peak elements Cr, Mn, Fe, Co, Ni, Cu, and Zn. The results are normalized to the solar abundances given in Anders & Grevesse (1989). We note that other combinations of α elements, in particular the addition of carbon, does not affect the results.

The $[\alpha/\text{Fe}]$ ratio of the cumulative ejecta of core-collapse SNe with progenitor masses $10\text{--}50 M_{\odot}$ integrated over a Salpeter IMF is indicated in Figure 3 as a solid horizontal line at ~ 0.36 dex. Such an IMF extending to high masses can reproduce the $[\alpha/\text{Fe}]$ ratios of virtually all globular clusters in spirals, and the majority of globular clusters in lenticular galaxies, but not the most extreme $[\alpha/\text{Fe}]$ ratios of globular clusters in elliptical galaxies. A significant contribution of massive stars ($\gtrsim 20 M_{\odot}$) is necessary to boost the $[\alpha/\text{Fe}]$ beyond ~ 0.4 dex (see Fig. 3). The ejecta of pair-instability SNe, which require very metal-poor progenitor stars, are expected to be rich in α -elements (Heger & Woosley 2002). Our calculations indicate that the parent gas clouds of globular clusters can be enriched to extreme $[\alpha/\text{Fe}]$ ratios by pair-instability SNe with masses $\sim 130\text{--}190 M_{\odot}$. We find that hypernovae with progenitor masses $6\text{--}16 M_{\odot}$ are ruled out as primary contributors to gas with $[\alpha/\text{Fe}] \gtrsim 0.4$, since their ejecta are not α -enriched enough.

We assume that the extreme globular clusters considered here have similar masses to Milky Way globular clusters. For example, for a typical mass of $\sim 10^{5.5} M_{\odot}$, and measured metallicities of up to $[Z/H] \approx 0$, the total *metal* content of the parent gas cloud amounts to up to $\sim 5600 M_{\odot}$. One way of producing this amount of metals is to assume a progenitor/enriching stellar population composed of high-mass ($\gtrsim 20 M_{\odot}$) stars only (i.e., a progenitor stellar population with an IMF truncated at the lower end at $20 M_{\odot}$), combined with a sufficiently high star-formation rate to enable the formation of such massive stars (see Goodwin & Pagel 2005). In any other scenario, the extreme $[\alpha/\text{Fe}]$ ratios require extremely short enrichment timescales, i.e., a very short time between the SN explosion of massive stars and the formation of globular clusters: of the order of the lifetime of a $20 M_{\odot}$ star, corresponding to a few Myr.

Our empirical result that globular clusters with such extreme chemical compositions mainly reside in early-type galaxies but seem absent in spirals suggests a fundamental difference in en-

richment timescales between some phase(s) of globular cluster system formation.

A bimodality in the $[\alpha/\text{Fe}]$ distribution, as hinted by the top right panel of Figure 2, would imply a cessation of globular cluster formation processes over a period short enough to be unresolved in age (on the scale of Fig. 3, $\sim 10^9$ yr), but lasting long enough to allow a significant chemical contribution from lower mass stars ($\lesssim 20 M_{\odot}$, i.e., a few 10^6 yr). Speculating whether such a delay could occur in the course of massive galaxy evolution, we note that it might be introduced by the re-ionization epoch at redshifts $6 < z \lesssim 20$, which, for a few 10^7 yr, may have halted, or at least suppressed, the formation of massive star clusters and enabled the generation of less α -enriched globular clusters that seem to dominate GCSs in lenticulars and spirals.

4.2. Comparison with Chemical Evolution Models

We compare our observational result for globular clusters with photochemical evolution models of elliptical galaxies by Pipino & Matteucci (2004). In Figure 3, we plot the predictions for $[\alpha/\text{Fe}]$ ratios for two galaxies with 10^{10} and $10^{12} M_{\odot}$ initial baryonic mass. The direct comparison shows that extreme $[\alpha/\text{Fe}]$ ratios can only be achieved within the first $\lesssim 0.2$ Gyr after the ignition of star formation processes. Furthermore, the models predict total metallicities similar to those of the most metal-rich extremely α -enhanced globular cluster in our sample. Note that the absolute starburst ignition time is arbitrarily set in the models; i.e., one can delay the starburst ignition time by an arbitrary amount that would leave the predictions of $[\alpha/\text{Fe}]$ as a function of time *after* the burst unchanged. The delay between the bursts of 10^{12} and $10^{10} M_{\odot}$, on the other hand, *is* fixed in the models, and depends on the total gas mass in a given halo. This implies that less massive starbursts, occurring later from material with a chemical composition similar to more massive starbursts, can produce globular clusters with similarly high $[\alpha/\text{Fe}]$ ratios, but with younger ages. In a hierarchical galaxy-formation picture, these younger clusters are subsequently merged into more massive halos.

It is important to realize that the very high $[\alpha/\text{Fe}]$ ratios for old globular clusters in elliptical galaxies are *not* mirrored in the *average* $[\alpha/\text{Fe}]$ of the field stellar population as measured from the diffuse light. Using the same SSP models as in this study, Thomas et al. (2005) recently found that early-type galaxies have lower luminosity-weighted $[\alpha/\text{Fe}]$ values ($\langle [\alpha/\text{Fe}] \rangle_E \approx 0.25$), with very few galaxies showing $[\alpha/\text{Fe}] > 0.3$ dex, i.e., values comparable to those of the low- $[\alpha/\text{Fe}]$ peak of globular clusters in ellipticals and most clusters in lenticular and spiral galaxies. This suggests that the formation of massive globular clusters with extremely high $[\alpha/\text{Fe}]$ ratios predates the formation of the *majority of stars* in elliptical galaxies. However, we emphasize that our findings do *not* exclude the presence of some extremely α -enriched field stars in elliptical galaxies.

Interestingly, this would be consistent with the popular scenario in which stars are born in star clusters and gradually become part of the diffuse light through evaporation by two-body relaxation and tidal stripping of the star clusters (e.g., Lada & Lada 2003; Fall et al. 2005). Indeed, the timescale of such disruption mechanisms is very long (more than a Hubble time) for massive globular clusters of $\sim 10^{5.5} M_{\odot}$ and shorter for less massive ones ($\dot{M}/M \propto M^{-1/2}$ for two-body relaxation; e.g., Fall & Zhang 2001), so that most of the diffuse light in ellipticals would originate, in such a scenario, from lower mass clusters, most of which dissolved after a few Gyr or sooner (see also Goudfrooij et al. 2004). This actually suggests that lower mass clusters in ellipticals should generally *not* show $[\alpha/\text{Fe}] \gtrsim 0.4$,

which would imply a later formation. These predictions should be testable in the near future.

5. SUMMARY

We present $[\alpha/\text{Fe}]$, metallicity, and age distributions of globular clusters in elliptical, lenticular, and spiral galaxies, that were derived from Lick line index measurement and identify a population of globular clusters with extreme $[\alpha/\text{Fe}]$ ratios. The main results of our study of extremely α -enriched globular clusters are: (1) they are predominantly found in early-type galaxies, (2) most of these highly α -enriched globular clusters are old ($t > 8$ Gyr), and cover the metallicity range $-1 \lesssim [Z/\text{H}] \lesssim 0$, (3) a comparison with supernova yield models suggests that the progenitor gas clouds of these globular clusters were predominantly enriched by massive stars ($\gtrsim 20 M_{\odot}$), and (4) given the lower *average* $[\alpha/\text{Fe}]$

ratios of the diffuse stellar population in early-type galaxies, our results suggest that the extremely α -enhanced globular clusters are members of the very first generation of star clusters formed, and that their formation epochs likely predate the formation of the *majority of field stars* in giant early-type galaxies.

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REFERENCES

- Anders, E., & Grevesse, N. 1989, *Geochim. Cosmochim. Acta*, 53, 197
 Ashman, K. M., Bird, C. M., & Zepf, S. E. 1994, *AJ*, 108, 2348
 Ashman, K. M., & Zepf, S. E. 1998, *Globular Cluster Systems* (New York: Cambridge Univ. Press)
 Beasley, M. A., Brodie, J. P., Strader, J., Forbes, D. A., Proctor, R. N., Barmby, P., & Huchra, J. P. 2004, *AJ*, 128, 1623
 Brodie, J. P., Strader, J., Denicoló, G., Beasley, M. A., Cenarro, A. J., Larsen, S. S., Kuntschner, H., & Forbes, D. A. 2005, *AJ*, 129, 2643
 Cohen, J. G., Blakeslee, J. P., & Ryzhov, A. 1998, *ApJ*, 496, 808
 Côté, P., et al. 2004, *ApJS*, 153, 223
 Fall, S. M., Chandar, R., & Whitmore, B. C. 2005, *ApJ*, 631, L133
 Fall, S. M., & Zhang, Q. 2001, *ApJ*, 561, 751
 Gebhardt, K., & Kissler-Patig, M. 1999, *AJ*, 118, 1526
 Goodwin, S. P., & Pagel, B. E. J. 2005, *MNRAS*, 359, 707
 Goudfrooij, P., Gilmore, D., Whitmore, B. C., & Schweizer, F. 2004, *ApJ*, 613, L121
 Harris, W. E. 1991, *ARA&A*, 29, 543
 Heger, A., & Woosley, S. E. 2002, *ApJ*, 567, 532
 Kissler-Patig, M., Brodie, J. P., Schroder, L. L., Forbes, D. A., Grillmair, C. J., & Huchra, J. P. 1998, *AJ*, 115, 105
 Kundu, A., & Whitmore, B. C. 2001a, *AJ*, 121, 2950
 ———. 2001b, *AJ*, 122, 1251
 Kuntschner, H., Ziegler, B. L., Sharples, R. M., Worthey, G., & Fricke, K. J. 2002, *A&A*, 395, 761
 Lada, C. J., & Lada, E. A. 2003, *ARA&A*, 41, 57
 Larsen, S. S., Brodie, J. P., Beasley, M. A., & Forbes, D. A. 2002, *AJ*, 124, 828
 Larsen, S. S., Brodie, J. P., Beasley, M. A., Forbes, D. A., Kissler-Patig, M., Kuntschner, H., & Puzia, T. H. 2003, *ApJ*, 585, 767
 Maraston, C., Greggio, L., Renzini, A., Ortolani, S., Saglia, R. P., Puzia, T. H., & Kissler-Patig, M. 2003, *A&A*, 400, 823
 Nakamura, T., Umeda, H., Iwamoto, K., Nomoto, K., Hashimoto, M.-a., Hix, W. R., & Thielemann, F.-K. 2001, *ApJ*, 555, 880
 Nomoto, K., Hashimoto, M., Tsujimoto, T., Thielemann, F.-K., Kishimoto, N., Kubo, Y., & Nakasato, N. 1997a, *Nucl. Phys. A*, 616, 79
 Nomoto, K., Iwamoto, K., Nakasato, N., Thielemann, F.-K., Brachwitz, F., Tsujimoto, T., Kubo, Y., & Kishimoto, N. 1997b, *Nucl. Phys. A*, 621, 467
 Olsen, K. A. G., Miller, B. W., Suntzeff, N. B., Schommer, R. A., & Bright, J. 2004, *AJ*, 127, 2674
 Peng, E. W., Ford, H. C., & Freeman, K. C. 2004, *ApJ*, 602, 705
 Pipino, A., & Matteucci, F. 2004, *MNRAS*, 347, 968
 Puzia, T. H., Kissler-Patig, M., Brodie, J. P., & Huchra, J. P. 1999, *AJ*, 118, 2734
 Puzia, T. H., Kissler-Patig, M., Thomas, D., Maraston, C., Saglia, R. P., Bender, R., Goudfrooij, P., & Hempel, M. 2005a, *A&A*, 439, 997
 Puzia, T. H., Kissler-Patig, M., Thomas, D., Maraston, C., Saglia, R. P., Bender, R., Richtler, T., Goudfrooij, P., & Hempel, M. 2004, *A&A*, 415, 123
 Puzia, T. H., Perrett, K. M., & Bridges, T. J. 2005b, *A&A*, 434, 909
 Puzia, T. H., Saglia, R. P., Kissler-Patig, M., Maraston, C., Greggio, L., Renzini, A., & Ortolani, S. 2002, *A&A*, 395, 45
 Recchi, S., & Danziger, I. J. 2005, *A&A*, 436, 145
 Schroder, L. L., Brodie, J. P., Kissler-Patig, M., Huchra, J. P., & Phillips, A. C. 2002, *AJ*, 123, 2473
 Searle, L., & Zinn, R. 1978, *ApJ*, 225, 357
 Silverman, B. W. 1986, *Density Estimation for Statistics and Data Analysis* (London: Chapman and Hall)
 Shapley, H. 1918, *ApJ*, 48, 154
 Strader, J., Brodie, J. P., & Forbes, D. A. 2004, *AJ*, 127, 295
 Thomas, D., Maraston, C., & Bender, R. 2003, *MNRAS*, 339, 897
 Thomas, D., Maraston, C., Bender, R., & de Oliveira, C. M. 2005, *ApJ*, 621, 673
 Thomas, D., Maraston, C., & Korn, A. 2004, *MNRAS*, 351, L19
 Tornambé, A., & Matteucci, F. 1986, *MNRAS*, 223, 69
 Trager, S. C., Worthey, G., Faber, S. M., Burstein, D., & Gonzalez, J. J. 1998, *ApJS*, 116, 1
 Whitmore, B. C., & Schweizer, F. 1995, *AJ*, 109, 960
 Whitmore, B. C., Schweizer, F., Leitherer, C., Borne, K., & Robert, C. 1993, *AJ*, 106, 1354
 Worthey, G., Faber, S. M., Gonzalez, J. J., & Burstein, D. 1994, *ApJS*, 94, 687
 Worthey, G., & Ottaviani, D. L. 1997, *ApJS*, 111, 377
 Zinn, R. 1985, *ApJ*, 293, 424