AN ABUNDANCE ANALYSIS FOR FIVE RED HORIZONTAL-BRANCH STARS IN THE EXTREMELY METAL-RICH GLOBULAR CLUSTER NGC 6553¹

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Received 1999 February 15; accepted 1999 May 8

ABSTRACT

We provide a high-dispersion line-by-line abundance analysis of five red horizontal-branch (HB) stars in the extremely metal-rich Galactic globular cluster NGC 6553. These red HB stars are significantly hotter than the very cool stars near the tip of the giant branch in such a metal-rich globular cluster, and hence their spectra are much more amenable to an abundance analysis than would be the case for red giants. We find that the mean $[\text{Fe}/\text{H}]$ for NGC 6553 is -0.16 dex, comparable to the mean abundance in the Galactic bulge found by McWilliam & Rich and considerably higher than that obtained from an analysis of two red giants in this cluster by Barbuy and coworkers. The relative abundance for the best-determined α -process element (Ca) indicates an excess of α -process elements of about a factor of 2. The metallicity of NGC 6553 reaches the average of the Galactic bulge and of the solar neighborhood.

Subject headings: globular clusters: individual (NGC 6553) — stars: abundances — stars: horizontal-branch

1. INTRODUCTION

The abundances of the Galactic globular clusters (henceforth GCs) are an important datum for study of the chemical evolution and the halo of the Galaxy, among many other areas. The determination of these abundances rests on spectroscopic observations of the brightest GC stars, the red giants at the tip of the giant branch. This subject has a very long history, with observations of the brightest globular cluster stars attempted as soon as was technically feasible, beginning with Helfer, Wallerstein, & Greenstein (1959) using the coude of the Hale Telescope. In the late 1970s, the commissioning of a pair of identical echelle spectrographs attached to the newly completed 4 m telescopes at KPNO and at CTIO made it possible to obtain high signal-to-noise ratio (S/N) spectra at suitably high spectral resolution for the brightest giants in the nearer GCs, and several groups undertook programs to provide the required abundance determinations (Cohen 1979; Pilachowski, Sneden, & Wallerstein 1983 and references therein). These programs produced excellent results for the more metal-poor GCs but faltered at the metallicity of M71 or 47 Tuc for reasons described in more detail below.

As no very metal-rich GC is close enough for the giants to be reachable with instrumentation available at that time on a 4 m telescope, there was no attempt to observe stars in any GC expected to be more metal rich than 47 Tuc. Cohen (1983) tried a few of the most metal-rich GCs on the Palomar 5 m Hale telescope, but at somewhat lower spectral resolution than ideal, to get preliminary abundance values.

Since there are roughly 150 Galactic GCs, detailed abundance analyses will only be available at best for a limited number of bright red giants in the nearer GCs. Over the years, many schemes have been devised to extend the abundance determinations for individual red giants in these few

GCs to the full sample of Galactic GCs. Some approaches, for example, those of Zinn & West (1984) and of Armandroff & Zinn (1988), use narrowband photometry or spectra of the integrated light of GCs; some (see Armandroff & Da Costa 1991) use the very strongest lines in individual GC red giants measured from low-dispersion spectra; while other abundance schemes rely on characteristics of the color-magnitude diagram (CMD), such as the color of the giant branch (Frogel, Cohen, & Persson 1983) or the slope of the giant branch in the infrared (Kuchinski & Frogel 1995). But the fundamental calibration of all these schemes rests on the high-dispersion spectroscopic abundance determinations for a limited number of individual GC red giants. Independent of these is the $\Delta(S)$ method for RR Lyrae stars developed by Preston (1959), with a recent calibration from high-dispersion abundance analyses of field RR Lyrae stars by Clementini et al. (1995). Unfortunately, there are no RR Lyrae stars in the most metal-rich GCs, hence this is only useful for the metal-poor GCs.

Up to the present the calibration of all these schemes at the extremely metal-rich end has been unsatisfactory, a situation we hope to remedy with the present work. NGC 6553 is the best GC to use as a calibrator for the very metal-rich GCs. It is reasonably close, populous, and very metal rich, with an abundance that is believed to lie near the maximum achieved among the Galactic GCs and with a reddening that is small compared with that of most such clusters. The purpose of this paper is to present a detailed abundance analysis for stars, avoiding the red giants in NGC 6553.

2. THE CHARACTERISTICS OF NGC 6553

The first photometric study of NGC 6553 was that of Hartwick (1975). Ortolani, Barbuy, & Bica (1990) provide a modern ground-based CCD study. Their key finding was that the giant branch in NGC 6553 as viewed in a CMD using a blue magnitude such as V , $B-I$ or V , $V-I$ is not monotonic but forms an arc such that the reddest of the presumed red giants in NGC 6553 are fainter than the somewhat bluer red giants. This anomalous behavior is also seen in their later study of NGC 6528 (Ortolani, Barbuy, & Bica 1991) and in the Galactic bulge field giants (Rich et al. 1998). It is less prominent in CMDs involving redder colors,

¹ Based in large part on observations obtained at the W. M. Keck Observatory, which is operated jointly by the California Institute of Technology and the University of California.

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i.e., I , $V - I$. It is not seen at all in CMDs involving only infrared wavelengths where the giant branch behaves as expected, with the stars becoming brighter as they become redder (Cohen & Sleeper 1995; Kuchinski & Frogel 1995). This anomalous behavior is ascribed to the extreme line/molecular band absorption found at blue wavelengths in such metal-rich cool stars.

Guarnieri et al. (1998) provide a definitive photometric study of NGC 6553 which combines V and I photometry from the *Hubble Space Telescope* (HST) with ground-based infrared photometry at J and K . They determine a distance based on the magnitude of the horizontal-branch (henceforth HB) stars for this GC of 5.2 kpc with a reddening of $E(B - V) = 0.7$ mag, in good agreement with that determined by Zinn (1980) [$E(B - V) = 0.78$ mag]. Guarnieri et al. (1998) obtain the reddening by forcing the red giant branch of NGC 6553 to overlay that of 47 Tuc and then adopting a correction for the difference in metallicity between the two GCs; to deduce this correction they adopt $[\text{Fe}/\text{H}] = -0.22 \pm 0.05$ dex for NGC 6553.⁴

Barbuy et al. (1992) compiled the abundance estimates for NGC 6553 over the period 1983–1992 from the literature. The values range from $+0.5$ to -0.7 dex, with none of them being particularly well calibrated or having adequate spectral dispersion to produce a highly accurate result. Barbuy et al. (1992) obtained a CCD echelle spectrum from ESO covering the spectral region 475–580 nm with a spectral resolution of $0.20 \text{ \AA}$ and an S/N of 40 of a single red giant in NGC 6553 (star III-17 as identified by Hartwick 1975), which is among the brightest red giants in the cluster (at V). They attempted an abundance analysis for this star. The available photometry for this star could not be used to determine T_{eff} as different colors gave inconsistent results. The line crowding in their spectrum was so severe that they were forced to use spectral synthesis techniques throughout. They obtained a preliminary result of $[\text{M}/\text{H}] = -0.2^{+0.2}_{-0.4}$ dex for this red giant in NGC 6553.

A detailed abundance analysis of two giants in NGC 6553 (stars II-85 and III-3, both slightly fainter than star III-17, but still among the brightest stars in the cluster at V) was carried out by Barbuy et al. (1999). This time the spectral region was shifted somewhat to the red, 500–750 nm and was covered at a spectral resolution of $R = 20,000$ with an S/N ≈ 50 . The effective temperatures for the two red giant stars were derived from the photometry of Guarnieri et al. (1998) and are 4000 K for both stars with $\log g = 0.8$. They obtained $[\text{Fe}/\text{H}] = -0.55 \pm 0.2$ dex with $[\alpha/\text{Fe}] \approx +0.5$ dex.

3. THE CHOICE OF STARS FOR OUR SAMPLE

3.1. Lessons from the Past

In the early 1980s, the initial surge of enthusiasm for abundance determination of Galactic GCs with the new generation of telescopes and instrumentation led to detailed results that have withstood the test of time for metal-poor GCs. But when efforts were made to extend this upward in metallicity to 47 Tuc and to M71, very controversial abundances were initially derived by both of the two groups involved that were considerably lower than anyone anticipated (-1.1 dex for 47 Tuc by Pilachowski, Canterna, &

Wallerstein 1980 and Pilachowski, Sneden, & Wallerstein 1983 and -1.3 dex for M71 by Cohen 1980). Subsequently, Cohen (1983) attempted to determine whether these low abundances for 47 Tuc and for M71 were real or resulted from some problem in the analysis. Cohen (1983) derived $[\text{Fe}/\text{H}] = -0.7$ dex for M71 using (for perhaps the first time for a GC star) a CCD spectrum and demonstrated that the abundances initially deduced for stars in M71 (and presumably 47 Tuc as well) were too low. This was ascribed to the difficulty in locating the proper continuum level in such cool high-metallicity stars and the tendency toward underestimating the continuum in such heavily blended spectra. Gratton, Quarta, & Ortolani (1986) also obtained $[\text{Fe}/\text{H}] = -0.8$ for M71 and for 47 Tuc, observing stars considerably warmer (and fainter) than the tip of the red giant branch, demonstrating yet again that there were problems with the initial abundances for these clusters obtained from the photographic 4 m echelle spectra. Note that the red giants near the tip of the giant branch in M71 and in 47 Tuc have $T_{\text{eff}} \sim 4100$ K with $\log g \approx 0.7$ dex, somewhat hotter than the two red giants in NGC 6553 analyzed by Barbuy et al. (1999).

After removing the reddening, the giant branch of NGC 6553 is even redder than that of 47 Tuc or M71 in a CMD. Hence, presumably the giants near the tip are even cooler and more metal rich than those of M71. Issues of line crowding and continuum determination must be taken very seriously. We must take every precaution to avoid stumbling over the same problem again.

3.2. Our Choice of Stars in NGC 6553

We are fortunate to have available the collecting power of the Keck Telescope and the efficient HIRES spectrograph (Vogt et al. 1994). This means that we can get reasonable spectral resolution and S/N in a 1 hr exposure for stars considerably fainter than the tip of the red giant branch (RGB) in NGC 6553. Instead of using red giants, even giants substantially fainter than the tip of the giant branch, we have chosen stars on the red HB in NGC 6553 for our sample. There are a number of major advantages of such a choice. The first is that the red HB stars are considerably hotter than those near the top of the RGB, with T_{eff} comparable to the luminous giants in more metal poor GCs. We can use the same set of absorption features as were used for the lower metallicity GCs, and they will be of roughly comparable strength in a red HB star in NGC 6553 as in an RGB star in a lower metallicity GC. We will thus be more able to maintain consistency of results over the full range of metallicity of the Galactic GCs.

Moving into the near-IR (630–870 nm with incomplete coverage due to gaps between the orders of HIRES) at high resolution ($R = 34,000$, corresponding to a $1''$ entrance slit) guarantees the minimum line crowding possible, while still avoiding excessive contamination by terrestrial atmospheric absorption and emission lines. We will see later that the resulting red HB star HIRES spectra, even in a GC as metal rich as NGC 6553, are sufficiently clean that we do not need spectral synthesis techniques and can instead determine abundances using individual absorption features as is normally done for the RG stars in the metal-poor GCs. Furthermore, with the powerful equipment of the Keck Telescope plus HIRES we can achieve an S/N of ≈ 70 per 4 pixel resolution element with exposure times of under 1 hr for an HB star in NGC 6553 in that spectral region.

⁴ We adopt the usual spectroscopic notation that $[A/B] \equiv \log(N_A/N_B)_{\text{star}} - \log(N_A/N_B)_{\odot}$. Also, unless otherwise specified, metallicity is arbitrarily defined as the stellar $[\text{Fe}/\text{H}]$ value.

TABLE 1
THE SAMPLE OF STARS OBSERVED IN NGC 6553

ID	V^a (mag)	I^a (mag)	J^a (mag)	K^a (mag)	v_r (km s ⁻¹)	Date of Observation	Exposure Time (s)
Red HB Stars							
30180	16.85	14.86	13.39	12.46	-4.9	1995 Aug 5	3000
30242	16.90	14.97	13.38	12.42	+2.2	1995 Aug 5	3000
30257	16.88	14.98	13.32	12.38	+1.6	1995 Aug 5	3000
40071	16.77	14.82	13.38	12.40	-4.5	1997 Aug 3	3000
40123	16.94	14.95	13.43	12.46	+12.6	1997 Aug 3	3000
Extremely Red Giants							
30291	16.92	12.15	8.90	7.17	+9.1	1995 Aug 6	2000
30297	16.62	12.04	8.81	7.31	+10.3	1995 Aug 6	2000
Comparison Star							
ζ Cyg (BS 8115).....	3.19		1.68	1.07	+14.4	1995 Aug 5	2

^a From Guarnieri et al. 1998, except for ζ Cyg, whose photometry is from Johnson 1964 and with K from Neugebauer & Leighton 1969.

Other advantages of working with red HB stars include a well-defined mass (assumed to be $0.8 M_{\odot}$) and luminosity so that once T_{eff} is specified, the surface gravity is determined as well. Furthermore, the use of a well-populated evolutionary state that occupies only a small area on a cluster CMD such as the red HB maximizes the probability that a star in that location in the CMD is a member of the GC and minimizes contamination by field stars, a nontrivial issue for a cluster with $(l, b) = (5.3, -3.0)$. In addition, the non-LTE corrections are smaller for these hotter and higher surface gravity stars. With these points in mind, we chose the least crowded red HB candidates in NGC 6553 from Guarnieri et al. (1998) to form the spectroscopic sample.

At the request of A. Renzini, two of the extremely red stars at the extreme end of the arc in the CMD for NGC 6553 found by Ortolani, Barbuy, & Bica (1990) were also observed in order to check that they are indeed members of the cluster. Since the spectra of these stars show very strong TiO bands, they were not used for the abundance analysis.

Table 1 lists the five red HB stars in NGC 6553 observed spectroscopically during a night in the summer of 1995 and one in the summer of 1997, as well as the two extremely red giants. The identification numbers are those assigned by Guarnieri et al. (1998), from which the photometry is taken. Star 30297, one of the extremely red stars, is star II-3 of

Hartwick (1975). The exposure times and dates of observation are also given.

The heliocentric radial velocity for this cluster was not well determined, hence measurements from our spectra are also given in Table 1. We find that all of the stars observed, including the two extremely red stars, are probably members of NGC 6553. The seven heliocentric radial velocities indicate that the cluster mean velocity is 4 km s^{-1} , with $\sigma = 7.1 \text{ km s}^{-1}$, in good agreement with the recent determinations of the mean cluster velocity from two stars of Barbuy et al. (1999) of 6 km s^{-1} and (from more stars, but at lower dispersion) of Rutledge et al. (1997a) of 8.4 km s^{-1} . The HB stars are all slow rotators; this will be discussed in B. Behr's thesis.

There is one possible disadvantage of using HB stars. Since they are in an even later stage of evolution than RGB stars, one might worry about the effects of mixing, gravitational settling, etc. In the stable atmosphere of a hot star, diffusion effects—both gravitational settling of He and radiative levitation of Fe and other metals—can significantly alter the photospheric composition, as predicted by Michaud, Vauclair, & Vauclair (1983) and observed by Heber (1987) and Glaspey et al. (1989). These effects, however, appear to be limited to $T_{\text{eff}} \geq 10,000 \text{ K}$ (Behr et al. 1999) and are thus not of concern for the red horizontal branch (RHB). Deep mixing on the RGB can also produce surface abundance anomalies in CNO (Kraft et al. 1998 and many prior reports), but these same variations will appear in any evolutionary stage beginning with the RGB and including any more advanced stage such as the HB. Such abundance anomalies are not expected to extend to the heavier elements from Ca to the Fe peak.

There have been a small number of high-dispersion abundance analyses of RR Lyrae stars (Clementini et al. 1995 for M4) and other HB stars in Galactic GCs (Cohen & McCarthy 1997 for M92) which demonstrate that, at least if one avoids the bluest HB stars, good consistency with abundances from giant branch stars in the same GC is obtained.

4. DETERMINATION OF ATMOSPHERIC PARAMETERS

The initial values of T_{eff} to be used in the high-dispersion abundance analysis are determined for each of the red HB

TABLE 2
ADOPTED MODEL ATMOSPHERE PARAMETERS

Star ID	T_{eff} (K)	$\log g$ (dex)	v_t (km s ⁻¹)
Red HB Stars			
30180	4700	2.3	1.8
30242	4630	2.3	1.8
30257	4750 ^a	2.3	1.6
40071	4725	2.3	2.5
40123	4830 ^b	2.3	1.4
Comparison Star			
ζ Cyg (BS 8115).....	4950	2.7	1.6

^a Initial $T_{\text{eff}} = 4600 \text{ K}$.

^b Initial $T_{\text{eff}} = 4625 \text{ K}$.

TABLE 3
EQUIVALENT WIDTHS FOR FIVE RED HB STARS IN NGC 6553 AND FOR ζ CYG^a

Ion	λ (Å)	χ (eV)	$\log gf$	EW (400071) (mÅ)	EW (40123) (mÅ)	EW (30180) (mÅ)	EW (30242) (mÅ)	EW (30257) (mÅ)	ζ Cyg (mÅ)
O I	7771.95	9.11	0.33	56.2	...	30.2	39.7	56.8	49.0
O I	7774.18	9.11	0.19	53.3	33.3	42.7	44.2	...	55.9
O I	7775.40	9.11	-0.03	45.9	31.7	39.7	42.5	43.3	47.8
Mg I	8717.80	5.93	-1.09	122.4	86.9	94.9	101.0	...	97.9
Si I	6848.57	5.86	-1.75	24.5	20.6	...	24.1	34.8	38.7
Si I	7034.90	5.87	-0.88	81.2	63.8	90.3	...	60.4	...
Si I	7405.79	5.61	-0.82	114.6	...	...	...	...	...
Si I	7932.40	5.96	-0.47	74.8	72.8	...	92.4	80.0	95.7
Ca I	6455.60	2.52	-1.29	...	108.6	102.8	...	...	...
Ca I	6462.57	2.52	0.26	334.5	230.6	315.4	311.1	311.0	...
Ca I	6471.67	2.52	-0.69	173.9	133.0	165.2	142.3	161.0	...
Ca I	6493.79	2.52	-0.11	251.8	...	199.0	176.9	170.4	182.8
Ca I	6499.65	2.52	-0.82	158.2	116.0	137.3	122.9	134.2	131.9
Ca I	6572.80	0.00	-4.32	186.1	108.5	131.9	129.7	137.6	105.9
Sc II	6604.60	1.36	-1.14	91.4	74.5	89.6	91.3	68.4	90.5
Ti I	6508.12	1.43	-2.05	41.7	41.3	42.5	...	42.7	...
Ti I	6743.13	0.90	-1.63	126.9	76.3	78.5	112.7	...	69.7
Cr I	6979.80	3.46	-0.22	111.2	...	90.6	...	...	...
Cr I	7400.19	2.90	-0.11	156.3	105.1	147.0	137.4	132.8	131.7
Fe I	6380.75	4.19	-1.34	98.2	80.8	91.3	86.0	97.4	100.8
Fe I	6392.54	2.28	-3.97	93.3	51.3	...	...	...	...
Fe I	6393.61	2.43	-1.43	271.4	167.0	218.1	235.4	223.7	208.5
Fe I	6400.32	3.60	-0.23	345.9	...	...	...	...	...
Fe I	6411.66	3.65	-0.60	236.4	125.2	156.8	...	161.3	168.2
Fe I	6421.36	2.28	-1.98	216.4	162.0	222.1	188.2	204.9	...
Fe I	6481.88	2.28	-2.94	158.7	106.3	142.8	124.4	124.9	132.5
Fe I	6498.95	0.96	-4.66	153.2	113.5	143.7	124.5	121.1	134.5
Fe I	6518.37	2.83	-2.56	133.6	95.0	...	...	...	...
Fe I	6533.94	4.56	-1.28	92.8	...	...	...	...	...
Fe I	6574.25	0.99	-4.96	142.6	100.0	122.6	121.9	117.2	...
Fe I	6581.22	1.48	-4.68	133.0	81.8	93.6	108.5	102.5	102.7
Fe I	6593.88	2.43	-2.30	183.8	146.0	170.9	170.9	163.7	157.0
Fe I	6608.04	2.28	-3.96	92.5	56.5	73.8	55.9	63.8	...
Fe I	6609.12	2.56	-2.65	161.5	121.4	137.5	136.4	122.9	...
Fe I	6625.04	1.01	-5.32	...	...	...	...	114.3	...
Fe I	6627.56	4.55	-1.50	69.3	65.2	...	52.0	63.7	64.7
Fe I	6703.58	2.76	-3.00	128.2	88.7	102.4	92.2	97.4	...
Fe I	6713.74	4.79	-1.41	...	32.2	...	47.4	...	...
Fe I	6725.36	4.10	-2.21	43.3	...	48.8	...	43.9	...
Fe I	6726.67	4.61	-1.05	76.3	59.0	63.3	...	77.1	86.0
Fe I	6733.15	4.64	-1.44	52.2	42.9	57.0	46.5	61.8	57.8
Fe I	6750.16	2.42	-2.58	...	...	155.0	147.7	145.6	128.1
Fe I	6786.86	4.19	-1.90	66.0	...	64.9	...	...	...
Fe I	6839.84	2.56	-3.35	96.6	83.3	100.4	...	102.3	...
Fe I	6843.66	4.55	-0.86	109.9	84.3	111.3	74.9	103.1	98.9
Fe I	6857.25	4.07	-2.07	51.6	36.0	54.6	31.1	...	51.7
Fe I	6858.16	4.61	-0.95	86.7	60.2	76.5	69.1	82.5	92.3
Fe I	6898.29	4.22	-2.08	45.5	...	...	43.7	...	48.5
Fe I	6916.69	4.15	-1.35	126.9	88.0	...	...	...	109.7
Fe I	6988.53	2.40	-3.42	126.6	106.0	...	107.3	115.1	106.2
Fe I	7007.97	4.18	-1.80	...	...	...	...	...	78.6
Fe I	7022.96	4.19	-1.11	121.0	...	...	122.9	120.9	...
Fe I	7130.93	4.22	-0.76	146.5	142.2	...	...	...	...
Fe I	7132.99	4.07	-1.66	83.9	63.6	...	...	...	...
Fe I	7142.52	4.95	-0.93	99.7	74.3	...	79.9	80.7	...
Fe I	7151.47	2.48	-3.58	103.2	...	...	107.5	...	...
Fe I	7180.00	1.48	-4.71	147.7	...	96.5	118.1	111.9	...
Fe I	7189.16	3.07	-2.77	96.5	64.0	...	...	...	...
Fe I	7190.13	3.11	-3.28	94.4	...	50.1	49.3	...	...
Fe I	7306.57	4.18	-1.55	63.9	48.9	70.2	63.2	59.5	69.0
Fe I	7401.69	4.19	-1.60	94.4	...	...	...	...	...
Fe I	7411.16	4.28	-0.48	...	134.9	161.0	143.6	172.8	168.3
Fe I	7418.67	4.14	-1.44	121.8	74.3	91.6	86.4	97.3	94.3
Fe I	7421.56	4.64	-1.69	30.2	...	...	27.2	...	33.4

TABLE 3—*Continued*

Ion	λ (Å)	χ (eV)	$\log gf$	EW (400071) (mÅ)	EW (40123) (mÅ)	EW (30180) (mÅ)	EW (30242) (mÅ)	EW (30257) (mÅ)	ζ Cyg (mÅ)
Fe I	7447.40	4.95	−0.95	64.8	...	...	...	...	...
Fe I	7461.53	2.56	−3.45	127.4	82.2	97.4	90.0	82.8	...
Fe I	7491.66	4.30	−1.01	106.0	78.5	113.4	91.3	100.5	82.1
Fe I	7568.91	4.28	−0.90	138.8	116.5	...	...	137.4	...
Fe I	7583.80	3.02	−1.93	151.3	124.6	...	169.9	151.5	...
Fe I	7719.05	5.03	−0.96	71.6	51.3	66.7	...	57.7	54.6
Fe I	7723.21	2.28	−3.62	...	72.5	123.0	...	98.8	...
Fe I	7751.11	4.99	−0.74	104.2	71.1	81.4	84.2	...	87.2
Fe I	7807.91	4.99	−0.51	104.5	...	96.1	94.8	89.8	108.6
Fe I	7912.87	0.86	−4.85	168.1	...	...	...	...	...
Fe I	7941.10	3.27	−2.29	109.8	86.0	...	111.7	107.7	82.1
Fe II	6416.93	3.89	−2.70	55.0	45.9	52.5	52.7	50.0	53.9
Fe II	6456.39	3.90	−2.10	...	...	80.8	...	...	...
Fe II	7449.34	3.89	−3.10	50.9	...	...	...	...	...
Ni I	6378.26	4.15	−0.82	45.9	61.5	63.5	51.8	...	...
Ni I	6384.67	4.15	−1.00	...	41.0	...	45.9	...	...
Ni I	6482.81	1.93	−2.78	145.1	95.6	120.4	121.8	105.0	104.6
Ni I	6532.88	1.93	−3.42	94.3	...	...	73.2	...	...
Ni I	6586.32	1.95	−2.78	136.4	77.8	105.4	110.0	93.3	97.3
Ni I	6635.14	4.42	−0.75	58.4	49.9	...	45.0	...	...
Ni I	6767.78	1.83	−2.06	161.6	128.1	165.1	142.2	151.9	132.7
Ni I	6772.32	3.66	−0.96	81.4	70.9	99.4	77.6	80.9	90.5
Ni I	7030.02	3.54	−1.70	63.0	46.4	...	54.1	47.6	53.9
Ni I	7110.91	1.93	−2.91	143.4	102.0	...	113.7	...	...
Ni I	7422.29	3.63	−0.29	153.1	127.0	155.2	149.0	147.8	147.3
Ni I	7555.61	3.85	−0.12	174.0	125.7	174.9	148.1	142.7	141.9
Ni I	7574.05	3.83	−0.61	...	92.0	...	...	...	...
Ni I	7715.58	3.70	−0.98	86.4	...	...	...	...	...
Ni I	7727.62	3.68	−0.30	164.7	128.2	143.7	125.7	148.5	133.8
Ni I	7797.59	3.30	−0.82	155.4	103.5	141.3	101.3	129.3	112.4

^a As described in the text, all W_λ are measured from convolved spectra.

stars from the observed $V-K$ colors of Guarnieri et al. (1998) using the latest version of the model stellar atmospheres from Kurucz (1992) and the latest update of the original calibration of Cohen, Frogel, & Persson (1978) which is given by Gratton, Carretta, & Castelli (1997). As has been discussed extensively in the past, the $V-K$ color offers maximum leverage in assigning T_{eff} . A reddening of $E(B-V) = 0.78$ mag corresponding to $E(V-K) = 2.12$ mag is assumed; we use the reddening curve of Cohen et al. (1981). We further assume that the mass of an HB star in NGC 6553 is $0.8 M_\odot$ and that the luminosity of a star on the red HB in NGC 6553 is $\log(L/L_\odot) = 1.62$. These then determine the surface gravity. The resulting atmospheric parameters are listed in Table 2.

5. EQUIVALENT WIDTH MEASUREMENTS

The spectra were reduced using the suite of routines for analyzing echelle spectra written by McCarthy (1988) within the Figaro image processing package (Shortridge 1988). The stellar data are flat-fielded with quartz lamp spectra, thereby removing most of the blaze profile, and the results are normalized to unity by fitting a 10th-order polynomial to line-free regions of the spectrum in each order.

We are trying to measure equivalent widths for weak lines from spectra which are of adequate resolution [$\lambda/\Delta(\lambda) = 34,000$] but of only marginally adequate S/N (70/4 pixel resolution element). Even in the near-infrared there will be some adjacent weak lines contaminating any attempt to measure equivalent widths. We therefore adopt

the following procedure to make the W_λ more stable to the presence of weak spectral features near the desired one. We smooth the spectra with a Gaussian curve whose FWHM is $0.3 \text{ \AA}$, which is slightly larger than the instrumental resolution near $8000 \text{ \AA}$. The definition of the continuum was then updated slightly as seemed appropriate. Equivalent widths were measured in the convolved spectra of HB stars 40071 and 40123 in NGC 6553 for about 40 lines spanning the full range in strength to be used and judged to be unblended. A linear relationship was established between W_λ and the central depth of an absorption line, and this relationship was used to determine W_λ for the rest of the features used in the abundance analysis. This process was repeated for the three HB stars in NGC 6553 which were observed in 1995. The fit between W_λ and central line depth determined for the spectra from 1995 is very slightly different from that of the 1997 data, as might be expected because of differing instrumental and/or telescope focus. In total, W_λ measurements were obtained for ~ 80 lines in each of the five HB stars in NGC 6553, including ~ 40 Fe I lines. The W_λ we obtained for the five RHB stars in NGC 6553 are listed in Table 3.

Figure 1 shows a montage of a section of the convolved spectra covering part of a single echelle order for the five NGC 6553 RHB stars and also for the convolved spectrum for the comparison star ζ Cyg. Our use of convolved spectra to measure W_λ and the fact that the stars involved have the low surface gravities characteristic of giants mean that any small variations in the intrinsic line profile due, for example,

FIG. 1.—Portion of the (convolved) spectra is shown for the five NGC 6553 RHB stars and for the comparison star ζ Cyg. The spectra are arbitrarily shifted with respect to that of star 40071 along the Y-axis to avoid confusion.

to variations in thermal width or to a small amount of hyperfine structure, will not significantly affect our measurements of W_λ .

Several checks have been made to verify that our procedure produces accurate measurements of W_λ . All of the five red HB stars in NGC 6553 have very similar atmospheric parameters (see Table 2). We compare the measured W_λ for the pair of stars 30180 and 30242 and find $W_\lambda(30242) = 0.96 \times W_\lambda(30180) - 3.0 \text{ m}\text{\AA}$ with an rms

FIG. 2.—Set of W_λ measured on the original ζ Cyg spectrum are plotted against those measured on the convolved spectrum. The dashed line corresponds to equality.

scatter about this relationship of $14.2 \text{ m}\text{\AA}$. Attributing equal errors to both sets of W_λ suggests that typical errors in W_λ are $\pm 10 \text{ m}\text{\AA}$ which arise largely from uncertainties in the location of the continuum.

A second check can be made using spectra of much brighter comparison stars taken with the identical configuration of HIRES on the same night as the NGC 6553 spectra. These were chosen to have well-known abundances and at least some of them are believed to be similar to the RHB stars in NGC 6553. The one we utilize in this paper is ζ Cyg (BS 8115). The spectrum of this star (which is also included in Fig. 1) has the same resolution as the RHB stars in NGC 6553, but much higher S/N. Thus the set of W_λ could be measured on both the original spectrum and the convolved spectrum; the W_λ for the latter are given in the last column of Table 3, and in Figure 2 these two sets of W_λ are compared. The regression line between W_λ measured in the original and convolved spectra is (for 47 lines) $W_\lambda(\text{conv}) = (1.033 \pm 0.026) \times W_\lambda(\text{orig}) - (2.1 \pm 8.1) \text{ m}\text{\AA}$, where the error on the constant term is the rms scatter of individual points along this regression line. If we consider the set of W_λ measured on the original spectra as “perfect,” there is no clear systematic error in the set of W_λ measured in the convolved spectra and typical errors are $\pm 8 \text{ m}\text{\AA}$. This estimate agrees quite well with the error of $\pm 10 \text{ m}\text{\AA}$ estimated for the stars in NGC 6553 (where the S/N is lower).

6. ABUNDANCE ANALYSIS

The guiding principle we have followed in the abundance analysis of the RHB stars in NGC 6553 is to adhere as closely as possible to the procedures used in earlier analyses of the less metal-rich GCs by Carretta & Gratton (1997, hereafter CG) so as to make the results for the NGC 6553 sample as consistent and comparable as possible with the earlier analyses. This means we use the same set of model atmospheres (those of Kurucz 1992 with convective overshooting), the same relationship between color and T_{eff} (that of Gratton et al. 1997), the same set of g_f -values whose sources are given in CG, the same line-by-line abundance code, etc. The solar abundances are those defined in CG and are obtained in a manner as consistently as possible as are those of the program stars, using a solar model from Kurucz (1992), etc.

The metal abundance for the model atmosphere used for each RHB star was determined by looking at the results of a first iteration for $[\text{Fe}/\text{H}]$, then repeating the analysis with models whose abundance is close to that inferred from the first iteration. The microturbulent velocity was determined in the usual manner by forcing the slope of the W_λ versus deduced abundance to be zero. No hyperfine structure corrections were used; none are necessary except perhaps for Sc II.

Clementini et al. (1995) demonstrate that the non-LTE corrections for HB stars are expected to be small. We assume LTE, except for oxygen. The O abundance is from the infrared triplet near $7770 \text{ \AA}$; a small non-LTE correction (-0.07 dex) has been applied for oxygen based on the calculations of Gratton et al. (1999).

We now consider the validity of our initial atmospheric parameters as judged by the results of the abundance analysis. For three of the five RHB stars in NGC 6553, adoption of the initial parameters led to no detectable trend of abundance versus excitation potential for the Fe I lines.

For stars 40123 and 30257, this was not true; to achieve this condition, a small adjustment was made in their T_{eff} , raising it by 150–200 K. This change could easily arise if the reddening were slightly larger than the mean for these two RHB stars. An increase in $E(B-V)$ by 0.08 mag above our adopted mean value for NGC 6553 of 0.78 mag is required for star 40123, while a somewhat smaller increase is needed for star 30257. With these two small adjustments of T_{eff} , the derived abundances are independent of the excitation potentials of the Fe I lines and the ionization equilibrium for Fe is quite good (see Table 4).

The resulting abundances deduced for the five RHB stars in NGC 6553 are listed in Table 4. First the deduced $[\text{Fe}/\text{H}]$ value is given as determined from the ions Fe I and Fe II. Then the element ratios $[\text{A}/\text{Fe}]$ are given as determined from various ions. These are calculated using Fe I, except for oxygen and singly ionized scandium, where Fe II is used. The final column gives the solar abundance that we use. When there is more than one line of a given ion, the rms dispersion about the mean is given in parentheses. The mean abundance of each element together with the rms dispersion about the mean for the cluster NGC 6553 as determined from the analysis of the five red HB stars is given in Table 5.

Figure 3 shows the deduced abundances for Fe I lines as a function of excitation potential in the five red HB stars in NGC 6553. The 1σ rms uncertainty in the slope of the best

linear fit is $0.026 \text{ dex eV}^{-1}$, implying an uncertainty in T_{eff} of $\sim 100 \text{ K}$.

6.1. Verification Using $\zeta \text{ Cyg}$

We observed several bright stars as possible comparison stars for this analysis of RHB stars in the extremely metal-rich GC NGC 6553. Of those, $\zeta \text{ Cyg}$ (BS 8115) is the one actually used since its atmospheric parameters are closest to those of the program stars. Just as for the GC stars, we obtain T_{eff} for $\zeta \text{ Cyg}$ from its colors, including the $V-K$ color, given by Johnson (1964) and by Neugebauer & Leighton (1969) using the same calibration as for the RHB stars. This star is so nearby that interstellar reddening can be ignored. The *Hipparcos* parallax (ESA 1997) is 21.62 mas, implying $M_V = -0.13 \text{ mag}$, somewhat brighter than the HB for old stellar systems. However, we do not know the mass of $\zeta \text{ Cyg}$ and hence must determine its surface gravity by forcing ionization equilibrium for Fe using the set of W_λ measured from the original nonconvolved spectra and checking that the implied mass is reasonable. The abundance for the model atmosphere was set in a manner similar to that used for the RHB stars, and an abundance analysis was carried out both for the set of W_λ measured from the original spectra and for those from the convolved spectra. The resulting abundances are listed in Table 6. The organization of Table 6 is similar to that of Table 4 described in detail above.

FIG. 3.—Abundances deduced from lines of Fe I are shown as a function of excitation potential of the lower level of the transition for the five NGC 6553 RHB stars.

TABLE 4
ABUNDANCES FOR FIVE RED HB STARS IN NGC 6553

ION	STAR 40071			STAR 40123			STAR 30180			STAR 30242			STAR 30257			SUN ABUNDANCE (dex)
	Number of Lines	Abundance (dex)		Number of Lines	Abundance (dex)		Number of Lines	Abundance (dex)		Number of Lines	Abundance (dex)		Number of Lines	Abundance (dex)		
[Fe/H]																
Fe I.....	50	-0.18 (0.20)		39	-0.18 (0.15)		32	-0.14 (0.32)		35	-0.26 (0.22)		36	-0.03 (0.18)		-4.50
Fe II	2	-0.11 (0.22)		1	-0.33		2	-0.18 (0.03)		1	-0.07		1	-0.20		-4.56
[A/Fe]																
O I ^a	3	+0.53 (0.07)		2	+0.34 (0.13)		3	+0.41 (0.32)		3	+0.56 (0.22)		2	+0.68 (0.03)		+1.18
Mg I.....	1	+0.50		1	+0.34		1	+0.31		1	+0.48					+0.04
Si I.....	4	+0.07 (0.22)		3	-0.01 (0.13)		1	+0.39		2	+0.27 (0.05)		3	-0.03 (0.24)		+0.04
Ca I.....	5	+0.36 (0.26)		5	+0.33 (0.12)		6	+0.23 (0.19)		5	+0.13 (0.12)		5	+0.26 (0.24)		-1.34
Sc II ^a	1	-0.16		1	-0.13		1	-0.04		1	+0.11		1	-0.38		-4.48
Ti I	2	+0.18 (0.12)		2	+0.23 (0.37)		1	+0.24		1	+0.10		1	+0.19		-2.52
Cr I.....	2	+0.10 (0.22)		1	-0.09		2	+0.14 (0.01)		1	+0.04		1	+0.01		-1.88
Ni I.....	14	-0.04 (0.23)		14	+0.02 (0.16)		9	+0.11 (0.17)		14	+0.02 (0.21)		9	-0.06 (0.17)		-1.25

^a O I and Sc II are calculated with respect to Fe II; all other ions are with respect to Fe I.

TABLE 5

MEAN ABUNDANCES FOR NGC 6553 AND COMPARISON WITH BAADE'S WINDOW RESULTS

Ion	NGC 6553 Mean (dex)	σ (dex)	Mean BW ^a (dex)	σ^a (dex)
[Fe/H]				
Fe I.....	-0.16	0.08	-0.33	...
Fe II.....	-0.18	0.10	...	...
[A/Fe]				
O I.....	+0.50	0.13	+0.03	0.18
Mg I.....	+0.41	0.10	+0.35	0.14
Si I.....	+0.14	0.18	+0.18	0.24
Ca I.....	+0.26	0.09	+0.14	0.17
Sc II.....	-0.12	0.18	+0.29	0.20
Ti I.....	+0.19	0.06	+0.34	0.10
Cr I.....	+0.04	0.09	-0.04	0.19
Ni I.....	+0.01	0.07	-0.04	0.08

^a Abundances for Baade's window are from the 11 giants studied by McWilliam & Rich 1994.

ζ Cyg has been the subject of at least five relatively recent high-dispersion abundance analyses according to the compilation of Cayrel de Strobel et al. (1997). The T_{eff} used in these five abundance analyses range from 4890 to 4990 K, and $\log g$ ranges from 2.0 to 2.9. The deduced [Fe/H] ranges from -0.17 to +0.10 dex, with typical errors quoted as ± 0.10 dex. The mean of the five abundance determinations for ζ Cyg from the literature is -0.04 dex. Our adopted T_{eff} is in the middle of the range of these values, as is our $\log g$; our value of [Fe/H] from Fe I is +0.05 dex. This is in some sense the expected abundance for a disk star. Thus we feel that this comparison demonstrates the validity of our procedure for measuring W_λ and of our abundance analysis procedure.

6.2. Verification Using Spectral Synthesis

To demonstrate how well the observed spectra can be fitted by spectral synthesis with the model atmosphere parameters we have derived and with the abundances obtained from our analysis, we display in Figure 4 a synthesis for the spectral region shown in Figure 1 for the five RHB stars in NGC 6553. In considering the different abundances shown (-0.4, -0.2, and 0.0 dex) all metals (except

Li) were scaled appropriately and a Ca overabundance of a factor of 2 ([Ca/Fe] = +0.3 dex) was used throughout. Figure 5 shows the same for the comparison star ζ Cyg, except that here the spectral syntheses shown utilize the abundances -0.2, 0.0, and +0.2 dex. The convolved spectra are shown for the NGC 6553 stars, while the original spectrum is shown for ζ Cyg.

The comparison with the predictions of spectral synthesis roughly confirm an abundance of about [Fe/H] = -0.2 for NGC 6553 ([Fe/H] = -0.4 appears definitely too low, while a solar Fe abundance is clearly too high), in agreement with the abundance given in Table 4 from the line-by-line analysis. For ζ Cyg, a higher abundance is indicated, as we expect from the discussion above.

6.3. Discussion of Errors

The dominant source of errors is in the W_λ because of the limited S/N of our spectra of such relatively faint metal-rich cool stars, which gives rise to an uncertainty in the continuum location. Also contributing are problems of cosmic-ray hits and accurate subtraction of night-sky emission features, which may perturb individual lines. Another important factor is the uncertainty in T_{eff} due to possible reddening variations across NGC 6553. As mentioned earlier, a change in $E(B-V)$ from 0.78 to 0.86 mag will produce an increase in T_{eff} of 200 K.

Figure 1 of Hartwick (1975) demonstrates that the outer isophotes of NGC 6553 (i.e., the stellar distribution) are highly noncircular, presumably the result of nonuniform interstellar absorption. The northeast quadrant in particular shows evidence for absorption that is higher than the mean. Cohen & Sleeper (1995) present evidence for a significant dispersion of the interstellar absorption in several other highly reddened GCs by analyzing the dispersion in color of the RGB measured at a fixed luminosity for a variety of colors. While NGC 6553 is not in their sample, NGC 6528, with a comparable $E(B-V)$, is included. The full width in $V-K$ of the upper giant branch in this cluster is ~ 0.6 mag. Ascribing this to reddening variations across the cluster implies a range in $E(B-V)$ of ~ 0.2 mag. Ortolani, Barbuy, & Bica (1991) and Ortolani, Bica, & Barbuy (1992) also noted reddening variations across the face of this GC of $\Delta[E(B-V)] \sim 0.3$ mag. Since these are full amplitudes, not rms dispersions, for the variation in reddening, the fact that two stars in NGC 6553 appear to

TABLE 6
ABUNDANCES FOR ζ CYG

Ion	Number of Lines	Original Spectrum Abundance (dex)	Number of Lines	Convolved Spectrum Abundance (dex)	Solar Abundance (dex)
[Fe/H]					
Fe I.....	43	+0.08 (0.12)	27	+0.05 (0.20)	-4.50
Fe II.....	3	+0.09 (0.17)	1	-0.06	-4.56
[A/Fe]					
O I.....	4	+0.35 (0.14)	3	+0.38 (0.18)	+1.18
Mg I.....	1	+0.15	1	+0.20	+0.04
Si I.....	3	+0.10 (0.11)	2	+0.11 (0.26)	+0.04
Ca I.....	5	+0.08 (0.14)	3	+0.07 (0.04)	-1.34
Sc II.....	1	+0.30	1	+0.12	-4.48
Ti I.....	2	-0.08 (0.16)	1	-0.28	-2.52
Cr I.....	4	+0.03 (0.06)	1	+0.02	-1.88
Ni I.....	16	+0.02 (0.14)	9	-0.08 (0.17)	-1.25

FIG. 4.—Spectral synthesis of the region shown in Fig. 1 for the five RHB stars in NGC 6553. The convolved observed spectra are shown by the thick lines, while the thin lines denote predictions for model atmospheres with the parameters indicated in the lower left corner of each box and for abundances of $[\text{Fe}/\text{H}] = -0.4, -0.2, \text{ and } 0.0$ dex (i.e., solar abundance).

have a somewhat larger reddening than the mean by about $\Delta[E(B-V)] \sim 0.08$ mag should not be surprising. However, it does indicate that considerably larger variations in $E(B-V)$ should not be seen within our relatively small sample.

FIG. 5.—Same as Fig. 4 for ζ Cyg. The original observed spectrum is shown prior to convolution. Here the abundances for the synthetic spectra are $[\text{Fe}/\text{H}] = -0.2, 0.0, \text{ and } +0.2$ dex.

For that change in T_{eff} of $+200$ K, without changing any other parameters, the Fe ionization equilibrium changes by -0.33 dex, and $[\text{Fe}/\text{H}]$ (from the more numerous Fe I lines) increases by $+0.10$ dex. $[\text{O}/\text{Fe I}]$ is quite sensitive to T_{eff} , but when it is compared with the dominant ionization stage Fe II, which unfortunately has far fewer measurable lines in this spectral region for these stars than does Fe I, the O abundance is relatively insensitive to a 200 K change in T_{eff} . However, in practice, part of any increase in T_{eff} will be taken up by adjustments of other parameters, particularly the microturbulent velocity. This is because there is a (loose) correlation between line strength and excitation in our list of measured spectral lines, with the lowest excitation lines in general being stronger. For this reason the impact of a change of T_{eff} on the derived abundances is much less than the value quoted above. We verified this by repeating our analysis with T_{eff} lower by 200 K and adjusting v_t again to avoid trends of derived abundances with W_λ . The average abundance we found for NGC 6553 was again $[\text{Fe}/\text{H}] = -0.16$. Furthermore, the ionization equilibria we have obtained with just our initial choice of model atmosphere parameters for three of the five red HB stars in NGC 6553 are extremely good.

Model atmospheres whose detailed abundances element by element are identical to the results we have found for NGC 6553 are not available. We have checked that the

error introduced by using models with the solar abundance ratios is small, less than 0.1 dex for all ions.

In summary, we feel that an uncertainty of ± 0.1 dex is reasonable for $[\text{Fe}/\text{H}]$ and ± 0.15 dex for the element-to-element abundance ratios in each of the five RHB stars in NGC 6553, with the caveat that the O abundance be compared with that of the dominant singly ionized ionization stage of Fe.

6.4. Element Ratios

In our discussion to this point we have concentrated on Fe I as it is the only ion for which our red spectra contain large numbers of measured lines. For all other ions the number of measured lines is small. Typical errors in abundances from individual lines are ± 0.2 dex and are dominated by uncertainties in the location of the local continuum and by the presence of blends. However, these error sources may represent systematic errors that behave in a similar way for a given line in different stars, so that the star-to-star scatter likely underestimates the real error bars.

While the O abundance is derived from the IR triplet at 7770 Å whose lines are clean (i.e., not blended at this spectral resolution) and are a well-known abundance indicator, the lines are of very high excitation from the dominant ion. Thus, as discussed above, O/Fe ratios are very sensitive to the adopted temperature and gravity when O abundances are compared with that given by Fe I lines. O/Fe ratios are much more robust when Fe II lines are used; unfortunately, our Fe II abundances are only based on one or two lines. Oxygen is clearly overabundant in NGC 6553 stars, with an abundance ratio similar to that measured in other GCs and metal-poor stars (Gratton & Ortolani 1986, 1989; Barbuy 1988). Our O abundance for ζ Cyg is also quite high; however, this star is known to be a mild Ba star (Snedden, Lambert, & Pilachowski 1981), and its surface abundances may have been modified by accretion of material from an evolved, originally more massive, companion.

Mg abundances are derived from the line at 8718 Å that appears clean both in the Sun and in all our spectra. Parameters for this line were taken from the Lambert & Luck (1978) solar analysis and give a solar Mg abundance in good agreement with that given by Anders & Grevesse (1989). Mg is then clearly overabundant in NGC 6553 stars.

Si abundances are obtained from a few (one to four) lines; these are clean solar lines used in the analysis by Lambert & Luck (1978). Results given by different lines are generally internally consistent with each other for each star. However, Si abundances are quite sensitive to the adopted effective temperatures: if T_{eff} is lowered by 100 K (i.e., within uncertainties of the present analysis), $[\text{Si}/\text{Fe}]$ increases by 0.12 dex. This sensitivity might explain the rather large star-to-star scatter. We conclude that our Si abundance for NGC 6553 may have an error bar as large as ± 0.2 dex.

Our Ca abundances are much more reliable than those for Si since they are derived from at least five lines in each star giving very consistent results. Highly accurate laboratory oscillator strengths are used for the Ca lines (Smith & Raggett 1981). Also, the sensitivity of the Ca abundances to atmospheric parameters is quite similar to that of Fe. Ca is then clearly overabundant in NGC 6553: the average value of $[\text{Ca}/\text{Fe}] = +0.26 \pm 0.1$ is very similar to that obtained by Gratton & Sneden (1991) for both field metal-poor stars ($[\text{Ca}/\text{Fe}] = +0.29 \pm 0.06$) and GCs ($[\text{Ca}/\text{Fe}] = +0.33 \pm 0.15$).

Finally, Ti abundances are obtained from only two Ti I lines, with solar oscillator strengths. However, they give very consistent star-to-star results, and the sensitivity to atmospheric parameters of the $[\text{Ti}/\text{Fe}]$ ratios is not large (although a little larger than for Ca). On the whole our $[\text{Ti}/\text{Fe}]$ ratio should have an error bar of about ± 0.15 dex. Again, our average $[\text{Ti}/\text{Fe}]$ ratio for NGC 6553 ($[\text{Ti}/\text{Fe}] = +0.19 \pm 0.15$) agrees well with the results for both field metal-poor stars ($[\text{Ti}/\text{Fe}] = +0.28 \pm 0.11$) and GCs ($[\text{Ti}/\text{Fe}] = +0.21 \pm 0.16$) obtained by Gratton & Sneden (1991).

In summary, our analysis consistently gives overabundances for all the classical α -elements in NGC 6553: for those elements having the most reliable results (O, Mg, Ti, and Ca), the abundance ratios are very similar to those obtained in the analysis of field metal-poor stars and other GCs. The error bar for Si is larger, so that we do not attribute much weight to the lower value of the overabundance we find for this element. (It still agrees with the value for field stars of $[\text{Si}/\text{Fe}] = +0.30 \pm 0.08$ obtained by Gratton & Sneden 1991.) Our abundances agree also quite well with the pattern observed by McWilliam & Rich (1994) for field giants in the Baade's window (although these authors do not find an O overabundance).

The most common interpretation of the overabundance of O and α -elements in metal-poor stars is that only massive stars exploding as Type II supernovae contributed initially to nucleosynthesis. This seems to be the case also for NGC 6553, pointing toward a fast formation of at least part of the Galactic bulge.

7. DISCUSSION OF RESULTS

We have carried out a detailed abundance analysis for five RHB stars in the GC NGC 6553. We obtain a mean $[\text{Fe}/\text{H}] = -0.16$ dex, with the total range of the values for the five stars being only 0.23 dex. The relative abundance for the best-determined α -process element $[\text{Ca}/\text{Fe}]$ is $+0.26$ dex. Because we have made a major effort to carry out this abundance analysis in a manner consistent with that adopted by Carretta & Gratton (1997), our results should be directly comparable with theirs. Their work represents the largest collection of Galactic GC abundances based on a uniform analysis using both their own spectra and re-analyzing W_λ from high-dispersion analyses in the literature. We have thus extended their abundance calibration up to the highest values of metallicity found among the Galactic GCs.

Zinn & West (1984) assigned $[\text{Fe}/\text{H}] = -0.29 \pm 0.11$ dex to NGC 6553. It is the GC with the highest metallicity among their calibrating clusters (Table 5 of their paper). The highest metallicity they assign to any Galactic GC is $+0.24$ dex to Terzan 1 and to Terzan 5, both heavily obscured clusters in the Galactic bulge. Their abundance for NGC 6553 is remarkably close (0.13 dex smaller) to the results of our abundance analysis. It is equal to the systematic difference of $+0.12 \pm 0.01$ dex found by CG between the results of their abundance analysis and those of previous investigators using the same set of W_λ .

CG compare their uniform well-calibrated scale for a limited number of GCs with that of Zinn & West (1984), which is the metallicity scale most commonly used for the family of Galactic GCs, over the full metallicity range spanned by each. They find a curvature such that at both low and high metallicities ("high" here is M71, 47 Tuc, and

NGC 6352), the Zinn & West scale appears to be somewhat high (by about 0.1 dex). The point we have added for NGC 6553 at the extremely metal-rich end appears to indicate that the comparison of the two metallicity scales for Galactic GCs is somewhat more complex.

Rutledge et al. (1997b) have introduced the parameter $W(\text{Ca II})$ which is determined from observations of the strength of the infrared Ca triplet in individual giants from low-resolution spectra as the basis for a new metallicity ranking scheme for the family of Galactic GCs. As is shown in Figure 6, with the addition of the point for NGC 6553, the relationship of the CG abundance scale with this parameter appears to be nonlinear. A detailed abundance analysis of a second extremely high metallicity GC seems desirable to confirm this.

The average metallicity for the five RHB stars in NGC 6553 is slightly higher than the average value of approximately -0.2 dex found for giants in Baade's window in the Galactic bulge by Rich (1988) as recalibrated by McWilliam & Rich (1994; see also Castro et al. 1995) and by Sadler, Rich, & Terndrop (1996). Castro et al. (1996) establish that the most metal-rich star known in Baade's window from this sample and the most metal-rich star known in the solar neighborhood (μ Leo) both have $[\text{Fe}/\text{H}] = +0.45$ dex, so there may well be Galactic GCs that are even more metal rich than NGC 6553 as suggested by the Zinn & West compilation.

7.1. Comparison with Barbuy et al. (1999)

We have found an abundance for NGC 6553 which is considerably higher than that of Barbuy et al. (1999). When comparing our abundances with those of Barbuy et al., we should recall that there are differences in procedure which

FIG. 6.—Parameter $W(\text{Ca II})$ defined by Rutledge et al. (1997b) is shown as a function of abundance on the scale of Carretta & Gratton (1997) for Galactic GCs with high-dispersion analyses. With the addition of the point representing NGC 6553, a quadratic fit appears to be superior to a linear fit.

we believe will produce a systematic difference in the derived abundances. In particular these lie in the choice of model atmospheres and in the calculation of the solar abundances. Barbuy et al. adopt the model atmospheres of Plez, Brett, & Norlund (1992) for their two giants in NGC 6553 while we use those of Kurucz (1992). They adopt the solar model of Holweger & Muller (1974). For these reasons, our Fe abundances are expected to be 0.1–0.15 dex higher. This explains part of the difference between our result and that of Barbuy et al., but not all. Some perhaps must be ascribed to our use of hotter stars and the higher S/N and dispersion of our spectra, leading to better continuum definition.

8. SUMMARY

We provide a high-dispersion line-by-line abundance analysis of five red HB stars in the extremely metal-rich Galactic GC NGC 6553. In such a metal-rich cluster, these red HB stars are significantly hotter than the red giants near the tip of the giant branch, and hence their spectra will be much less crowded. Since accurate location of the continuum is the critical key to success for abundance analyses of such metal-rich objects, our approach offers the potential for a more reliable abundance determination.

We find that the mean $[\text{Fe}/\text{H}]$ for NGC 6553 is -0.16 dex, comparable to the mean abundance in the Galactic bulge found by McWilliam & Rich (1994) and considerably higher than that obtained from an analysis of two red giants in this cluster by Barbuy et al. (1999). The relative abundance for the best-determined α -process element indicates an excess of α -process elements of a factor of 2 as $[\text{Ca}/\text{Fe}] = +0.26$ dex. The metallicity of NGC 6553 reaches the average of the Galactic bulge and of the solar neighborhood. It is likely that there are even more metal-rich Galactic GCs that have solar metallicity.

Our analysis of the abundance of NGC 6553 provides an important calibration point for determining the metallicity of the more distant/more heavily reddened extremely metal-rich GCs found exclusively in the nuclear bulge. It also provides an important clue regarding the mean abundance of the stellar population in the Galactic bulge and in luminous elliptical galaxies in general.

We are grateful to Maria Donata Guarnieri and her collaborators for providing access to their *HST* and IRAC photometry of NGC 6553 prior to publication and for providing finding charts for candidate HB stars from their images and to Jim McCarthy for help during the 1997 observing run. We also thank Beatriz Barbuy and Sergio Ortolani for having provided a copy of their recent paper in advance of publication. The entire Keck/HIRES user community owes a huge debt to Jerry Nelson, Gerry Smith, Steve Vogt, and many other people who have worked to make the Keck Telescope and HIRES a reality and to operate and maintain the Keck Observatory. We are grateful to the W. M. Keck Foundation, and particularly its late president, Howard Keck, for the vision to fund the construction of the W. M. Keck Observatory. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. The work of J. G. C. was partially supported by NSF grant AST-9819614.

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