THE AGES AND ABUNDANCES OF A SAMPLE OF GLOBULAR CLUSTERS IN M49 (NGC 4472)¹

JUDITH G. COHEN,² J. P. BLAKESLEE,³ AND P. CÔTÉ⁴

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ABSTRACT

We present a study of the metallicity and age of the globular clusters system of M49 (NGC 4472), the most luminous galaxy in the Virgo Cluster. We measure Lick indices for 47 globular clusters (GCs) in M49 from LRIS/Keck spectra and establish their metallicity parameters qualitatively in comparison to the Galactic GCs and to published data for 150 M87 GCs. We then compare our measurements with the predictions of models for the integrated light of old single-burst stellar systems by Worthey and by Thomas, Maraston, & Bender. We find that the metallicity of the M49 GC system spans the range from $[\text{Fe}/\text{H}]_Z = -2.0$ to $+0.4$ dex. We show that the metallicity and age parameters for these two GC systems are basically identical, except that the M49 GCs reach slightly higher metallicities than do those of M87. We find that the GCs of both of these giant elliptical galaxies are α -enhanced by a factor of about 2 above the solar value, as is also true of the Galactic GCs. Thus the most metal rich GCs in M49 reach $[Z/\text{H}] \sim +0.8$ dex, comparable to that of M49 itself. While adoption of the α -enhanced models of Thomas et al. has eliminated most of the previous discrepancies with observations, the most metal rich M49 GCs have Na D lines that are still considerably stronger than those predicted by any model, and there are still issues involving the metallicity scale of these models. We find that in the mean, the M49 GCs are at least 10 Gyr old. However, the grids of models we used differ in how they treat the horizontal branch, and this perceptibly affects the predicted $\text{H}\beta$ index. Hence our current incomplete understanding of the role of the horizontal branch limits our ability to derive a more detailed distribution for the ages of the GCs in M49 and in M87.

Subject headings: galaxies: abundances — galaxies: evolution — galaxies: formation — galaxies: individual (NGC 4472, NGC 4486) — galaxies: star clusters

1. INTRODUCTION

M49 (NGC 4472) is the most luminous galaxy in the Virgo Cluster, with $M_V = -22.6$, and is more luminous than any closer galaxy. It is, however, not located at or near the dynamical center of the cluster. Instead, M87 resides at the center of this deep potential well, surrounded by a huge amount of X-ray-emitting gas, while M49 is at the center of the modest Virgo B subcluster more than 4.5° away. The globular cluster (GC) system of M49 is rich, with a signal-to-noise ratio $S/N = 3.6 \pm 0.6$ (~ 5900 GCs in total; Rhode & Zepf 2001), but that of M87 is even richer ($S/N = 14 \pm 4$, with $\sim 13,450$ GCs in total; McLaughlin, Harris, & Hanes 1994). The enormous GC system of M87 made it a tempting target, and J. Cohen and collaborators carried out an exhaustive study of the kinematics of the GC system of M87 (Cohen & Ryzhov 1997; Cohen 2000) and of the ages and abundances of a large sample of M87 GCs (Cohen, Blakeslee, & Ryzhov 1998). We then felt a need to investigate the GC system of M49 to understand which attributes of the GC system of M87 might be unique to its special location and which generic to luminous giant elliptical galaxies. Our analysis of the kinematics of the GC system of M49 and inferences concerning the distribution of mass and dark

matter in M49 and the isotropy of the GC orbits are given in Côté et al. (2003), while the most recent radial velocity tabulation and kinematic analysis for the M87 GC system can be found in Hanes et al. (2001) and Côté et al. (2001). Here we utilize the best of our spectra to explore the distribution in age and in metallicity as well as the abundance ratios of the GC system of M49.

The first attempts to determine the metallicity of the Virgo GC system were based on wide-field photometry. This began with the work of Strom et al. (1981) for M87 and that of Cohen (1988) for M49, but we jump to the ground-based wide-field Washington photometry of Geisler, Lee, & Kim (1996) and to the *Hubble Space Telescope*-based analysis of Whitmore et al. (1995). In these recent studies, the key new result was the detection of strong bimodality in the color distribution of the GCs. Although no separation of age and metallicity was possible, the observed color distribution of the GCs was assumed to reflect the intrinsic metallicity distribution. Such a bimodal metallicity distribution might arise through GC formation in major mergers, through the hierarchical assembly of the galaxy, through numerous dissipationless mergers, or through multiple, internally driven bursts of star and cluster formation (for a review of the various formation models, see Carney & Harris 2001).

Mould et al. (1990) obtained the first spectra of GCs in M49 and from their sample of 26 GCs suggested the mean metallicity of the M49 GC system was $\frac{1}{6}$ solar. Sharples et al. (1998) presented spectra and a kinematic analysis for an additional 47 GCs in M49. Spectra of another 87 GCs in M49 were obtained by Zepf et al. (2000), who presented a kinematic analysis. Beasley et al. (2000) carried out an analysis of the available spectra for 131 GCs in M49. However, their spectra have low S/N s, and they could not derive

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² Palomar Observatory, MS 105-24, California Institute of Technology, Pasadena, CA 91125.

³ Department of Physics and Astronomy, Center for Astrophysical Sciences, Johns Hopkins University, 3400 North Charles Street, Baltimore, MD 21218.

⁴ Department of Physics and Astronomy, Rutgers University, 136 Frelinghuysen Road, Piscataway, NJ 08854-8019.

any relevant parameters for individual M49 GCs. Instead, they summed the spectra into four bins in the $C-T_1$ color of the Washington photometry of Geisler et al. (1996), assuming this correlated with metallicity, to derive mean abundances and ages.

The advantage of LRIS (Oke et al. 1995), which is a multi-slit instrument utilizing the large collecting area of the 10 m Keck Telescope, in this situation is crucial. We are able to derive credible parameters for individual GCs in Virgo Cluster galaxies. Since the work of Cohen et al. (1998), the sophistication of the available models of the integrated light of old stellar systems has increased, and we explore here the issue of possible α -enhancement (nonsolar ratios of Mg/Fe or Na/Mg) in both M87 and in M49 as well as the metallicity (i.e., $[\text{Fe}/\text{H}]^5$) and age of the GCs in these two galaxies.

2. SELECTION OF CANDIDATES AND OBSERVATIONS

The photometric study of the GC system of M49 (NGC 4472) with the intermediate-band Washington filter system by Geisler et al. (1996) was used to define the sample of candidate GCs, which are identified using their numbering system. Coordinates for the candidates were determined as described in Côté et al. (2003). A color cut of $1.0 \leq (C-T_1) \leq 2.25$ mag, similar to that used by Geisler (1996), was imposed to avoid contamination by foreground Galactic stars or background galaxies. In practice, essentially no genuine GC candidates are found outside this range (Lee & Geisler 1993; Ostrov, Forte, & Geisler 1998). For the present work, we preferentially selected those spectroscopically confirmed GCs in M49 (either from our own radial velocity catalog as it existed in early 2000 or from the literature) that were bright, with $T_1 < 20.5$, where T_1 is very close to R (Geisler & Forte 1990). The positions of these bright GCs were then used to design two LRIS slit masks. Additional bright candidate GCs from the database of Geisler et al. (1996) were added to maximize the number of slits per mask.

The two slit masks were observed with LRIS (Oke et al. 1995) at the Keck Telescope on the night of 2000 May 1. The weather conditions were good, with seeing $0''.7-0''.8$. A 600 groove mm^{-1} grating blazed at 5000 Å (spectrum centered near 5400 Å, and covering roughly the range from $\text{H}\beta$ to $\text{H}\alpha$ for a slitlet near the center line of the slit mask) gave a spectral resolution of 1.2 Å pixel^{-1} , or 5.8 Å , for the $1''.0$ wide slitlets. Three 3000 s exposures were obtained for the first slit mask and two for the second. The spectra from this run, which are the only ones utilized in the present paper, are the best of the 196 new spectra for M49 GCs discussed in Côté et al. (2003).

The spectra were reduced using Figaro (Shortridge 1993) scripts developed for analysis of LRIS multislit spectra as described in our work on the GC system of M87 (Cohen & Ryzhov 1997). One improvement from our earlier work was in the wavelength calibration of the spectra. As before, we used the a third-order polynomial fit to the night-sky emission lines in the spectrum from each slitlet to calibrate the wavelength scale. A problem encountered in our previous work on M87 was the lack of any detectable night-sky lines

TABLE 1
BACKGROUND GALAXIES

Identification ^a	R.A. (B1950.0)	Decl. (B1950.0)	R (mag)	z
(1650).....	12 27 23.68	+8 13 42.3	>23.5	0.629 ^b
1982.....	12 27 09.13	+8 13 42.1	20.6	0.086
(1982).....	12 27 09.97	+8 13 42.3	23.7	0.434
(2569).....	12 27 11.68	+8 14 31.6	23.3	0.091
(1798).....	12 27 12.48	+8 13 25.0	22.1	0.314 ^c

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

^a Identifications in parentheses denote serendipitous galaxies found in the slitlet intended for the GC candidate listed. The database of Geisler et al. 1996 is used.

^b This redshift is based on a single emission line assumed to be that of $[\text{O II}]$ at 3727 Å.

^c The redshift for this galaxy comes from H+K absorption. For all the other galaxies in this table, it is derived from emission lines.

blueward of the 5199 Å $[\text{N I}]$ line. (Keck spectra do not show Hg or other emission features from city lights in 1 hr exposures with LRIS.) Since we wished to examine the region around $\text{H}\beta$, we were forced to extrapolate the wavelength fit uncomfortably far; such a procedure sometimes leads to runaways in the fit in the unconstrained region at the beginning or end of the spectrum. Thus in the present work a search was made for additional night-sky emission lines in these spectra blueward of 5199 Å. A very weak line was found at 4968.8 Å, whose reality was checked on several spectra of other objects. With this additional line, arising from a transition in O I, the wavelength scale is now more robust at $\text{H}\beta$.

The radial velocities of the M49 GC candidates were determined as described in Cohen & Ryzhov (1997). Typical 1σ errors in the wavelength fit are less than 0.1 Å ; these are a minor contributor to the assigned v_r errors, which are based on the S/N of the spectra. Comparison of the v_r measured from various features suggests that these assigned errors are quite conservative. The radial velocities from these observations are included as part of our larger database on GCs in M49 presented in Côté et al. (2003) and are tabulated there.

The resulting one-dimensional spectra, summed along the slit and over the available exposures, cannot be fluxed effectively because of the variable slit losses inherent in the use of a multislit mask with fairly narrow slits.

2.1. Foreground and Background Objects

Geisler 1982 appeared extended on the slit-mask alignment setup images, and its spectrum is that of a galaxy. The redshifts of four additional galaxies that turned up serendipitously in the slitlets, as well as that of Geisler 1982, are given in Table 1. The R magnitudes given in the table are from our photometry carried out on the slit mask alignment images taken with LRIS. Only one Galactic star, Geisler 2860, was found among the objects observed. After elimination of foreground and background objects, we have a sample of 47 GCs in M49 with LRIS spectra.

3. MEASURED INDICES

We have measured the standard Lick indices (Faber et al. 1985; Burstein et al. 1986) as well as the $\text{H}\alpha$ index defined in

⁵ The standard nomenclature is adopted; $[\text{X}/\text{H}] = \log_{10}[\text{N}(\text{X})/\text{N}(\text{H})] - \log_{10}[\text{N}(\text{X})/\text{N}(\text{H})]_{\odot}$, and similarly for $[\text{X}/\text{Fe}]$.

our earlier work (Cohen et al. 1998) on the M87 GC system. The codes with which this was accomplished are the same Figaro (Shortridge 1993) routines used in Cohen et al. (1998). These take the standard bandpasses, shift them in accordance with the radial velocity of each object, and then calculate the indices.

The results of this automatic procedure were examined, and discrepant and/or problem cases were checked individually. The Na D indices in these faint objects are particularly difficult as the corresponding emission lines from the night sky must be removed. Some of the spectra were rereduced manually in an effort to improve the night-sky

subtraction. $H\alpha$ is beyond the red end of the spectra for a few of the M49 GC candidates; for several others, this index had to be measured by hand when the red continuum bandpass for this feature was only partially included.

The resulting set of indices are listed in Table 2. Because the spectra are not fluxed and are not matched to the spectral response used to define the Lick system, as no Lick standard stars were observed, those indices that span wide ranges in wavelength may have systematic offsets from the nominal Lick system. The narrower feature indices that we will use, such as $H\beta$, $Mg\ b$, $Fe5270$, and Na D, are not significantly affected by this concern.

TABLE 2
MEASURED INDICES

Identification ^a	$H\beta$ (Å)	Mg_2 (mag)	Mg_1 (mag)	$Mg\ b$ (Å)	$Fe5270$ (Å)	$Fe5335$ (Å)	Na D (Å)	TiO1 (mag)	TiO2 (mag)	$H\alpha$ (Å)	S/N ^b
1475.....	2.13	0.14	0.045	2.11	3.14	0.59	0.46	0.031	0.060	2.04	16.3
1508.....	0.30	0.31	0.081	4.81	2.60	1.71	5.58	0.055	0.201	2.25	5.4
1650.....	1.31	0.31	0.101	5.50	2.65	2.91	3.98	0.038	0.058	0.74	15.1
1731.....	1.60	0.24	0.101	4.54	2.57	4.20	1.66	0.039	0.106	1.62	11.8
1798.....	1.33	0.36	0.117	5.81	2.78	3.45	5.73	0.044	0.095	0.81	14.7
1846.....	0.03	0.37	0.201	5.61	3.36	3.28	5.56	0.084	0.109	1.97	8.7
1889.....	2.42	0.03	-0.010	0.67	1.00	0.30	0.90	-0.014	-0.084	2.60	14.1
1892.....	0.89	0.07	0.018	1.82	-0.03	-0.55	0.37	0.052	0.021	2.48	9.4
1905.....	2.85	0.08	0.015	2.04	2.58	1.20	3.60	-0.007	-0.004	3.25	13.4
2013.....	2.47	0.08	0.044	0.61	1.50	1.14	2.41	0.030	0.043	2.35	13.2
2031.....	2.87	0.10	0.027	1.80	2.07	1.25	1.72	-0.012	0.010	2.19	17.2
2045.....	1.58	0.19	0.105	2.92	3.16	2.38	3.00	0.034	0.063	1.95	15.2
2060.....	1.74	0.08	0.017	1.02	1.33	1.78	0.92	0.006	-0.159	2.63	27.6
2178.....	1.59	0.04	0.010	1.86	-0.04	1.35	1.25	-0.013	0.024	2.68	10.8
2188.....	0.90	0.13	0.027	2.60	1.75	0.37	1.30	0.025	0.040	2.03	13.1
2306.....	1.86	0.18	0.087	2.80	2.74	0.64	1.87	0.034	0.048	2.24	19.9
2406.....	0.66	0.35	0.157	5.39	3.96	3.01	5.42	0.052	0.092	...	13.6
2421.....	2.33	0.13	0.011	1.47	3.55	0.76	1.26	0.018	-0.027	2.17	14.3
2502.....	2.41	0.23	0.098	3.92	3.50	2.25	3.54	0.035	0.048	...	12.7
2528.....	2.33	0.09	0.038	2.14	1.57	0.98	1.12	0.012	0.039	2.00	22.0
2543.....	2.13	0.08	0.020	1.47	2.21	1.51	1.34	-0.010	0.029	...	25.6
2569.....	1.75	0.29	0.131	5.10	3.30	2.64	4.72	0.039	0.063	...	23.3
2813.....	2.16	0.30	0.168	5.20	2.57	2.12	4.62	0.016	0.078	...	10.4
3150.....	1.78	0.26	0.112	4.15	2.74	2.04	3.14	0.020	0.119	1.49	13.0
3603.....	2.14	0.26	0.098	5.24	3.27	2.70	3.12	0.037	0.083	2.05	12.8
3788.....	2.61	0.18	0.086	5.13	4.64	0.50	2.33	0.018	0.069	3.18	8.5
3900.....	0.64	0.43	0.177	6.31	1.87	3.69	7.39	0.018	0.083	1.24	8.5
4017.....	1.37	0.08	0.037	1.92	1.00	1.56	2.12	-0.002	0.011	1.20	17.1
4062.....	0.14	0.37	0.106	7.32	2.98	5.38	6.98	-0.018	0.080	2.08	6.9
4144.....	2.23	0.04	0.009	1.91	1.44	0.78	0.48	0.011	0.015	2.31	19.7
4168.....	2.14	0.17	0.067	2.83	2.66	1.98	1.21	0.022	0.060	1.49	21.6
4217.....	2.13	0.26	0.062	4.20	3.96	2.31	2.95	0.034	0.037	2.85	11.1
4296.....	2.14	0.05	0.012	1.91	0.86	-0.66	1.39	-0.018	0.004	2.47	12.7
4351.....	1.54	0.05	-0.021	1.08	0.97	0.00	0.78	0.031	-0.016	2.20	12.5
4401.....	1.64	0.30	0.115	4.81	3.12	4.29	4.69	0.043	0.075	2.09	14.2
4513.....	1.79	0.27	0.139	4.64	2.19	2.02	3.14	0.043	0.083	1.08	22.1
4541.....	2.34	0.09	0.020	2.69	1.48	1.05	1.06	0.024	0.085	2.33	11.4
4663.....	1.54	0.24	0.100	4.27	3.42	2.29	2.84	0.030	0.059	1.96	17.0
4682.....	1.31	0.17	0.044	3.33	3.15	2.39	5.4	-0.033	0.059	3.61	9.0
4834.....	1.53	0.05	0.011	1.79	0.98	1.08	2.11	-0.031	0.035	...	13.0
4852.....	2.06	0.32	0.153	6.32	2.94	2.94	5.09	0.034	0.088	...	10.8
4864.....	1.92	0.18	0.078	3.60	0.20	1.56	0.76	0.005	-0.008	...	22.1
5003.....	1.62	0.11	0.019	2.89	1.09	1.69	0.67	0.029	0.056	...	15.2
5018.....	1.19	0.36	0.165	5.34	3.78	2.87	7.98	0.050	0.103	...	12.0
5097.....	1.27	0.46	0.225	7.47	3.37	3.25	9.19	0.070	0.100	...	12.2
5217.....	2.80	0.07	-0.008	1.36	0.60	2.29	1.21	0.000	0.011	...	15.5
6051.....	3.61	0.12	0.042	3.43	1.94	1.39	1.35	0.000	0.658	...	15.6

^a From Geisler et al. 1996.

^b Signal-to-noise ratio per spectral pixel over the region 5950–6250 Å.

The last column of this table gives the S/N per spectral pixel in the final spectrum, measured over the interval 5950–6250 Å. Within this wavelength interval the observed spectra are approximately constant in DN pixel⁻¹ and there are few strong spectral features. The signal level in the continuum at H β is 60%–75% of that at 6100 Å. The errors for the indices were computed from these measurements of the S/N in the continuum. This too is a departure from our earlier work, where the S/N was calculated from the signal level in the spectrum and in the background. The sky and the spatially variable light from the halo of M49 contribute to the background. Furthermore slit losses depend on the accuracy of the coordinates and the alignment of the slit mask. Hence the S/N may not be a smoothly increasing function of the brightness of the GC candidate.

4. QUALITATIVE ANALYSIS

We begin with a qualitative examination of our data, considering the correlations among the indices measured for the M49 GC sample, comparing with those found in our earlier study of the M87 GCs (Cohen et al. 1998) and also with those of the Galactic GC system.

4.1. Correlations of Indices

We display the correlation of Na D with Mg *b* in Figure 1. The errors in each index, computed as described above, are indicated in the right-hand panel of this figure. The expected correlation of increasing Na D with increasing Mg *b*, presumably arising primarily from increasing metallicity, is seen. The coefficients of the weighted second-order polynomial fit to this relationship, shown in the right-hand panel of this figure, are given in Table 3. This fit is shown over the range that includes 95% of the GC candidates, excluding one GC at each end.⁶ The limits of this range for

⁶ A larger sample, such as that of Cohen et al. (1998) in M87, would make this measure more robust and less affected by isolated outliers or bad measurements.

TABLE 3
COEFFICIENTS OF INDEX-INDEX FITS^a

<i>X</i> (Index)	<i>Y</i> (Index)	Sample	A	B	C
Mg <i>b</i>	Na	All	1.674	-0.660	0.225
Mg <i>b</i>	⟨Fe⟩	All	0.927	0.241	0.023
Mg <i>b</i>	H β	All	2.010	0.0113	-0.037
Mg <i>b</i>	H α	All ^b	2.728	-0.286	0.010
H β	H α	High S/N ^b	0.795	0.624	-0.003

^a Fits to $Y = A + Bx + Cx^2$.

^b Only 34 of the 47 M49 GCs in our sample have measured H α indices, seven of which are highly uncertain.

each index are given in Table 5. The dispersion around this fit, assuming no errors in Mg *b*, is 1.16 Å, consistent with the uncertainties in the Na D indices of the M49 GCs and the problems of subtraction of the night-sky emission that affect this index.

We display the correlation of the mean of the Fe5270 and the Fe5335 indices (denoted ⟨Fe⟩) with the Mg *b* index in Figure 2. The expected increase of ⟨Fe⟩ with increasing Mg *b* index, presumably arising primarily from increasing metallicity, is seen in this figure. The coefficients of the weighted second-order polynomial fit to this relationship are given in Table 3, and the 95% range is again given in Table 5. The dispersion around this fit, assuming no errors in Mg *b*, is only 0.6 Å, consistent with the uncertainties in the Fe5270 and Fe5335 indices of the M49 GCs.

The correlation of H β with Mg *b* is shown in Figure 3. H β is the bluest index measured and has the lowest signal level in the continuum of any of the measured indices. Since H β in high-metallicity old GCs is expected to be weak, we anticipate and we see substantial scatter in this figure. However, these two indices are clearly anticorrelated, as is expected from models of old single-burst stellar populations. The coefficients of the weighted second-order polynomial fit to this relationship are given in Table 3, and the range is again given

FIG. 1.—Na D index is shown as a function of the Mg *b* index for the 47 GCs in M49. Objects with S/N < 10 are indicated by open circles. In the left-hand panel, the solid curve is the weighted second-order fit to all the M49 GCs. In the right-hand panel, 1 σ error bars are shown for each GC.

FIG. 2.—Average of the Fe5270 and Fe5335 indices is shown as a function of the Mg b index for the 47 GCs in M49. Objects with $S/N < 10$ are indicated by open circles. In the left-hand panel, the solid curve is the weighted second-order fit to all the M49 GCs. In the right-hand panel, 1σ error bars are shown.

in Table 5. The dispersion around this fit, assuming no errors in Mg b , is only 0.6 Å, consistent with the uncertainties in the H β indices of the M49 GCs.

The correlation of H α with Mg b is shown in Figure 4 for the 34 GCs in our sample with detected H α lines. The expected correlation between the two indices is seen. The coefficients of the weighted second-order polynomial fit to this relationship are given in Table 3, and the 95% range is again given in Table 5. The dispersion around this fit, assuming no errors in Mg b , is only 0.6 Å, consistent with the uncertainties in the H α indices of the M49 GCs.

The correlation of the H α indices of the M49 GCs with their H β indices is shown in Figure 5. The expected increase of H α with increasing H β is seen. The coefficients of the

weighted second-order polynomial fit to this relationship are given in Table 3, and the range is again given in Table 5. The dispersion around this fit, assuming no errors in H β , is 0.45 Å, consistent with the uncertainties in the H α indices of the M49 GCs.

4.2. Comparison with M87

The general correlations among the Lick indices that we see in the GC system of M49 were also found by Cohen et al. (1998) to hold in the M87 GC system. Figure 6 shows the best-fit second-order curves to the index-index plots Na D, $\langle Fe \rangle$, H β , and H α as a function of Mg b from Figures 1–4 for M49. The fits to the indices of the 150 GCs in M87 from Cohen et al. (1998) are also shown. These fits are displayed

FIG. 3.—H β index is shown as a function of the Mg b index for the 47 GCs in M49. Objects with $S/N < 10$ are indicated by open circles. In the left-hand panel, the solid curve is the weighted second-order fit to all the M49 GCs. In the right-hand panel, 1σ error bars are shown.

FIG. 4.— $H\alpha$ index, detected in 34 of the M49 GCs, is shown as a function of the Mg b index. Objects with $S/N < 10$ are indicated by open circles. In the left-hand panel, the solid curve is the weighted second-order fit to all the M49 GCs. In the right-hand panel, 1σ error bars are shown.

over the range that includes 95% of the GCs in our sample in each system. These ranges for the M87 sample with suitable LRIS spectra are given in Table 5.

The radial distribution of the spectroscopic sample in M49 and in M87 is compared in Table 4. The final column gives the median galactocentric radius R_{GC} in units of the galaxy scale length (R_S). The minimum R_{GC} and the R_{GC} of the first quartile are comparable for the two spectroscopic GC samples. However, the M87 GC spectroscopic sample extends to larger R_{GC} . Since the radial gradient in GC properties is small in the outer region of M87 (e.g., Cohen et al. 1998), this difference in sample spatial distribution should not cause a significant bias in the relative abundance distributions of the GC systems in these two galaxies.

We see in Figure 6 that the fits to the index-index correlations for the two Virgo gEs are essentially identical. However, the upper range limits are larger for each of the major metallicity indices Mg b , Na D, and $\langle Fe \rangle$ for M49 than for M87. Following upon our previous work in M87, we thus assert that to first order both systems are composed of predominantly old clusters spanning a wide range of metallicity, with the range of metallicity extending to a somewhat higher value in M49 than in M87.

4.3. Comparison with Galactic Globular Clusters

We next compare the behavior of the index-index plots for the M49 GCs with those of the Galactic globular

FIG. 5.— $H\alpha$ index is shown as a function of the $H\beta$ index for the GCs in our sample in M49 where $H\alpha$ was detected (34 GCs). Objects with $S/N < 10$ are indicated by open circles. In the left-hand panel, the solid curve is the weighted second-order fit to the high S/N data only. In the right-hand panel, 1σ error bars are shown.

FIG. 6.—Four panels display the second-order fits to the index-index plots Na D, $\langle\text{Fe}\rangle$, $\text{H}\beta$, and $\text{H}\alpha$ as a function of $\text{Mg } b$ shown in Figs. 1–4 for the M49 GCs (*solid curves*) and for those of M87 from Cohen et al. (1998) (*dashed curves*). The curves extend over the 95% range in each case.

clusters. The indices for the Galactic globular clusters are taken from Cohen et al. (1998), Puzia et al. (2002), Covino, Galletti, & Pasinetti (1995), or Burstein et al. (1986) (in decreasing order of preference for clusters with multiple observations). This gives a sample of 35 Galactic GCs observed, spanning the full range of metallicity of the Galactic GC system. In particular, with the work of Cohen et al. (1998) and subsequently of Puzia et al. (2002), the most metal rich Galactic GCs and those in the bulge are well sampled, while Covino et al. (1995) concentrated on the metal-poor end.

Figure 7 shows the relationships for the index pairs $\text{Mg } b$ –Na D, $\text{Mg } b$ – $\langle\text{Fe}\rangle$, $\text{Mg } b$ – $\text{H}\beta$, and $\text{H}\alpha$ – $\text{H}\beta$ for the M49 and for the Galactic GC samples. In each case, the behavior is similar, but the M49 GCs reach higher values of the metallicity-sensitive indices than do the most metal rich Galactic GCs. The comparison of the anticorrelation between $\text{H}\beta$ and $\text{Mg } b$ suggests that the age of the M49 GCs is comparable to that of the Galactic GCs, which we take to be (almost all) uniformly old, with an age of 12 Gyr (see, e.g., Rosenberg et al. 1999).⁷

⁷ We ignore the GCs associated with the accretion of the Sgr dwarf galaxy (Ibata et al. 1997), which may be ~ 3 Gyr younger (Fusi Pecci et al. 1996).

FIG. 7.—Four panels display the Na D, $\langle\text{Fe}\rangle$, $\text{H}\beta$, and $\text{H}\alpha$ indices as a function of the $\text{Mg } b$ index for the 47 GCs in M49 (*large open circles*), only 34 of which have detections at $\text{H}\alpha$. Small open circles denote the objects with $\text{S/N} < 10$. The Galactic globular clusters with data from Cohen et al. (1998), Puzia et al. (2002), Covino et al. (1995), or Burstein et al. (1986) are shown as filled squares.

Furthermore, although there is extremely good agreement in the mean relationship between $\text{Mg } b$ and $\langle\text{Fe}\rangle$ indices between the M49 and the Galactic GCs, there is a systematic vertical offset upward (with some scatter) in the panel of Figure 7 displaying $\text{Mg } b$ versus Na D. We suggest that this arises because of Na D absorption from the interstellar medium (ISM) in the disk of our Galaxy; this absorption is presumably absent in M49, which has essentially no gas and no disk. This effect will appear large both for GCs with high reddening and for the more metal-poor clusters, where even a small contribution from the ISM can perturb the weak Na D lines in the integrated light of the cluster. A similar offset is seen for the M87 GCs (see Fig. 9 of Cohen et al. 1998).

4.4. “New” versus “Old” Lick Indices

To maintain consistency with our earlier work on the M87 GC system (Cohen et al. 1998), we have used the standard Lick indices (Faber et al. 1985; Burstein et al. 1986) together with an $\text{H}\alpha$ index defined in Cohen et al. (1998). We can then use with confidence the transformation

TABLE 4
RADIAL DISTRIBUTIONS OF THE SPECTROSCOPIC GC SAMPLES IN M49 AND IN M87

Galaxy	Minimum R_{GC} (arcsec)	First Quartile (arcsec)	Median R_{GC} (arcsec)	Third Quartile (arcsec)	Median R_{GC}/R_s^b
M49	33	107	159	224	1.0
M87 ^a	24	120	214	313	1.7

^a Data from Cohen et al. 1998.

^b Galaxy scale lengths from Côté et al. 2003 for M49 and from Côté et al. 2001 for M87.

previously determined by Cohen et al. (1998) between $[\text{Fe}/\text{H}]_{\text{W}}$, the metallicity inferred directly from the Worthey (1994) grid of models, and $[\text{Fe}/\text{H}]_{\text{Z}}$, the metallicity on the well-calibrated and commonly used Zinn & West (1984) scale. The exact definition of the wavelength bandpasses for the Lick indices has evolved somewhat with time. Worthey et al. (1994) presented updated definitions of these indices, which are slightly wider to better accommodate the high velocity dispersions found in massive galaxies. For a few of these indices, Trager et al. (1998) further modify slightly the definitions of the wavelength bandpasses.

Since the most recent model grids tabulate “new” Lick indices, we need to consider the effect of switching between the “old” and the “new” Lick indices on determinations of metallicity and age. Given that GCs have small internal velocity dispersions ($\sigma_v \leq 25 \text{ km s}^{-1}$) and that the change in bandpass wavelengths is generally less than 2 Å, we expect any resulting differences in measured index strengths to be small. Puzia et al. (2002) have calculated indices on both systems from their spectra of Galactic GCs and found maximum differences of 0.2 Å for H β and for Mg *b*, 0.15 Å for Fe5270, and 0.1 Å for Fe λ 5335 and Na D. We have done the same for the spectra of 12 Galactic GCs from Cohen et al. (1998) and find similar differences. There is no change in any of the indices used here larger than 0.2 Å, with the exception of Fe5335 in the most metal rich Galactic GCs. This is a relatively weak Fe line, in a region where the continuum is chopped up by many features only slightly weaker (e.g., the Cr I blend at 5297 Å, the blend of Fe I lines between 5363 and 5371 Å, etc.), and hence a small change in the bandpass locations may affect the value of this index, and only this index, by more than 0.2 Å out of a total of about 3 Å.

We thus conclude that switching between the various definitions of the Lick indices does not introduce substantive changes in the measured indices of a feature for GCs. For our sample of Galactic GCs, changing from the “old” to the “new” Lick indices and then deriving their metallicities and ages as described in Cohen et al. (1998) produces a mean decrease in deduced age of 1 Gyr (the median difference is 0 Gyr). $[\text{Fe}/\text{H}]$ is decreased in the mean for such a switch by 0.05 dex; the median change in $[\text{Fe}/\text{H}]$ is also -0.05 dex.

The one published claim that large differences in the measured Lick indices are produced by switching between the “new” and “old” index bandpass definitions by Maraston et al. (2003) has been withdrawn; see the note added in proof in their paper.

5. QUANTITATIVE INTERPRETATION WITH MODELS

A model of the integrated light of a stellar population can be constructed assuming a star formation history, a suitable set of stellar evolutionary models and hence isochrones, and a set of integrated spectra as a function of stellar atmosphere parameters (see, e.g., Vazdekis 1999). These spectra can then be manipulated to yield parameters that can be compared with observations of such systems. For the old stellar systems considered here, we assume a single-burst model with all stars being coeval.

Models for the Lick indices as a function of metallicity and age such as those of Worthey (1994), used in our previous work on M87, did not, in fact, integrate synthetic spectra to determine indices but rather used fitting functions

based on the Lick group’s observations of a grid of calibrating stars that define the feature strength as a function of effective temperature, surface gravity, and metallicity of a star (see, e.g., Worthey et al. 1994).

These models assumed solar abundance ratios, or more precisely, they assumed that the mean of the calibrating stellar grid observed is equivalent to the solar abundance ratios. High-dispersion abundance analyses of Galactic GCs, however, have revealed that enhancement of the α -elements, specifically Mg and Ca, is almost universal. In particular, this is seen in NGC 6528 by Carretta et al. (2001) and in NGC 6553 by Cohen et al. (1999). These are two of the most metal rich Galactic GCs known. High-precision analyses of somewhat more metal-poor Galactic GCs also show this. For example, in M71 Ramírez & Cohen (2002) find the mean $[\text{Ca}/\text{Fe}]$ and the mean $[\text{Mg}/\text{Fe}]$ to be $+0.35 \pm 0.02$ dex, and in M5 Ramírez & Cohen (2003) find the mean $[\text{Mg}/\text{Fe}]$ to be $+0.29 \pm 0.03$ dex while the mean $[\text{Ca}/\text{Fe}]$ is $+0.33 \pm 0.03$ dex. Similar α -enhancements are found in very metal poor halo field stars, as shown by Cohen et al. (2002) and Carretta et al. (2002), with references to earlier work by many groups therein.

Early-type galaxies also show enhanced Mg/Fe ratios, with typical values being about twice solar (Worthey, Faber, & Gonzalez 1992; Trager et al. 2000; Davies et al. 2001; Proctor & Sansom 2002; Eisenstein et al. 2003). The origin of such enhancements in terms of galactic chemical evolution is well understood; see, for example, the review of McWilliam (1997). They are expected to occur when star formation proceeds rapidly, exhausting the gas prior to the time when Type Ia supernovae (SNe Ia) begin to spew out Fe and related elements, whereas the more rapid evolution of massive stars permits contributions to the ISM from SNe II.

Trippico & Bell (1995) explored the sensitivity of the Lick indices to changes in the element abundance ratios, while in the absence of detailed stellar evolutionary grids of models with nonsolar elemental ratios, Chieffi, Straniero, & Salaris (1991) suggested rescaling of the solar composition isochrones using the total $[Z/\text{H}]$ to obtain α -enhanced isochrones. Recently stellar evolution codes and the resulting isochrones have been computed with nonsolar abundance ratios (see, e.g., Vandenberg et al. 2000); hence calculations that predict the Lick indices as a function of Z , α/Fe , and age are becoming available. We adopt those of Thomas, Maraston, & Bender (2003, hereafter TMB).⁸ The metallicity scale of these models, a subject to which we will return later, is defined in Maraston et al. (2003), where their tests using Galactic GCs are described. TMB present Lick indices calculated from their models tabulated at six metallicities, $[Z/\text{H}] = -2.25, -1.35, -0.33, 0.0, +0.35$, and $+0.67$ dex, and at 10 ages ranging from 1 to 15 Gyr.

Figure 8 shows the mean of the indices covering the strong Fe lines at 5270 and at 5335 Å, denoted $\langle \text{Fe} \rangle$, as a function of Mg *b* for the 47 GCs in M49. The 1σ uncertainties are shown only for Geisler 4168; Figure 2 shows uncertainties for each of the M49 GCs. The crosses represent the positions of the TMB models with an age of 12 Gyr from $[Z/\text{H}] = -2.25$ to $+0.67$ dex. Line segments connect the predictions of the models at these metallicities with $[\alpha/\text{Fe}] = 0.0$ (solar), $+0.3$, and $+0.5$ dex. Note that

⁸ TMB tabulate “new” Lick indices.

FIG. 8.—Average of the Fe5270 and Fe5335 indices is shown as a function of the $Mg\ b$ index for the 47 GCs in M49. Objects with $S/N < 10$ are indicated by open circles. The 1σ uncertainty is shown for Geisler 4168 only; Fig. 2 shows the uncertainties for each GC. The crosses connected by lines denote the predictions of the grid of models of TMB for an age of 12 Gyr at $[Z/H] = -2.25, -1.35, -0.33, 0.0, +0.35$, and $+0.67$ dex for $[\alpha/Fe] = 0.0$ (upper curve, solid line), $+0.3$ (dashed line), and $+0.5$ dex (lowest curve, dot-dashed line).

$[Z/H] \approx [Fe/H] + 0.94[\alpha/Fe]$ (TMB). The loci of the M49 GCs are inconsistent with the solar α/Fe ratio; a mean enhancement of about a factor of 2 in α/Fe is required for a reasonable fit to the observations. This enhancement, which is similar to the enhancements found by high-dispersion abundance analyses for the Galactic GCs and to that required for luminous early-type galaxies, is found over the full range of metallicities within the M49 GC system, although this is less certain among the most metal poor GCs, where the separation of indices for the models between α -enhanced and solar abundance ratios is, as shown in Figure 8, smaller.

The range of metallicity of the majority of the M49 GCs as judged from their position on Figure 8 and the comparison to the TMB models, appears to be $[Z/H]$ from -1.3 to $+0.5$ dex, which for $\alpha/Fe = +0.3$ dex corresponds to $[Fe/H] = -1.6$ to $+0.2$ dex.

Figure 9 shows the Na D index as a function of $Mg\ b$ for the 47 GCs in M49. Again the 1σ errors are shown only for Geisler 4168; Figure 1 shows uncertainties for each of the M49 GCs. The crosses represent the positions of the TMB models with an age of 12 Gyr with six metallicity values. Line segments connect the predictions of the models for these metallicities with $[\alpha/Fe] = 0.0$ (solar), $+0.3$, and $+0.5$ dex.

In our earlier work on the M87 GC system, the most obvious shortcoming of the Worthey (1994) models was that, at the metal-rich end, the Fe indices of the M87 GCs were always smaller for a given $Mg\ b$ index than those predicted by the models. As is shown in Figure 10, this problem is now cured by the use of the new α -enhanced TMB models

FIG. 9.—Na D index is shown as a function of the $Mg\ b$ index for the 47 GCs in M49. Objects with $S/N < 10$ are indicated by open circles. The 1σ uncertainty is shown for Geisler 4168 only; Fig. 1 shows the uncertainties for each GC. The predictions of the grid of models of TMB for an age of 12 Gyr are shown in a manner similar to that of Fig. 8.

for both M87 and for M49. The major remaining issue, illustrated in Figure 9 for M49 and in Figure 11 for M87, is the very strong Na D indices seen in a few of the most metal rich M49 and M87 GCs, an issue also noted as problematical in

FIG. 10.—Average of the Fe5270 and Fe5335 indices is shown as a function of the $Mg\ b$ index for 150 GCs in M87 from Cohen et al. (1998). The predictions of the grid of models of TMB for an age of 12 Gyr are shown in a manner similar to that of Fig. 8.

FIG. 11.—NaD index is shown as a function of the Mg *b* index for 150 GCs in M87 from Cohen et al. (1998). The predictions of the grid of models of TMB for an age of 12 Gyr are shown in a manner similar to that of Fig. 8.

Cohen et al. (1998). We suggest that this is a genuine problem with the models, which are, as noted above, poorly calibrated for such high metallicities.

Na D and Mg *b* are the strongest indices analyzed here. But the Na D index is dominated by the contribution from the sodium doublet, while the Mg *b* index includes the three strong Mg triplet lines as well as several weaker Fe features. Thus the Na D lines should reach the damping part of the curve of growth at a lower abundance than any of the other features used here. If the lines are becoming damped for the majority of the stars contributing to the integrated light, then line strength $\propto (X/H)^{1/2}$, and the line index will increase rapidly with increasing abundance of the appropriate element. An even more rapid dependence of index on abundance is expected because of a second effect: higher abundance clusters have cooler red giant branches, hence stronger lines.

The slopes of the predicted indices from TMB as a function of $[Z/H]$ suggest that the Na D index of the integrated light has in effect reached the damping part of the curve of growth at $[Z/H]$ near +0.4 dex, but the Mg *b* index has not yet done so in their models even at the highest metallicity included. We ascribe the very strong Na D lines seen in the strongest lined GCs in M49 and in M87 to metallicities near $[Mg/H] + 0.7$ dex (i.e., $[Fe/H] \sim +0.4$, $[Z/H] \sim +0.7$ dex), but not much larger.

5.1. Extrapolating the Models

In the case of both the Worthey (1994) and TMB models, the highest metallicity case tabulated has indices that are weaker than those of the strongest lined M87 or M49 GCs. This means a small extrapolation of the models toward higher metallicity is required. For the Worthey (1994) models, this was carried out assuming that all the indices were

on the damping part of the curve of growth. The derived abundances of 8 M49 GCs were affected. In the case of M87, we extrapolated the abundances of the five GCs for which this is necessary; Cohen et al. (1998) did not do so.

Only three of the M49 GCs are more metal rich than the most metal rich α -enhanced model tabulated by TMB. We extrapolated slightly beyond the lowest and highest metallicities of the TMB model grid to -3.0 and $+1.0$ dex, which range includes all the M49 GCs.

5.2. Calculation of Metallicity for the M49 GCs

We have established above that the M49 GC indices, including the key $H\beta$ and $H\alpha$ indices, show similar correlations to those seen among the Galactic GCs and those of M87 (Cohen et al. 1998). We therefore assume an age of 12 Gyr for all of the M49 GCs and proceed to calculate their metallicities in two different ways. We use the Mg *b*, Na D, and $\langle Fe \rangle$ indices, giving double weight to the former because of its larger range⁹ with comparable accuracy, with the $[\alpha/Fe] = +0.3$ dex models of TMB. These produce $[Z/H]$, not $[Fe/H]$. The resulting $[Z/H]$ and its 1σ error are given for each M49 GC in the second and third columns of Table 6. For the three M49 GCs with the strongest Na D lines, we indicate in Table 6 the resulting (lower) abundance $[Z/H]$ deduced by ignoring the Na D index. These GCs are all above the maximum metallicity considered in the Worthey (1994) models.

We derive a second metallicity, denoted $[Fe/H]_Z$, using the same procedures and codes as in our earlier work on M87 (Cohen et al. 1998). This relies upon the Worthey (1994) models and produces $[Fe/H]$ on a scale tied to the GC abundances adopted by Zinn & West (1984), denoted $[Fe/H]_Z$. These values are listed in the fourth column of Table 6.

The two resulting sets of metallicities for the M49 GCs are shown in Figure 12. The results are closely correlated. A linear fit to the 47 M49 GCs is

$$[Fe/H]_Z = -0.27 \pm 0.04 + (0.80 \pm 0.07)[Z/H](TMB), \quad (1)$$

with a 1σ rms variance around this line of only 0.15 dex. The origin of this relationship will be discussed in § 5.3.

5.3. Comparison of Metallicity Scales

In this paper we utilize three metallicity scales, the one used in M87 by Cohen et al. (1998), the one adopted by Geisler et al. (1996) to analyze their photometry, and that of TMB. Although we used the Worthey (1994) models in our M87 analysis, we rescaled our results to the Zinn & West (1984) metallicity scale by calibrating with Galactic GCs. The scaling relation derived by Cohen et al. (1998) was

$$[Fe/H]_Z = -0.265 + 0.76[Fe/H]_W. \quad (2)$$

We continue to use this transformation for the M49 GCs, except those beyond the upper limit of the Worthey (1994) model grid, where it is assumed that $[Fe/H]_Z = [Fe/H]_Z(\text{max of grid}) + \Delta$, where Δ is computed as described in § 5.1.

⁹ The Na D index has a similar range but has problems with removal of night-sky emission.

FIG. 12.—Comparison of the metallicity of the M49 GC sample assuming an age of 12 Gyr using two independent sets of models; as deduced from the Worthey (1994) models set to the Zinn & West (1984) metallicity scale for $[\text{Fe}/\text{H}]$ vs. those derived from the α -enhanced models of TMB. Objects with $S/N < 10$ are indicated by open circles. A linear fit is shown.

Geisler et al. (1996) also used the Zinn & West (1984) $[\text{Fe}/\text{H}]$ scale with a calibration through Washington photometry of Galactic GCs. Geisler & Forte (1990) found $[\text{Fe}/\text{H}] = 2.35(C-T_1) - 4.39$, calibrated over the range -2.25 to -0.25 dex, which transformation is adopted by Geisler et al. (1996) throughout their analyses, even though the colors of the reddest GCs in M49 exceed the upper limit of the metallicity calibration. We are able to present a new calibration of $(C-T_1)$ with metallicity, incorporating photometric data for the Galactic GCs from Harris & Canterna (1977) with reddenings from Harris (1996), the GCs of M87 (data from Hanes et al. 2001), and those of M49 (data from Geisler et al. 1996), adopting the reddenings for M87 and for M49 from Schlegel, Finkbeiner, & Davis (1998). The metallicities are taken from Zinn & West (1984) for the Galactic GCs and the spectroscopic analyses of Cohen et al. (1998) for the M87 GCs and the present paper for the M49 GCs. Figure 13 shows the result, i.e., $[\text{Fe}/\text{H}]_Z$ as a function of the dereddened $C-T_1$ color for this database of 241 GCs. We find that the linear relationship of Geisler & Forte (1990) is overall a good fit to the data, except among the most metal poor GCs, where the actual relationship is steeper than their adopted fit, as might be expected since any photometric system will lose sensitivity among the most metal poor systems. The second-order fit that we obtain after rejecting the 12 most discrepant GCs is $[\text{Fe}/\text{H}]_Z = -5.64 + 4.438(C-T_1) - 0.75(C-T_1)^2$. The dispersion of the 228 GCs around this fit is only 0.20 dex. This second-order fit is only slightly better than the original linear fit of Geisler & Forte (1990); both fail to reproduce well the very steep drop in $[\text{Fe}/\text{H}]$ at the lowest values of $(C-T_1)$ below 1.1 mag. Adopting $[\text{Fe}/\text{H}]_Z = 2.27(C-T_1) - 4.21$ for $(C-T_1) > 1.16$ mag and $[\text{Fe}/\text{H}]_Z = 6.21(C-T_1) - 8.81$ for $(C-T_1) < 1.16$ mag yields a slightly better fit, particularly at the lowest metallicities.

FIG. 13.—Dereddened $(C-T_1)$ index of the Washington photometry is shown as a function of $[\text{Fe}/\text{H}]_Z$ from Zinn & West (1984) for the Galactic GCs (triangles), and of spectroscopic metallicity for the M87 (filled circles) and M49 GCs (open circles), with sources of data and reddenings given in the text. The solid line denotes the relation adopted by Geisler & Forte (1990). The dashed line is the second-order fit derived here.

The Galactic GC metallicity scale of Zinn & West (1984) is in turn tied to the early high- and moderate-resolution spectroscopic work on individual stars in Galactic GCs of Cohen (1983) and references therein. The high-metallicity end of the Galactic GCs, where accurate calibration data were very limited until quite recently, remains an area of concern. It has taken almost 20 yr from J. Cohen's initial efforts to properly calibrate the high-metallicity end of the Galactic GCs, but recently this was carried out through high-dispersion analyses of stars in the very metal rich Galactic GCs NGC N553 and NGC 6528 by Cohen et al. (1999) and by Carretta et al. (2001).

We consider the relationship between the Zinn & West (1984) $[\text{Fe}/\text{H}]$ determinations for the Galactic GCs and those found from their Lick indices with the models of TMB. The Na D lines are ignored when the cluster reddening is high because of possible contributions from the interstellar medium. This is shown for the 35 calibrating Galactic GCs in Figure 14. The resulting best linear fit is

$$[\text{Fe}/\text{H}]_Z = -0.27 \pm 0.05 + (0.68 \pm 0.03)[Z/\text{H}]/(\text{TMB}) . \quad (3)$$

The 1σ rms around this fit is 0.20 dex. The major outliers are NGC 6528 (which is 0.25 dex above the mean line), NGC 7006, and NGC 362. The first may actually represent the probable presence of curvature (i.e., a second-order term), while for the last two, we suggest that the observed indices may be inaccurate. The constant offset arises from the α -enhancement included in $[Z/\text{H}]$. One would expect the slope in equation (3) to be unity, but it is not. In fact, it is very close to the slopes of equations (1) and (2).

FIG. 14.—[Fe/H] values from Zinn & West (1984) for the 35 calibrating Galactic globular clusters are compared to those assigned using the α -enhanced models of TMB. GCs with data from Cohen et al. (1998) are denoted by stars, those from Puzia et al. (2002) by filled circles, those from Covino et al. (1995) by triangles, and those from Burstein et al. (1986) by open circles. Only the Mg b and $\langle\text{Fe}\rangle$ indices are used for GCs with substantial reddening. The linear fit is $[\text{Fe}/\text{H}](\text{Zinn}) = -0.27 + 0.68[\text{Z}/\text{H}]$.

We next consider the relationship, shown in Figure 15, between the photometric metallicities for the M49 GCs derived by Geisler et al. (1996) and the spectroscopic metallicities we obtain using the α -enhanced TMB models. It looks fairly good except at the low-metallicity end. There any photometric metallicity indicator is rapidly losing sensitivity, and even precise photometry cannot easily produce accurate GC metallicities. The linear fit shown in the figure is

$$[\text{Fe}/\text{H}](\text{Geisler}) = -0.11 \pm 0.04 + (0.79 \pm 0.07)[\text{Z}/\text{H}](\text{TMB}). \quad (4)$$

The dispersion around this fit is 0.31 dex. Again we see a constant offset due to the use of α -enhanced models by TMB with a slope comparable to those of equations (1), (2), and (3).

In order to understand the origin of the nonunity slope in equations (1)–(4), we must look carefully at the three metallicity scales involved. The abundances of the most metal rich Galactic GCs are still controversial. Cohen et al. (1999) and Carretta et al. (2001) analyze the spectra of red horizontal branch stars to derive $[\text{Fe}/\text{H}] = -0.06$ dex and $[\text{Fe}/\text{H}] = +0.07$ dex (with an error of ± 0.15 dex) for NGC 6553 and NGC 6528, respectively. However, other recent spectroscopic analyses still obtain much lower values. We do not consider the work of Coelho et al. (2001) because of the low dispersion of their spectra. The work of Barbuy et al. (1999), who found $[\text{Fe}/\text{H}] = -0.55 \pm 0.2$ dex for NGC 6553, is suspect because of the complexity of the spectra of the very cool giants near the tip of the red giant branch. Origlia, Rich, & Castro (2002) obtained, from spectra in the

FIG. 15.—Metallicities assigned by Geisler et al. (1996) to the M49 GCs from their Washington photometry are compared with those assigned from LRIS spectroscopy using the TMB α -enhanced model grid assuming a uniform age of 12 Gyr. Objects with $S/N < 10$ in their spectra are indicated by open circles.

near-IR, $[\text{Fe}/\text{H}] = -0.3 \pm 0.2$ dex, which agrees to within 1σ with our adopted result.

All of the high-dispersion studies mentioned above find that these very metal rich galactic GCs show α -enhancements of about a factor of 2. It is, however, much harder to get the absolute abundances, i.e., $[\text{Fe}/\text{H}]$, correct than to obtain reasonably accurate abundance ratios. We adopt here the $[\text{Fe}/\text{H}]$ values from Cohen et al. (1999) and Carretta et al. (2001) to define the metal-rich end of the galactic GC calibration.

The values adopted by Zinn & West (1984) for NGC 6553 and NGC 6528 are $[\text{Fe}/\text{H}]_Z = -0.29 \pm 0.11$ and $+0.12 \pm 0.21$ dex, respectively; for NGC 6528, this is close to our adopted value, but their abundance for NGC 6553 is 0.23 dex lower than ours. The values for these two GCs from the TMB models are (ignoring the Na D index) $[\text{Z}/\text{H}] = -0.01$ and -0.06 dex, respectively. These values are significantly lower than those we adopt when the α -enhancement is factored in. The spectroscopic evidence cited above suggests that the Zinn & West (1984) scale is closer to the best data available today than is the metallicity scale of TMB. Carretta et al. (2001) discuss in detail the calibration of the Zinn & West (1984) metallicity scale using the set of the best high-dispersion spectroscopic analyses of individual stars in Galactic GCs available to date.

Another important part of this problem of the origin of nonunity slopes found in equations (1)–(4) lies at very low metallicities. On the basis of the Mg b indices alone, the eight most metal poor calibrating Galactic GCs, with $-2.24 < [\text{Fe}/\text{H}]_Z < -1.7$ dex, all fall somewhat below the lower end of the metallicity of the Worthey (1994) model grid at $[\text{Fe}/\text{H}]_W = -2.0$ dex and well below the end of that of TMB metallicity models at a nominal $[\text{Z}/\text{H}]$ of -2.25

dex. (In their metallicity calibration, they consider only Galactic GCs with $[\text{Fe}/\text{H}]_Z \geq -1.5$.)

Together, these differences in scale at the metal-poor and the metal-rich end of the Galactic GC distribution give rise to the slope of the linear relationship between the Zinn & West (1984) and TMB or Worthey (1994) metallicity scales being ~ 0.8 in equations (1)–(4).

An additional and very serious concern is that Galactic GCs simply do not span the full range of metallicity achieved by the M49 and M87 GCs, and so the models for the highest metallicity range of interest for the Virgo GCs are poorly calibrated and poorly tested. Fitting functions for the Lick indices based on observations of field stars are not well defined at such high metallicities either. Worthey (1994) provides data to $[\text{Fe}/\text{H}]_W = +0.5$ dex, while TMB calculate indices to $[Z/\text{H}] = +0.67$ dex.

6. METALLICITY DISTRIBUTION OF THE M49 GCs

We first need to establish whether the spectroscopic sample is representative of the M49 GC system. We assume that the complete list of GC candidates of Geisler et al. (1996), within the broad color cut we adopt, is free of selection effects that are color dependent. This may not be true, as foreground stars will mostly be M dwarfs at the red end of the color distribution of the GC candidates. Background galaxies and M dwarfs, however, appear to be rare interlopers within the central region of the Geisler et al. (1996) sample. Figure 16 displays a histogram of the GC candidates extracted from photometric database of Geisler (1996) within the radial range of our M49 GC sample and brighter than our limiting magnitude, as well as similar histogram for the sample of M49 GCs observed spectroscopically, including those candidates that turned out not to be M49 GCs. (Note that the vertical scale is different for the two samples; that of the former is 8 times larger.) The spectroscopic sample appears to be a reasonably fair representation of the M49 GC system.¹⁰ Hence the correlations of the indices among the spectroscopic sample of M49 GCs can be

¹⁰ A Kolmogorov-Smirnov test shows that the probability that the two distributions are identical is low (19%), but our goal is a rough estimate of a small number (a maximum of two) of parameters describing the metallicity distribution of the M49 GCs.

FIG. 16.—Histogram of the $C-T_1$ color of the full sample of candidate GCs in M49 from Geisler et al. (1996) is shown as the thin line. A histogram of this color for the spectroscopically observed sample of GCs is shown as the thick line. It is plotted on a vertical scale 1/8 as high as that of the full sample.

used to delineate the trends of metallicity and age and related statistical properties within the M49 GC system. Note in particular that we have sampled close to the full range in $C-T_1$ color of the M49 GCs candidates.

The 95% low-metallicity level given in Table 5 for the M49 GCs is obtained by sorting the abundances from Table 6 (Table 1 of Cohen et al. 1998, for M87) and is ~ -2 dex; the upper end of the metallicity range is obtained in a similar manner. The maximum metallicity achieved by the M49 GC system is $[\text{Fe}/\text{H}]_Z = +0.4$ dex, with $\alpha/\text{Fe} \sim +0.3$ dex.

The mean metallicity of the GC system of M49 is substantially below that of the galaxy itself, for which several Lick indices have been measured by Davies, Sadler, & Peletier

TABLE 5
95% RANGE FOR INDICES AND ABUNDANCES IN THE GC SYSTEMS OF M49, M87, AND THE GALAXY

INDEX	M49		M87		M92 (Å or dex)	NGC 6553 and NGC 6528 (Å or dex)
	Minimum (Å or dex)	Maximum (Å or dex)	Minimum (Å or dex)	Maximum (Å or dex)		
Mg <i>b</i>	0.67	7.32	0.39	5.19	0.57	3.80
$\langle \text{Fe} \rangle$	0.10 ^a	3.70	0.28	3.40	0.45	2.69
Na D	0.46	7.98	0.40	6.35	0.67	4.16 ^b
H β	0.14	2.87	0.67	2.98	2.53	1.70
H α	0.81	3.25	0.97	3.39	2.35	1.29
$[Z/\text{H}]$	-1.99	0.90 ^c	...	...	-2.76	-0.03 ^d
$[\text{Fe}/\text{H}]$ (Zinn)...	-1.90	0.41	-2.25	0.19	-2.24	-0.08

^a This would increase to ~ 0.5 if negative equivalent widths for the Fe5335 index were ignored.

^b Na D lines may be affected by interstellar absorption.

^c This decreases to 0.85 dex when only the Mg *b* and $\langle \text{Fe} \rangle$ indices are used, ignoring the very strong Na D lines found in the strongest lined of the M49 GCs.

^d The Na D indices have been ignored here.

TABLE 6
METALLICITIES FOR M49 GCs

Identification ^a	[Z/H] ^b (dex)	Error ^c (dex)	[Fe/H] _Z ^d (dex)
1475	-0.94	0.39	-1.12
1508	0.32	0.46	0.11
1650	0.36	0.20	-0.04
1731	0.10	0.29	-0.38
1798	0.56	0.15	0.23
1846	0.54	0.27	0.22
1889	-1.99	0.43	-1.90
1892	-1.36	1.36	-1.66
1905	-0.56	0.32	-0.63
2013	-1.93	0.78	-1.22
2031	-1.04	0.44	-0.98
2045	-0.26	0.32	-0.48
2060	-1.88	0.49	-1.43
2178	-1.30	0.82	-1.22
2188	-0.68	0.51	-0.86
2306	-0.60	0.29	-0.68
2406	0.50	0.19	0.19
2421	-1.16	0.70	-1.10
2502	-0.06	0.22	-0.24
2528	-0.98	0.31	-1.03
2543	-1.06	0.54	-1.12
2569	0.38	0.12	0.05
2813	0.36	0.31	0.00
3150	-0.06	0.22	-0.29
3603	0.24	0.29	-0.14
3788	0.24	0.49	-0.25
3900	0.80 ^e	0.26	0.35
4017	-0.98	0.36	-0.92
4062	0.90	0.33	0.41
4144	-1.10	0.36	-1.32
4168	-0.56	0.29	-0.71
4217	-0.04	0.26	-0.27
4296	-1.14	0.77	-1.28
4351	-2.06	0.99	-2.05
4401	0.34	0.20	0.05
4513	0.06	0.15	-0.24
4541	-0.70	0.58	-0.84
4663	-0.04	0.17	-0.29
4682	0.05	0.29	-0.04
4834	-0.94	0.66	-1.00
4852	0.56	0.20	0.23
4864	-0.22	0.14	-0.69
5003	-0.52	0.44	-0.83
5018	0.60 ^f	0.25	0.32
5097	0.98 ^g	0.30	0.49
5217	-1.50	0.51	-1.25
6051	-0.26	0.31	-0.62

^a From Geisler et al. 1996.

^b This is the total [Z/H] obtained using the models of TMB as described in the text.

^c The 1 σ rms error in [Z/H].

^d [Fe/H] on the scale of Zinn & West 1984 with the Worthey 1994 models obtained following the procedures of Cohen et al. 1998.

^e This decreases to 0.53 dex when only the Mg *b* and (Fe) indices are used, ignoring the very strong Na D lines.

^f This decreases to 0.45 dex when only the Mg *b* and (Fe) indices are used, ignoring the very strong Na D lines.

^g This decreases to 0.85 dex when only the Mg *b* and (Fe) indices are used, ignoring the very strong Na D lines.

(1993) and by Fisher, Franx, & Illingworth (1995) from long-slit spectra. The highest metallicity reached by the M49 GCs is, however, comparable to that of the central region of the galaxy M49 itself, given as [Fe/H] = +0.24 dex, with [Mg/Fe] = +0.25 dex, by Terlevich & Forbes (2002). This is also true for the Galactic GC system. M49 is a very luminous galaxy, and a metallicity-luminosity relation exists among early-type galaxies (e.g., Kuntschner et al. 2002), so it is not surprising to find that the mean metallicity of M49 and of the most metal rich of its GCs to be 2–3 times solar in [Fe/H], but with a significant α -enhancement.

Table 7 lists the total luminosity of the galaxy and the mean metallicity and the approximate location of the peaks in the metallicity distribution for the five best-studied GC systems, M49, M87, NGC 1399 (the central galaxy in the Fornax Cluster), M31, and the Galaxy as determined from ground-based and *Hubble Space Telescope* (*HST*) photometry and from our spectroscopy. These values are all given on the Zinn & West (1984) scale. The locations of the two peaks determined from our spectroscopic sample in M49 is quite uncertain (± 0.3 dex) because of the relatively small size of the sample. Yet another metallicity calibration is required here to convert the *V*–*I* photometry from *HST* to [Fe/H]; we adopt the relationship given by Barmby et al. (2000). The agreement between the photometric and spectroscopic determinations of the peaks in the M87 GC system is good.¹¹ All three measures agree to within the stated uncertainties for the lower metallicity peak in M49.

7. M49 GC AGES

H β is the index among those used here with the highest sensitivity to cluster age. H β versus strong metal-line equivalent width relations have been used to attempt to determine ages from integrated light spectra for many years (see Rabin 1982 for an early example). However, the separation with age of the metallicity-H β contours of the models for ages exceeding 5 Gyr is small and decreases as the metallicity increases. The observational errors in the H β index are fairly large, certainly larger than the separation of the contours between 8 and 15 Gyr and are to first order independent of metallicity. This makes the determination of ages quite uncertain. It is impossible to determine ages for individual GCs in M49, and we must resort to median lines, polynomial fits to the index-index relations of the GCs as a whole, or summing of the spectra of individual GCs.

In addition, the treatment in the models of the horizontal branch, whose hotter stars can contribute strongly to H β (Lee, Yoon, & Lee 2000), has improved with time. Although Worthey (1994) included the horizontal branch as a red clump for all clusters, TMB add a horizontal branch whose characteristics depend on the metallicity of the GC. This change produces a nonnegligible change in the predicted H β index in the integrated light of an old very metal poor cluster. It should also be noted that the TMB models without α -enhancement predict lower Mg *b* indices than the Worthey

¹¹ The *V*–*I* conversion of Kissler-Patig et al. (1998) when applied to the *HST* photometry yields significantly worse agreement with the spectroscopic metallicities. The Kissler-Patig et al. (1998) metallicity scale may not be properly calibrated at high metallicities; $\Delta[\text{Fe}/\text{H}]/\Delta(V-I)$ appears to be too small.

TABLE 7
METALLICITY OF PEAKS IN GC SYSTEMS

Galaxy	M_V (mag)	Low Peak ^a (dex)	High Peak (dex)	Mean (dex)	Sample Size	Reference
M49 (spectroscopy).....	-22.63 ^b	-1.1	-0.1	-0.6	47	1
M49 (Washington photometry).....	...	-1.3	-0.1	-0.90	1800	2
M49 (<i>HST</i> photometry) ^c	...	-1.42	-0.30	...	532	3
M87 (spectroscopy).....	-22.41 ^b	-1.3	0.0: ^d	-0.95	150	4
M87 (Washington photometry).....	...	-1.3	-0.1	-0.86	407	5
M87 (<i>HST</i> photometry) ^c	...	-1.40	-0.30	-0.84	709	3, 6
NGC 1399 (spectroscopy).....	-21.3 ^b	...	...	-0.80	18	7
NGC 1399 (Washington photometry).....	...	-1.29	-0.18	...	2864	8
NGC 1399 (<i>HST</i> photometry) ^c	...	-1.38	-0.39	...	408	3
M31 (spectroscopy).....	-21.2 ^b	-1.44	-0.50	-1.21	301	9
Galaxy.....	-20.61 ^e	-1.59	-0.56	-1.27	147	10

^a [Fe/H] on the Zinn & West 1984 metallicity scale is given.

^b Apparent mag from de Vaucouleurs et al. 1991, assuming distance of 0.77 Mpc for M31 and 16 Mpc for Virgo. For NGC 1399, we adopt their v_r with H_0 of 71 km s⁻¹ Mpc⁻¹; see Freedman et al. 2001.

^c The conversion of $V-I$ color to [Fe/H] of Barmby et al. 2000 is used for the *HST* data.

^d Uncertain as the spectroscopic sample in M87 is dominated by GCs from the metal-poor peak.

^e de Vaucouleurs & Pence 1978.

(1) This paper; (2) Geisler et al. 1996; (3) Larsen et al. 2001; (4) Cohen et al. 1998; (5) Lee & Geisler 1993; (6) Whitmore et al. 1995; (7) Kissler-Patig et al. 1998; (8) Dirsch et al. 2003; (9) Perrett et al. 1996; (10) Harris 1996.

(1994) models of the same metallicity, although they agree in their predictions for the (Fe) and Na D indices. This may be due to the contribution of these hotter stars at the bluest wavelengths relevant here.

We determined the ages of the M49 GCs using each of the two model grids. First, we used the $H\beta$ observations of the GCs to define a median line in $H\beta$ versus $Mg\ b$. This was combined with the Worthey (1994) models, just as was done for the M87 GCs in Cohen et al. (1998). The GCs were sorted by metallicity and binned into groups of 10. The median age within each group is given in Table 8. The deduced ages are 10 Gyr or older for all clusters with $[Fe/H]_Z \leq -0.8$ dex. Since Beasley et al. (2000) also used the Worthey (1994) models, they too deduced that all the M49 GCs are older than 14 ± 5 Gyr.

Geisler 6051 has the strongest observed $H\beta$ index of all the M49 GCs; it is 2σ stronger than expected for an age of 8 Gyr. Since for a Gaussian distribution we would expect 5% of the sample to lie off the mean line by 2σ or more, it is unlikely that this single discrepant cluster is young.

Splitting the M49 GCs into metal-rich and metal-poor groups at $[Fe/H]_Z = -0.6$ dex, we find (Table 8) mean ages of 13.9 ± 0.8 and 12.8 ± 0.5 Gyr for each of these, respectively, using the models of Worthey (1994). This is a very small age difference.

TABLE 8
AGES OF THE M49 GCs USING THE WORTHEY (1994) MODELS

[Fe/H] _Z Range (dex)	Number	Median Age (Gyr)	σ (Gyr)
>0.1.....	10	16	2.8
-0.29 to 0.05.....	10	13	4.3
-0.84 to -0.29.....	10	11	3.7
-1.22 to -0.85.....	10	13	2.4
<-1.26.....	7	14	1.6
<-0.6.....	23	13.9	4.1
>-0.6.....	24	12.8	2.6

We also attempted a similar treatment using the models of TMB of $H\beta$ as a function of $Mg\ b$ and as a function of $[MgFe](Mg\ b/Fe)^{1/2}$, which Puzia (2003) found to be a metallicity index with minimum sensitivity to possible variations in α/Fe . We sorted the sample in order of the $[Fe/H]_Z$, ignoring those with low S/N (<10), and summed the spectra into five bins, each of which contains eight M49 GCs. The metallicity range of each bin is given in Table 9. The resulting spectra are shown in Figure 17. These summed spectra have 8000–10,000 DN pixel⁻¹ in the continuum at 5200 Å, and each has a minimum S/N of 28.3. The figure also shows the spectrum of Geisler 2860, which is a Galactic star and whose single spectrum has a S/N of 29.9. Almost all of the features seen in this figure are real. Furthermore, the increase in metallicity from bin to bin and the corresponding decrease in $H\beta$ line strength are obvious in the summed spectra. We measured the $H\beta$ index for the summed spectrum of each bin. This is shown as a function of $[MgFe]^{12}$ in Figure 18. The thin lines represent the models of TMB for ages of 5, 8, 12, and 15 Gyr. The thick dashed line is the second-order fit to the M87 GCs.

Table 9 gives the result. If the models of TMB are correct, the ages of the M49 GCs systematically decrease as the

¹² Here in calculating $[MgFe]$ we set any negative Fe5335 or Fe5270 indices to 0.3 Å.

TABLE 9
AGES OF THE M49 GCs USING THE TMB MODELS

[Z/H] Range (dex)	Number	Median Age (Gyr)	σ (Gyr)
>+0.7.....	8	5	-2, +6
+0.3 to +0.7.....	8	8	3
-0.5 to +0.3.....	8	10	3
-0.85 to -0.5.....	8	15	3
<-0.85.....	8	>15	~2

FIG. 17.—Sums of eight spectra per bin for five bins of M49 GCs are plotted with metallicity increasing from top to bottom; the metallicity range of each bin is given in Table 9. The lowest spectrum displayed (*thin line*) is that of the Galactic star Geisler 2860 ($S/N = 29.9$). The short horizontal lines at the left edge together with the bottom of the plot denote the location of zero intensity for each spectrum.

FIG. 18.— $H\beta$ index is shown as a function of the $[MgFe]$ index for the 40 M49 GCs with $S/N < 10$ sorted in metallicity and summed into groups of 8. GCs with low S/N spectra are excluded. The X error bar illustrates the range in $[MgFe]$ for each bin, while the Y 1σ error bars are those expected for the $H\beta$ index of the summed spectrum of each group. The thick dashed curve indicates a second-order fit to the sample in M87 of Cohen et al. (1998). The models of TMB are shown for $\alpha/Fe = +0.3$ dex and for ages of 5 (*highest thin curve*), 8, 12, and 15 (*lowest thin curve*) Gyr.

metallicity increases from a mean age of more than 15 Gyr for the most metal poor GCs to a mean age of 5 Gyr for the most metal rich, with a mean age for the GC system as a whole of ~ 10 Gyr. Furthermore, the M87 GCs then have ages exceeding 15 Gyr for all metallicities (see Fig. 18).

We look again at the Galactic globular clusters for clues as to which set of models for the key $H\beta$ index are better. The very strong $H\beta$ indices predicted for the most metal poor GCs for any age by the TMB models are not present in the M49 GC sample, where the mean $H\beta$ for the most metal poor bin is $1.95 \text{ \AA}$ and the deduced age exceeds 15 Gyr. The Worthey (1994) models predict $H\beta$ to be $2.44 \text{ \AA}$ for very low metallicity and an age of 12 Gyr, which is a better fit to our observations in M49 and to those of Cohen et al. (1998) in M87, this difference presumably arising from the different treatment of the horizontal branch between the two sets of models. Evidence from the Galactic globular clusters (see Fig. 7) suggests an intermediate value for the mean $H\beta$ index among the most metal poor GCs, but still not as high as the TMB models suggest. The scatter of $H\beta$ measured among the low-metallicity Galactic globular clusters, shown in Figure 7, is large. If the uncertainties given by Covino et al. (1995) are realistic, then this range is too large to be due to measurement errors and may represent variations in the relative contribution to the integrated light of the horizontal branch or variations in the distribution of stars along the horizontal branch.

If one wishes to overinterpret the data and if one believes that the TMB models better represent reality for the Balmer lines, which they unquestionably do for the metallic lines because of the incorporation of α -enhancement, one could claim that the most metal poor GCs in M49 are the oldest, and the mean age of the M49 GCs decreases from 15 to 5 Gyr as the metallicity increases. For present purposes, we adopt the age results from the Worthey (1994) models.

However, the only safe statement in our view is that the M49 GCs are in the mean older than 10 Gyr. Further speculation about the details of the age distribution of the M49 GCs requires observational data of still higher quality as well as an exquisite understanding of the nature of the horizontal branch in extragalactic GC systems, neither of which is currently available.

8. IMPLICATIONS FOR GLOBULAR CLUSTER FORMATION

We have discovered here that enhancement of the α elements (Mg, Ca, Na) is common in the GC systems of massive galaxies. Following upon the work of Cohen et al. (1998), we have detected this in both M49 and in M87. Such an enhancement is a well-known feature of Galactic globular clusters, and those few that are known or suspected to be young in the Galaxy are also known to have no or smaller α -enhancements (Brown, Wallerstein, & Zucker 1997; Smith, Sneden, & Kraft 2002). J. Cohen (2003, in preparation) also has found that a similar α -enhancement is characteristic of the M31 GCs.

In the Galaxy, where detailed study with exquisite precision of at least nearby individual stellar populations is possible, Reddy et al. (2003) have demonstrated that the stars of the thin disk in the solar neighborhood (i.e., with R_{GC} between 7 and 10 kpc) show very small scatter in element ratios, with element ratios essentially solar. Separating the sample into thick disk stars and thin disk stars on the basis of their kinematics, they find the former to have in the mean higher enhancements for the α -elements Mg, Si, Ca, and Ti than do the thin disk stars. Furthermore, they find a relatively clean age-metallicity relationship characterized by a slow monotonic decrease of metallicity with age, with considerable scatter around this trend.

A model for the chemical evolution of a galaxy requires adding up the contributions of SNe II and SNe Ia and asymptotic giant branch stars. If the contribution of SNe Ia, which produce a smaller ratio of α /Fe elements in their ejecta, is delayed compared to that of SNe II, which produce copious amounts of α elements but little Fe, α -enhancements can result. Such circumstances prevailed in the young galaxy, before SNe Ia, with their longer required timescale, started exploding, while SNe II come from massive stars with short lifetimes.

The roughly equal α -enhancement seen in these four GC systems, and the fact that this is seen among both metal-rich and metal-poor GCs within these systems, provides a crude chronometer and suggests that the GCs in these systems are mostly old, with ages of 10 Gyr or longer. Additional recent spectroscopic studies with much smaller samples of GCs in quiescent massive bulge-dominated galaxies, including the Sombbrero galaxy (M104 = NGC 4594) (Larsen et al. 2002) and NGC 1399, the central galaxy in the Fornax Cluster (Forbes et al. 2002), find similar old ages.

Relative ages for subsamples within a GC system can be obtained with a number of assumptions about the GC mass

function from photometric analyses by measuring the brightness of the turnover of the GC luminosity function and comparing to predictions from single-burst population models. This technique has been applied to M49 by Puzia et al. (1999), who found no difference in age larger than 3 Gyr between the metal-poor and metal-rich GC populations. Jordan et al. (2002) have applied such techniques to M87, where again no age difference of more than 0.5 Gyr was found between the metal-rich and metal-poor populations. Thus the uniformly old ages found through spectroscopic observations in M87 and in M49 when the Worthey (1994) models are used are supported by photometric analyses. The old ages of the GCs in these galaxies, and the small difference in their relative ages, are consistent with the predictions of empirical models for the hierarchical growth that involves no GC formation (e.g., Côté et al. 1998). However, the very steep protogalactic mass spectra required to explain the detailed shape of the GC metallicity distributions in the context of this scenario remains problematical.

Models for GC formation that involve the formation of GCs in late epoch mergers, such as those of Ashman & Zepf (1992) and Bekki et al. (2002), must somehow push those mergers back earlier in time, earlier than $z \sim 2$. Evidence from the study of distant galaxies in situ at such redshifts also suggests that massive galaxies are more or less completely assembled by $z \sim 1$ (Cohen 2002) and are at least partially assembled without major ongoing star formation at $z \sim 2$ (Labbe et al. 2003). Beasley et al. (2002) investigate the formation of GCs within the framework of the treatment of semianalytical galaxy formation of Cole et al. (2000). They find age differences of 1–7 Gyr between the metal-poor GCs, which are formed at high redshift in protogalactic fragments, and the metal-rich GCs, which are formed during subsequent mergers. The inferred age differences, however, ultimately depend on their assumption of a truncated formation history for the metal-poor cluster and a metallicity-dependent cluster formation efficiency. It appears that fully successful model of GC formation does not exist at the present time.

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