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SPECTROSCOPY OF SUBGIANTS IN ω CENTAURI (NGC 5139 = C1323−472)

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ABSTRACT

SIT Vidicon spectra having 3–4 Å resolution have been obtained with the CTIO 4 m telescope for a nearly complete sample of faint subgiant stars in Cannon and Stewart's color-magnitude diagram for the peculiar southern globular cluster ω Centauri. From radial velocities, fewer than 25% of the redder stars are cluster members, while 75% of the bluer stars are members. More generally, at this radial distance ($\sim 0.3r_t$) from the center of ω Cen, which is the minimum where crowding permits observations of such faint stars, approximately half of all stars are v_r nonmembers, indicating the particular care that must be exercised when evaluating conclusions from ω Cen studies lacking membership information. Spectra of faint v_r members reflect real temperature and abundance differences, with a total range similar to that observed for more highly evolved stars. We show that there is a range of [M/H] among subgiants at a given $B-V$, and that the stars with different abundances all follow isochrones for an age of about 18×10^9 yr. The spectral differences and the $B-V \approx 0.2$ mag range for confirmed subgiant and faint giant members are similar to the properties seen in brighter stars. Furthermore, the abundance histograms for ω Cen's bright giant, RR Lyrae, and faint giant and subgiant stars show a similar, relatively uniform distribution between [M/H] = −1.0 and −2.0, with a few stars being as metal-rich as [M/H] ≈ -0.7. These results show conclusively that the wide range of colors, etc. observed among giants in ω Cen originates near, if not on, its main sequence, a result for which there is still no completely compelling explanation.

Subject headings: clusters: globular — radial velocities — stars: abundances — stars: late-type

I. INTRODUCTION

In 1980 June we used the SIT Vidicon detector on the Ritchey-Chrétien spectrograph of the Cerro Tololo Inter-American Observatory's (CTIO) 4 m telescope for a reconnaissance of the spectral properties of 11 faint stars found in the giant/subgiant ($+2 < M_V < 3.5$) region of the color-magnitude diagram (CMD) of the peculiar globular cluster ω Centauri (Bell *et al.* 1981, hereafter Paper I). Prior observations of brighter stars by numerous investigators (see Paper I for references) had established the existence of a large range of metallicities among the highly evolved stars, with both the CNO group elements and some heavier ones showing large star-to-star differences. This range of metallicities had been suspected for some time owing to the unusually wide giant branch in V, $B-V$ CMDs for ω Cen (Woolley *et al.* 1966, hereafter ROA; Dickens and Woolley 1967; Geyer 1967; Cannon and Stobie 1973; Hesser, Hartwick, and McClure 1977). The recent work of Cannon and Stewart (1981), DaCosta and Villumsen (1981), and Rodgers and Harding (1983) suggests that colors of subgiant and turnoff-region stars *also* exhibit scatter greater than the observational errors, implying that at least a portion of the abundance range seen among giant stars originates on the main sequence.

In Paper I we found that five of the 11 stars (generally the reddest) had radial velocities incompatible with membership. In turn, this suggested that once the radius is reached where diminished crowding permits photometry of the upper main sequence, about half the stars are field stars. From comparison with synthetic spectra, five of the probable members have abundances[3] $-1 <$ [M/H] < -1.5, with some evidence for carbon depletion. The sixth probable member, CS 13-35, which lies ~ 0.1 mag redward of the other members selected in Paper I, has [M/H] ~ -0.5, which is as high an abundance as has been detected in any of the more highly evolved stars of ω Cen. The latter star seemed to show an enhancement of nitrogen, possibly as large as a factor of 3. Four possible reasons for the nitrogen abundance variations were explicitly discussed in Paper I: mixing of the stars during their evolution, differences in abundances at the time of star formation, accretion by the subgiant and main-sequence stars of CNO-processed material lost by the cluster red giants, and accretion of material lost by a binary companion.

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[3] $[X] = \log X^* - \log X_\odot$. [A/H] refers to abundances employed in calculations, A being any element other than H and He. Abundances deduced from observations are denoted by [M/H] or [Fe/H].

In this paper we present the results of survey observations made with the same CTIO equipment in 1981 April. When combined with Paper I, these data represent a nearly complete sample of stars lying between $16.00 < V < 17.80$ mag in six of the nine sectors of Cannon and Stewart (1981). Among other results, these data allow us for the first time to use known radial velocity members of this anomalous globular cluster for comparison with theoretical isochrones for age determination. Preliminary accounts of some aspects of this research have been presented elsewhere (Hesser *et al.* 1983, 1984a; Bell *et al.* 1984).

II. OBSERVATIONS

Spectra of the ω Cen stars were obtained during the nights of 1981 April 6–9 UT with the same instrumentation used in 1980, namely the 16 mm SIT detector with UV transmitting optics (Atwood *et al.* 1979) on the Ritchey-Chrétien spectrograph of the CTIO 4 m telescope. The nominal reciprocal dispersion of the spectra is ~ 60 Å mm^{-1}, each pixel is ~ 1.6 Å, and the resolution is ~ 3–4 Å.

We attempted to measure a complete sample of faint subgiant stars from the lists of Cannon and Stewart (1981), whose CMD is shown as Figure 1. The starting sample consisted of all 57 stars with $16.0 < V < 17.80$ in sectors 11–13 and 21–23. Of these, one (12-62) has an ROA proper motion incompatible with cluster membership; three (13-36, 21-01, and 21-42) were known to have radial velocities incompatible with membership (K. C. Freeman, private communication); two (12-13 and 23-24) have $V > 17.5$ and $B-V > 1.1$ and thus are almost certainly field stars; and two (13-24 and 21-24) had nearby companions which prevented us from obtaining good sky spectra with the spectrograph slit oriented east-west. We obtained spectra of 29 of the remaining stars, to which can be added six member stars measured in Paper I. (Two of the Paper I stars were repeated here: 13-35 since it was the most extreme example of a high-metallicity faint member, and 23-42 since its membership remained in doubt due to radial velocity uncertainties.) This leaves 14 potentially observable stars in the initial sample for which we do not have spectra. All 14 are on the blue side of the broad spread of subgiants in the CMD (Fig. 1); four (12-11, 13-34, 22-23, and 22-43) have been confirmed as cluster members by Freeman (private communication); and our results for other, similar stars indicate that three-quarters of these blue stars are members. Within the narrower magnitude range $17.0 < V < 17.5$, all 20 measurable stars have been observed either by Freeman or by us. It should be noted that the original Cannon and Stewart sample, obtained by iris photometry of photographic plates, is itself incomplete due to crowding. However, there is unlikely to be any significant color bias introduced by this selection effect, and the incompleteness is not believed to vary greatly over the limited range of apparent magnitude and cluster radial distance encompassed by the present sample.

The spectral data were reduced to fluxes and wavelengths with the "old" La Serena software package (Schaller, *et al.* 1978) following the precepts outlined by Hesser and Harris (1981).[4] The only change from their procedures was that a cross-correlation algorithm (kindly written for us by J. A. Baldwin) was used to measure the shift of the comparison spectra at each telescope position relative to spectra secured at the zenith, instead of averaging measurements of individual lines. Details of the observational procedures and reductions to

[4] As mentioned by Hesser and Harris (1981), the wavelengths adopted for the lines measured are essentially those derived from an extensive analysis of image tube spectra (having resolution comparable to the SIT data) for IAU radial velocity standard stars (cf. Shawl, Hesser, and Meyer 1981; Shawl *et al.* 1985). At our resolution most lines are, of course, blends. Among the features typically included (with their adopted wavelengths) are: Ca II H, K $\lambda\lambda$3968.04, 3933.29; Hδ λ4101.25; Ca I λ4225.92; Fe I + CH $\lambda\lambda$4272.00, 4324.83; Hγ λ4339.83; and Fe I λ4384.68.

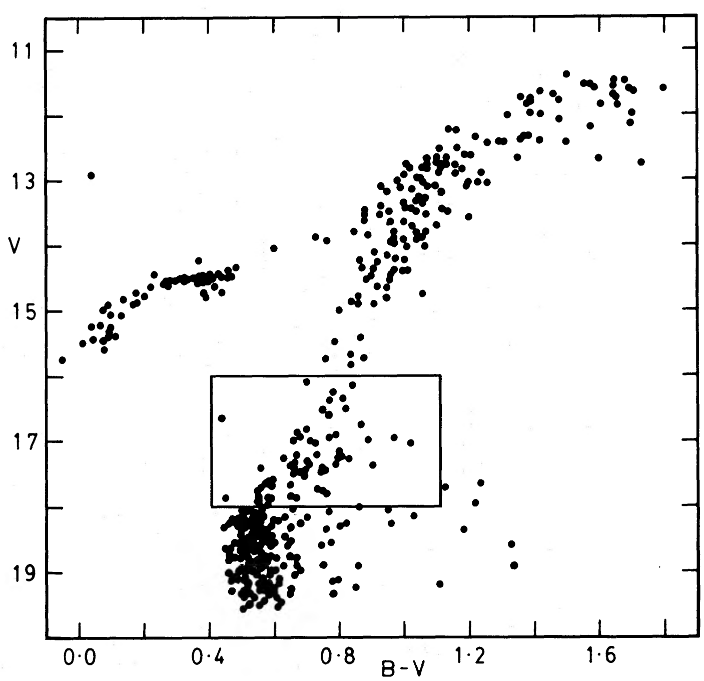

FIG. 1.—CMD for ω Cen from Cannon and Stewart (1981); the region in which we observed is enclosed in the box

velocities for the 1981 run are given elsewhere (Hesser *et al.* 1984*b*).

All subsequent spectral analysis (plotting, index calculations, etc.) was performed with the RETICENT software (Pritchet, Mochnacki, and Yang 1982) at DAO.

III. RADIAL VELOCITIES

Because ω Cen has a high radial velocity ($v_r = 228$ km s^{-1}, according to Webbink's 1981 tabulation), we can, in principle, separate probable members from nonmembers on that basis alone. Nevertheless, an element of judgment inevitably enters, leading us to review some aspects of our velocity results in detail prior to assessing membership of the fainter stars in the ω Cen sample.

In Table 1 we present the individual measurements of velocities for four bright giants, using the ROA numbering system. Immediately under the name we present the radial velocity from earlier determinations as summarized by Webbink (1981).

TABLE 1

SUMMARY OF OBSERVATIONAL DATA FOR BRIGHT ω CENTAURI STARS

STAR	V (mag)	B−V (mag)	UT START (April 1981) dd:hh:mm	HA START (hh:mm)	EXP (mm:ss)	v_r (km s^{-1})	n	
ROA 40	11.37	1.50	04:09:38	4.31 W	00:45	260	11	
(v_r = 223.0)			05:02:34	2:40 E	00:50	250	12	
			05:09:49	4:35 W	01:20	250	13	
			06:01:32	3:38 E	01:30	240	11	
			06:08:25	3:15 W	00:45	230	9	
			07:01:24	3:42 E	01:10	230	11	Cloudy,
			07:01:27	3:40 E	01:00			Overexposed
			07:09:02	3:56 W	01:00	250	11	
			08:01:21	3:42 E	00:35	260	10	
			08:08:59	3:57 W	00:30	250	12	
			09:01:56	3:02 E	01:45	230	11	Cloudy
			09:03:55	1:03 E	00:35	230	12	Cloudy
			09:08:01	3:03 W	00:35	240	10	Cloudy
					Mean	240 ± 4 (s.d.m.)		
ROA 65	11.61	1.50	04:09:48	4:31 W	00:45	270	8	
(v_r = 244.6)			05:02:30	2:44 E	00:40	240	9	
			05:09:45	4:31 W	00:40	280	11	
			05:09:46	4:32 W	01:00			
			06:01:26	3:45 E	01:00	250	9	
			06:01:29	3:42 E	01:00			
			06:05:26	0:15 W	00:40	250	10	
			06:08:19	3:09 W	01:00	260	11	
			07:01:22	3:42 E	00:40	250	11	Cloudy
			07:06:24	1:18 W	00:35	230	12	Cloudy
			07:08:59	3:53 W	00:40	260	10	
			08:01:15	3:48 E	00:30	220	12	
			08:01:19	3:44 E	00:30			
			08:08:54	3:52 W	00:30	240	11	
			08:08:55	3:53 W	00:40			
			09:01:51	3:07 E	01:00	220	8	Cloudy
			09:03:52	1:06 E	00:35	260	12	Cloudy
			09:07:59	3:01 W	00:35	250	12	Cloudy
					Mean	250 ± 5 (s.d.m.)		
ROA 253	12.34	1.37	09:05:49	0:52 W	02:00			Cloudy
			09:05:55	0:57 W	02:00	220	13	Cloudy
			09:06:00	1:02 W	02:00			
ROA 542 (v_r = 274)	12.92	0.04	04:09:45	4:27 W	00:35	290	5	

The V and $B-V$ data are photoelectric measures from Eggen (1972) for star ROA 65, and from Cannon and Stobie (1973) for the other three. Two of the bright giants were observed repeatedly as local velocity reference stars throughout the 1981 run (including the nights of April 4 and 5, which were used for observations of globular clusters in NGC 5128—see the Appendix of Hesser *et al.* 1984*b*); v_r is the heliocentric radial velocity (rounded to the nearest 10 km s^{-1}), and n is the number of lines used in determining a particular v_r. The mean velocity of ROA 40, 240 ± 4 km s^{-1} (standard deviation of the mean), may be compared to the value 223.0 ± 5.8 km s^{-1} tabulated by Webbink (1981). Similar quantities for ROA 65 are 260 ± 5 km s^{-1} and 244.6 ± 2.5 km s^{-1} respectively. While the mean errors of our observations are acceptably small, the total range observed for ROA 40 is 30 km s^{-1}. For ROA 65, it is 60 km s^{-1} if two points at large, western hour angles (where the image on the SIT target becomes distorted; see Hesser and Harris 1981) are included; if these points are excluded, the range is 40 km s^{-1}. The existence of a total range of ~35 km s^{-1} in the measurements of bright stars presumably sets a lower limit to the range that should be accepted for inclusion of fainter stars as cluster members.

In Figure 2 a histogram of the standard deviation of a *single* spectral line (relative to the mean velocity of the particular spectrum) is plotted versus B magnitude for three magnitude ranges. (B should be reasonbly representative of the 3800–4500 Å region we studied.) Stars observed on portions of the same nights in the cluster NGC 1851 (Hesser, Bell, and Cannon 1982), NGC 6352, and NGC 6752 (Bell, Hesser, and Cannon 1984) are also included in order to increase the sample size. As expected, the error of a single line measurement is substantially increased in the fainter group relative to the brighter group (the median value in the former being ~55 km s^{-1}). Nevertheless, the standard deviation of the mean for a spectrum of a faint star with about nine measured lines is formally ~20 km s^{-1}, which should be adequate for ascertaining membership.

The velocity results (rounded to the nearest 10 km s^{-1}) for the 1981 observations of faint ω Cen stars are summarized in Table 2. The stars have been divided into two groups; the numbering system and the photometric data are from Cannon and Stewart (1981), who also give a finding chart. The resultant velocity histogram, Figure 3, shows rather broad peaks centered near 0 and 225 km s^{-1}, the latter being the cluster velocity. The distinction between cluster stars with low measured velocities and field stars with high ones is rather blurred, necessitating judgment in defining the cutoff. Much of this blurring may be presumed to be due to the measuring uncertainties described above, but Seitzer and Freeman (1982, private communication) have remarked on a similar phenomenon occurring in their more precise and numerous velocity data for much brighter stars in the vicinity of the cluster. In our case, we note that from the viewpoint of separating probable cluster members, most of the "worst" velocities in Table 2A and Figure 3 are from spectra obtained under cloudy conditions: apart from star 13-22 (see below), all the clear-sky observations lie between +180 and 260 km s^{-1}, which is one-half the range (160–320 km s^{-1}) seen for the "cloudy" measures. Since most measures in a sample the size of ours should lie within ~2 σ of the mean, it appears that our errors are indeed ~ ±20 km s^{-1} for good measures, but may be up to ~ ±40 km s^{-1} for measures of faint stars observed through clouds. Accordingly, to consider a particular star a probable member, we adopted 160 and 320 km s^{-1} as the lower and upper velocity cutoffs respectively. The only star in the higher velocity group in Figure 3

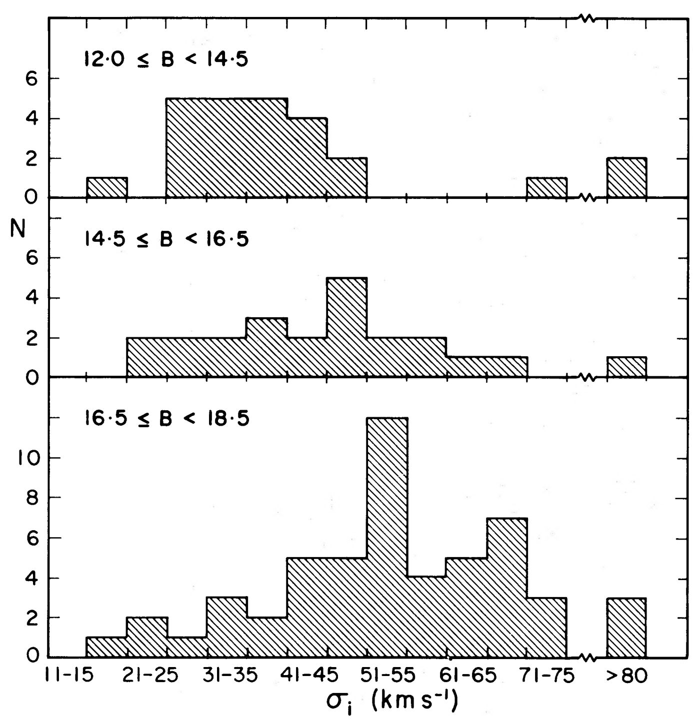

FIG. 2.—Histogram of dispersion in the measurement of *an individual spectral line* in our spectra showing how the errors increase as a function of increasing magnitude; see text.

TABLE 2

SUMMARY OF OBSERVATIONAL DATA FOR FAINT ω CENTAURI STARS

STAR	V (mag)	B−V (mag)	UT START (April 1981) dd:hh:mm	HA START (hh:mm)	EXP (min)	v_r (km s^{-1})	n	
A) PRESUMED MEMBERS								
12-42	16.74	0.87	06:01:40 06:02:16	3:29 E 2:53 E	30 30	320	8	Cloudy Cloudy
12-49	16.98	0.67	07:01:33 07:02:07	3:33 E 2:28 E	30 30	200	10	Cloudy Cloudy
22-35	16.98	0.67	09:06:47	1:49 W	30	270	6	Cloudy
22-25	16.99	0.71	09:07:24	2:27 W	30	300	4	Cloudy
11-32	17.21	0.67	07:02:42	2:24 E	30	200	6	Cloudy
13-35	17.22	0.80	07:03:21	1:44 E	30	160	5	Cloudy
21-17	17.36	0.71	08:03:15	1:46 E	30	230	8	
22-28	17.39	0.56	08:05:03	0:02 W	30	260	8	
13-04	17.43	0.75	06:05:33 06:06:11 06:06:45	0:24 W 1:01 W 1:36 W	30 30 30	240	8	
21-52	17.46	0.76	07:07:42 07:08:24	2:37 W 3:20 W	30 30	240	9	
23-42	17.50	0.66	08:06:15	1:14 W	30	190	8	
13-23	17.65	0.57	08:06:53 08:07:27	1:51 W 2:26 W	30 30	180	6	
21-49	17.71	0.73	07:05:13 07:05:48	0:07 W 0:43 W	30 30	200	7	
11-45	17.78	0.75	07:03:57 07:06:30	1:08 E 1:25 W	30 30	220 200	7 4	
12-01	17.83	0.65	06:07:24	2:15 W	45	180	5	V. noisy
B) PRESUMED NONMEMBERS								
13-21	16.60	0.77	09:02:03	2:54 E	30	10	11	Cloudy
11-23	16.65	0.44	06:04:11	0:58 E	30	-50	5	
12-59	16.90	0.79	06:02:51	2:18 E	30	50	7	
21-47	16.93	0.77	09:06:10	1:13 W	30	-80	8	Cloudy
12-20	16.94	0.97	09:02:41	2:16 E	30	30	12	Cloudy
23-16	16.97	0.89	09:03:17	1:40 E	30	70	10	Cloudy
23-44	17.02	0.73	08:05:40	0:38 W	30	-50	11	
13-22	17.02	1.02	08:08:02 08:08:28	3:01 W 3:27 W	20 20	140	8	
23-23	17.27	0.83	08:01:27 08:02:02 09:04:01 09:04:34	3:34 E 2:48 E 0:55 E 0:23 E	30 30 30 30	80 50	12 8	 Cloudy Cloudy
22-04	17.34	0.65	08:03:51 08:04:28 09:05:10	1:09 E 0:33 E 0:13 W	30 30 30	80 120	11 7	 Cloudy
21-38	17.36	0.90	07:07:05	2:00 W	30	-70	13	
21-34	17.39	0.75	08:02:39	2:22 E	30	-60	10	
13-10	17.46	0.67	06:04:49	0:20 E	30	20	7	
12-06	17.53	0.69	06:03:30	1.39 E	30	100	6	
22-13	17.80	0.76	07:04:35	0.29 E	30	30	10	

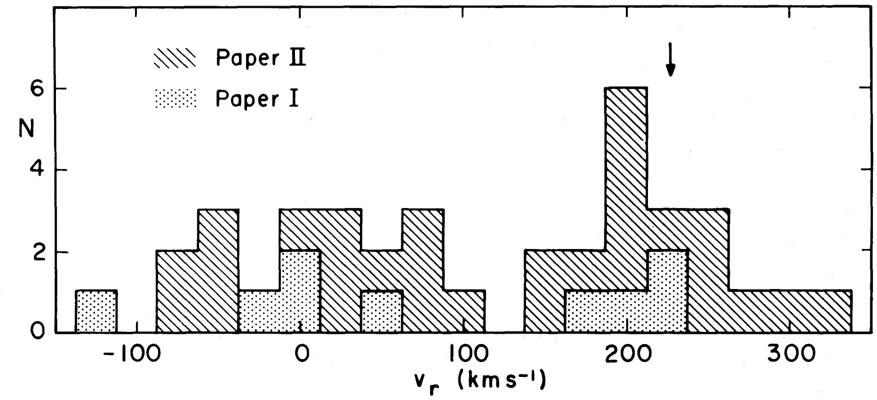

FIG. 3.—Histogram of v_r values for stars observed in this paper and Paper I; the arrow indicates the ω Cen velocity; see text

thus excluded from membership by the adopted low-velocity cutoff is 13-22.[5]

The second result to arise from the velocity measurements is that, as found in Paper I, about half the sample may be presumed to be field stars. The combined membership results of Papers I and II are shown in the CMD of Figure 4, where the greater percentage of v_r nonmembers on the red side of the subgiant branch is apparent. Thus, even at the minimum radial distance where crowding permits observation of faint stars, field-star contamination is an important factor.

The mean cluster velocity deduced from the values of Table 2 for ω Cen is 230 ± 12 (s.d.m.) km s^{-1}. This may be compared to the cluster velocity tabulated by Webbink (1981), 228 ± 1.7 km s^{-1}, and to the mean value for the presumed nonmember stars in Table 2, 30 ± 17 km s^{-1}. As a final remark on the radial velocity results, we note that Cannon and Stewart's (1981) suggestion that star 11-23 is a "blue straggler" member of ω Cen is not supported by the velocity measurements; Hanes (1983) has reached a similar conclusion.

[5] From the available spectrum, CS 13-22 is either very cool, or strong in CN, or both. Its observed color, $B-V = 1.02$, is the reddest in our sample. Analysis of this star as a cluster member following the precepts of § IV*b* implies the need for a cool model [$T_{\rm eff} \ll 5000$ if $E(B-V) = 0.14$, as argued in § V]. The spectrum is similar to that of the v_r field star CS 23-23, but is slightly more metal-weak, a difference which may be quite consistent with CS 13-22 being a high-velocity field star. The photometry itself is not seriously in error, since a completely independent measurement by Kontizas on different plate material (Cannon and Kontizas 1974) confirms the very red color. An independent v_r measurement would be helpful.

IV. ANALYSIS OF STELLAR SPECTRA

a) Appearance of the Spectra

Comparison of the spectra of v_r members and nonmembers (cf. Fig. 5) provides support for the velocity criteria used to analyze cluster membership. We show here that sample of our spectra which was obtained under photometric skies, but the same conclusion is valid in all cases—namely, that the field stars are substantially more metal-rich than the cluster stars and seem to be essentially normal Population I stars of moderate to low luminosity. Furthermore, it is unlikely that any cluster members have been eliminated by the velocity criteria (but see note 5). The fact that the spectra of stars chosen as members on the basis of velocities seem more similar to each other than to the field stars gives us added confidence in our discrimination.

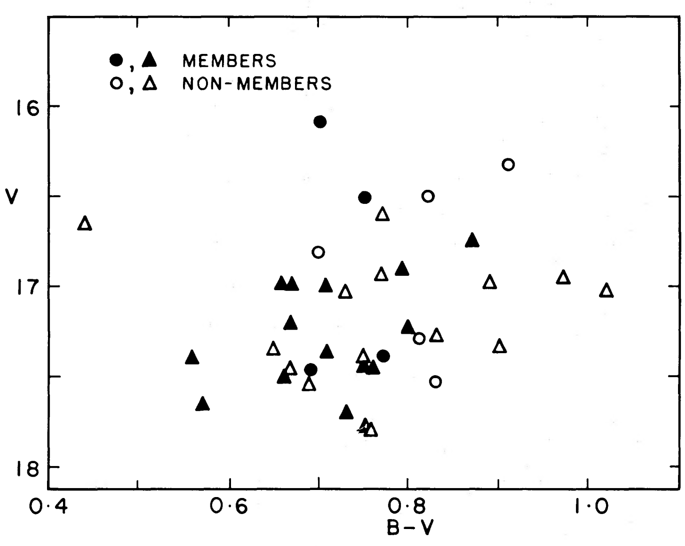

FIG. 4.—CMD of the stars from Paper I (*circles*) and this paper (*triangles*); filled symbols indicate stars judged on the basis of v_r to be cluster members. Note the small percentage of v_r members with $B-V > 0.8$.

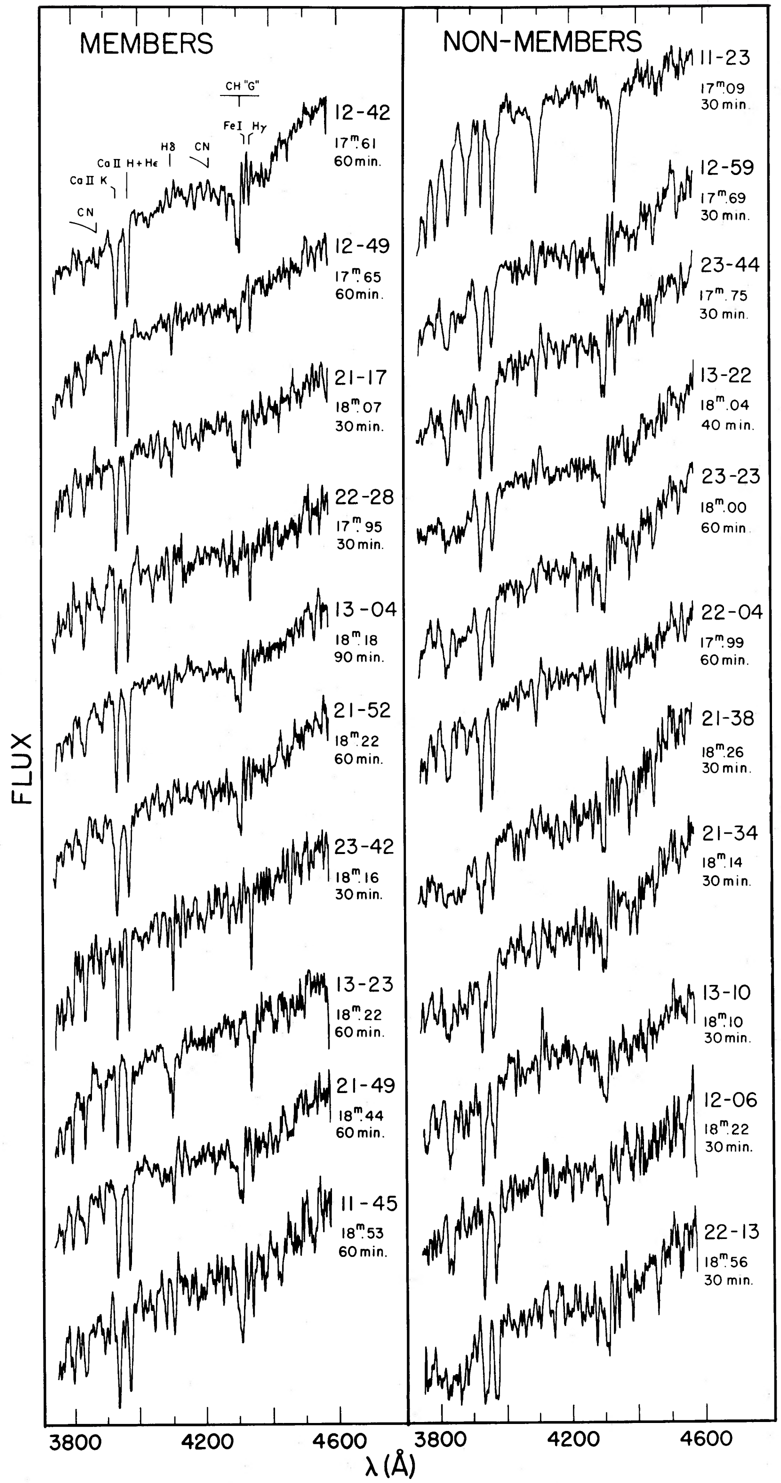

FIG. 5.—A spectral montage of flux (linear but arbitrary scaling) vs. wavelength for stars observed in 1981. With the exception of the upper two member stars, all spectra were obtained under photometric conditions. The observed B magnitude and the exposure time in minutes are given below each star name. Spectra of additional faint member stars observed in 1980 are given in Paper I.

Inspection of the spectra of, for example, member stars CS 13-23 and 22-28 at $B-V = 0.57$ and 0.56 show that they have stronger Balmer lines and are clearly hotter than stars CS 11-32 (0.67) and 12-49 (0.67). Thus, a temperature-correlated color range of ~ 0.2 mag in $B-V$ persists (after removal of field stars) for the stars in the lower giant branch and subgiant region of ω Cen's CMD. (In the latter region, of course, a temperature range is expected to arise from normal stellar evolution.) However, the situation appears more complicated, for, in addition to the temperature effect, we also infer a range of metal line strengths in cluster members exhibiting similar $B-V$s (for example, among stars CS 23-42, 11-32, and 12-49). These impressions of temperature and abundance characteristics can be more explicitly discussed, as in Paper I, by comparison of observed with synthetic spectra, to which we now turn, and by analysis of photometric indices, to which we turn in § V.

b) *Comparison with Synthetic Spectra*

We compared our observed spectra with synthetic spectra, calculated as in Paper I using techniques described elsewhere (Bell, Dickens, and Gustafsson 1979; Hesser and Bell 1980). We patterned our comparison technique after normal spectral classification procedures using the models as "standards" (some parameters of the models used are given in Table 5, see § V). We used an iterative approach in which we first estimated the temperature from the hydrogen lines, the G band, and the H and K lines, and then we evaluated abundances from comparison with models of the appropriate temperature. In the noisier spectra the temperature determination is probably more secure than the abundance estimate because the features used for temperature estimation are intrinsically stronger; there is also the worry that higher frequency noise in some observed spectra may occasionally induce erroneously high abundance estimates. During visual inspection it is also difficult not to be influenced by continuum slopes which may be subject to uncertainties arising from, say, differential refraction and our 2″ slit. In general, from these visual comparisons we expect the abundance estimates to be indicative of differences at the ~ 0.5 dex level. We now describe the results of the visual comparisons for individual member stars in order of decreasing luminosity; for reference, where observed $B-V$ colors are mentioned, Cannon and Stewart (1981) suggest errors of ~ 0.03 mag for $V < 17.5$.

CS 12-42.—Comparison with $5000/3.0/-1.0$ ($T_{\rm eff}/\log g/$[A/H]) and $5000/3.0/-2.0$ models whose colors, 0.76 and 0.72, are similar to the observed $B-V = 0.87$ [$(B-V)_0 = 0.73$ if $E(B-V) = 0.14$, see § V] suggests that $[M/H] \approx -1.5$. There seems to be little or no CN in the stellar spectrum, even at the sensitive $\lambda 3883$ feature.

CS 12-49.—The hydrogen lines show that this star is hotter than CS 12-42, in agreement with its observed bluer color of $B-V = 0.67$. Comparison with the $5500/3.0/-2.0$ model suggests that [M/H] is somewhat higher than -2.0, perhaps -1.5.

CS 22-35.—This spectrum, obtained under cloudy conditions, is quite noisy. The comparison with the $5500/3.75/-2.0$ model (whose color, 0.54, is similar to the observed value, 0.66, after dereddening) is fairly good; but, again, the [M/H] seems to be higher, perhaps -1.7 to -1.5. The star seems hotter, however, and probably would be better matched by a model of $5750/3.75/-1.5$, but the implied color would then be somewhat inconsistent with its observed value. Relative to CS 12-49 and 22-25, whose colors are similar, CS 22-35 also appears to have stronger metal lines.

CS 22-25.—Our noisy spectrum suggests that CS 22-25 is cooler than CS 22-35, in agreement with the difference in their observed colors. CS 22-25 also shows signs of both $\lambda 3883$ and $\lambda 4215$ CN, although the poor quality of the spectrum makes their identification (particularly that of $\lambda 4215$) uncertain. Comparison with available models suggests probable parameters of $5500/3.75/-1.0$.

CS 11-32.—The spectrum of this star is superficially like that of CS 12-49 (which has the same $B-V$ color), but much noisier. The $5500/3.75/-2.0$ model fits the hydrogen lines, the G band, and the H and K lines well, but many other features seem to be enhanced in the star. Perhaps $[M/H] \approx -1.8$.

CS 13-35.—Our 1981 reobservation of this star from Paper I was made under cloudy conditions and gave a velocity ~ 40 km s^{-1} lower than the previously determined value of 200 km s^{-1}. While the resultant velocity is disturbingly close to our adopted velocity cutoff for cluster membership, the current 30 minute exposure is clearly inferior to the 60 minute one obtained for Paper I, for which we believe the data are more reliable. Independent comparison of the 1981 data with the models suggests that the star is somewhat cooler than 5500 K and has [M/H] between -0.5 and -1.0.

CS 21-17.—This spectrum seems to be intermediate between those calculated for $5500/3.75/-1.5$ and -2.0; we take [M/H] to be -1.8.

CS 22-28.—The $B-V$ value, 0.56, is the bluest of our sample, and the general appearance of the (noisy) spectrum confirms a temperature above 5500 K. The model spectrum corresponding to $6000/3.75/-1.0$ yields a fairly satisfactory fit.

CS 13-04.—This star is at the same apparent magnitude as CS 22-28, but 0.19 mag redder. The hydrogen lines in our 90 minute exposure compare well with those of the model $5500/3.75/-2.0$, but [M/H] appears to be intermediate between -2.0 and -1.5 (at -1.5 the model G band is stronger than the observed one, but we note that the latter's strength did not reproduce perfectly in the individual exposures). The $B-V$ color of the -2.0 model, 0.54, is 0.06 mag bluer than the observed color following dereddening.

CS 21-52.—The best match of our observed spectrum to a model spectrum occurs for $5500/3.75/-1.0$, but we also note that the line absorption below H and K may be less in the star than in the model.

CS 23-42.—This star is quite hot and, according to the strengths of the hydrogen lines, appears to form a temperature sequence with the somewhat more luminous stars CS 11-32 and 12-49, in spite of their virtually identical colors. (The sense is that 23-42 is the hottest, 12-49 the coolest.) [M/H] appears to be strongest in the hottest of the three and weakest in the coolest, as expected since their $B-V$ colors are the same. The best match between observation and theory seems to occur for models with $6000/3.75/-1.0$ to -0.5, suggesting that $[M/H] \approx -0.8$. Note that the predicted colors of these models are ~ 0.05 mag bluer than the observed ones. The new velocity measurement virtually removes the doubt raised by one of the two velocity measures in Paper I regarding membership.

CS 13-23.—The spectrum of this star implies that it is hotter than CS 22-28, although their colors are observed to be virtually the same. Comparison with the redder star CS 23-42 indicates generally weaker metal features in 13-23, in agreement with their color differences. Extrapolation suggests that the best model would be one with $6000/3.75/-1.5$.

CS 21-49.—The spectra are noisy, with poor agreement between the two exposures; but, in general, they compare moderately well with 5500/3.75/ − 1.5 to − 2.0 models.

CS 11-45.—The two very noisy spectra suggest 5500/3.75/ − 1.0 to − 1.5.

V. OBSERVED AND COMPUTED SPECTRAL INDICES

a) *Procedures*

In order to quantify more precisely the phenomena revealed by the visual comparison of observed and computed spectra described in the previous section, we calculate several spectral indices from our low-resolution spectra. The indices used are those defined by Canterna, Harris, and Ferrall (1982) and are given in Table 3. Their observations of giant stars have been analyzed by Bell (1984), while Bell, Hesser, and Cannon (1984) have used these indices to analyze spectra over a 5 mag range in NGC 6752. The observed indices for the ω Cen stars are given in Table 4, where we also include indices for the 1980 June data discussed in Paper I. The latter data were obtained with a different grating setting, and the wavelengths covered do not allow us to measure the m_{Fe} index. Indices for the same star from different observing runs have been combined by weighting according to the relative exposure times. Internal errors of these indices were estimated by averaging the 13 observations of ROA 40 and 65 as well as smaller samples of repeated observations for a few of the fainter stars (see the last line of Table 4). The standard deviations thus found are similar and serve as a guide to the errors in the remaining data. (A subsequent test in § V*b* using m_{Ca} gives somewhat higher values but is affected by errors in $B-V$).

Quantitative interpretation of the observed spectral indices requires the use of models with suitable values of T_{eff}, log g, and [A/H]. For a cluster of a particular abundance and age, the variation of log g with T_{eff} can, in principle, be obtained from evolutionary tracks. In our earlier work cited above, we used theory to relate colors to temperatures and we used observation to supply gravities from M_V. The recent work of VandenBerg (1983) shows that evolutionary tracks now give very good fits to CMDs in the absolute magnitude range of our stars. We consequently use VandenBerg's models after making the $B-V$ colors of his isochrones bluer by 0.02 mag to account for more recent color calculations of subdwarf models (VandenBerg and Bell 1985) and changing the M_V scale by 0.14 mag to preserve the M_V of the Sun as 4.79 (Allen 1963).

For this analysis of ω Cen we take the distance modulus to be $V_0 - M_V = 13.5$ [M_V(horizontal branch) = +0.6] and the reddening to be $E(B-V) = 0.14$. The latter value, from Cannon (1974), is used for consistency with Paper I but is 0.03 mag larger than deduced by Newell, Rodgers, and Searle (1969) from the blue horizontal branch stars.[6]

A vexing problem which arises when comparing observed with calculated indices is the existence of zero-point differences between them. The arbitrary nature of the zero-point shifts required appears to be an inevitable consequence of observing (very faint stars) through the narrow slits necessary for v_r values of acceptable precision, and of our having conservatively avoided any change, even slit widths, in spectrograph configuration during an entire run. Stetson (1984) has carefully described some of the observational difficulties involving measurement of indices as well. Experience also shows that different shifts are required to fit the same synthetic spectra to observations of the same type of star made by different observers, which again suggests that much of the need for such shifts arises with the observations. Our ω Cen spectra were taken on the same nights as those used for other clusters, in particular NGC 6752, and we have consequently adopted essentially the same zero-point shifts for both clusters (cf. Bell, Hesser, and Cannon 1984). We further assume the shifts are independent of abundance, even though we recognize that the solar spectrum computed using the same techniques as those described here is brighter than the Sun by ~8% at 3900 Å (Gustafsson and Bell 1979).[7]

The computed indices for a series of models are given in Table 5. The log g values from VandenBerg's (1983) isochrones for helium mass fraction Y of 0.2 and an age of 18×10^9 yr have been found for $Z = 0.0001$, 0.001, and 0.003 ([A/H] = −2.2, −1.2, and −0.7 respectively). The same interpolation and extrapolation was carried out for the M_V values. The $B-V$ colors were obtained from a new grid of dwarf models computed by Eriksson, Gustafsson, and Bell (1984) with the zero points being found by identifying the 9650/3.9/0.0 model of Dreiling and Bell (1980) with Vega.

TABLE 3

BANDPASS DEFINITIONS

Bandpass	λ_c (Å)	$\Delta\lambda$ (Å)
CN38	3840	140
HK	3965	110
HK continuum	4075	110
Ca I	4226	30
CH	4276	80
CH continuum	4335	40
Fe	4397	85
Fe continuum	4530	60

NOTE.—Index definitions: m_{CN} = CN38 − HK continuum, m_{HK} = HK − HK continuum, m_{Ca} = Ca I − CH continuum, m_G = CH − CH continuum, m_{Fe} = Fe − (Fe continuum + CH continuum)/2, where CN38 = $-2.5 \log \int_{3770}^{3910} F(\lambda) d\lambda$, etc.

[6] We can make an indirect derivation of $E(B-V)$ by noting that the unreddened color of the giant branch at the level of the horizontal branch, $(B-V)_{0,g}$, is tightly correlated with metal abundance—see, for example, Sandage (1982) and Bell and Gustafsson (1983). From Fig. 1 we see that the observed color of the blue side of ω Cen's giant branch is $(B-V)_g = 0.84$. The most metal-poor giant and RR Lyrae stars in ω Cen have [M/H] ≈ −2.0, an abundance for which Bell and Gustafsson (1983) find $(B-V)_{0,g} = 0.70$, from which $E(B-V) = 0.14$ follows. The small difference between the adopted reddening and that from Newell, Rodgers, and Searle's (1969) study is not resolved by developments in synthetic color calculations (Kurucz 1979) subsequent to their work which allow one of their assumptions to be relaxed; unfortunately, the resultant fit of newer model colors to observations is no better than they achieved.

[7] We make two additional observations. First, comparison of the multiple observations of ROA 65 in the 1980 and 1981 observing runs shows that it is necessary to increase the 1980 m_{CN} values by 0.15 mag to put them on the 1981 system; the shifts needed for the other indices are 0.01 mag or less for these stars. Second, for some indices it is possible to make an empirical test of the need for shifts between observations and computations, as well as for the approximate magnitude of the shifts. The abundance deduced from the m_{HK}, $B-V$ diagram should match those deduced from the M_V, m_{HK} diagram. Inspection of these diagrams reveals the need for the reduction of the observed m_{HK} values by about 0.07 mag to achieve consistency with the computed ones, although the validity of this check is clouded by the reddening uncertainty.

TABLE 4

Observed Spectral Indices

Star	m_{CN}	m_{HK}	m_{Ca}	m_G	m_{Fe}	$(B-V)_0$[2]	M_V	# of Obs.	Plotting
					MEMBERS				
ROA40	1.181	0.586	0.301	0.308	0.153	1.36	-2.55	14	
ROA65	0.965	0.589	0.293	0.255	0.127	1.36	-2.31	27	
ROA67	0.832	0.616	0.287	0.263		1.15	-2.36	5	
ROA253	1.311	0.573	0.338	0.299	0.107	1.23	-1.58	3	
ROA542	0.080	-0.074	-0.114	-0.110	-0.050	-0.10	-1.00	2	
11-32[1]	0.241	0.093	0.074	0.073	0.022	0.53	3.29	1	O
11-45[1]	0.375	0.255	0.011	0.118	0.087	0.61	3.86	2	+
11-57	0.458	0.225	0.077	0.076		0.61	2.59	1	O
12-01[1]	0.484	0.291	0.072	0.114	-0.049	0.51	3.91	2	+
12-42	0.505	0.331	0.072	0.206	0.119	0.73	2.82	2	●
12-49	0.312	0.196	0.094	0.117	0.048	0.53	3.06	4	O
13-04	0.355	0.204	0.050	0.128	0.074	0.61	3.51	4	●
13-23	0.264	0.116	-0.020	-0.044	0.004	0.43	3.73	2	●
13-35[1]	0.609	0.307	0.122	0.180	0.096	0.66	3.30	3	●
13-53	0.218	0.203	0.078	0.101		0.55	3.51	2	●
21-17	0.300	0.197	0.046	0.111	0.069	0.57	3.44	1	●
21-49[1]	0.327	0.210	0.069	0.127	0.083	0.59	3.79	2	+
21-52	0.391	0.383	0.134	0.181	0.090	0.62	3.54	2	+
22-25[1]	0.428	0.231	0.009	0.078	0.002	0.57	3.07	1	O
22-28[1]	0.300	0.135	-0.026	0.026	0.042	0.42	3.47	1	O
22-35[1]	0.262	0.162	0.020	0.063	0.018	0.52	3.06	1	O
22-52	0.324	0.180	0.097	0.092		0.56	2.16	1	O
23-42	0.298	0.144	-0.024	0.044	0.031	0.52	3.58	3	●
32-48	0.358	0.215	0.078	0.075		0.63	3.48	2	●
					NONMEMBERS				
C1	0.964	0.524	0.171	0.237		0.69		1	
11-23	0.348	0.095	-0.227	-0.207	-0.081	0.30		1	
12-06	0.583	0.412	0.091	0.180	0.081	0.55		1	
12-20	0.926	0.416	0.192	0.300	0.162	0.83		1	
12-59	0.644	0.361	0.134	0.227	0.105	0.65		1	
12-61	0.866	0.435	0.204	0.274		0.77		1	
13-10	0.561	0.361	0.037	0.119	0.081	0.53		1	
13-21	0.713	0.386	0.114	0.190	0.088	0.63		1	
13-22	0.811	0.451	0.184	0.267	0.120	0.88		2	
21.34	0.817	0.442	0.217	0.268	0.147	0.61		1	
21-38	0.984	0.404	0.250	0.281	0.168	0.76		1	
21-47	0.469	0.262	0.076	0.129	0.018	0.63		1	
22-04	0.408	0.275	0.027	0.097	0.058	0.51		3	
22-13	0.742	0.367	0.143	0.223	0.105	0.62		1	
22-15	0.702	0.435	0.210	0.249		0.68		2	
23-01	0.495	0.314	0.113	0.160		0.56		1	
23-16	0.815	0.439	0.207	0.267	0.178	0.75		1	
23-23	0.710	0.388	0.180	0.258	0.116	0.69		4	
23-44	0.542	0.364	0.054	0.154	0.047	0.59		1	
32-55	0.847	0.407	0.145	0.250		0.67		2	
σ	0.025	0.011	0.010	0.013	0.010				

[1] Noisy spectrum (usually taken under cloudy conditions).

[2] $(B-V)_0$ value for nonmembers calculated with the full $E(B-V) = 0.14$ appropriate for ω Centauri.

b) Abundance Estimates from the Indices

Indices from the observations and from the models are presented in Figures 6–12, from which abundance estimates are derived and tabulated in Table 6. The M_V, m_{HK} diagram (Fig. 6) for stars in NGC 6752 and 47 Tuc (Bell, Hesser, and Cannon 1984*b*, 1983 respectively) shows that the NGC 6752 stars are in the position expected for an abundance of $[M/H] \approx -1.5$ and the 47 Tuc stars are consistent with $[M/H] \approx -0.8$. *In contrast, the faint ω Cen members plotted in Figure 6 are distributed throughout the range defined by the other two clusters.* The m_{HK}, $B-V$ diagram (Fig. 7) is not completely consistent with the previous one, in the sense that the m_{HK}, $B-V$ diagram suggests that some stars have $[M/H] > -0.5$, whereas the M_V, m_{HK} diagram contains no such stars. There also seems to be a tendency for many other stars to appear to be more metal-poor in the m_{HK}, $B-V$ diagram than in the M_V, m_{HK} diagram, an effect which a lower reddening for ω Cen would exacerbate. Owing to the sensitivity to both small errors in $B-V$ and $E(B-V)$, we give less weight to the abundances from the m_{HK}, $B-V$ diagram than from the M_V, m_{HK} diagram. In Figure 7 and subsequent ones we anticipate a later decision to adopt the [M/H] values from Figure 6 for the age analysis by plotting

TABLE 5

COMPUTED INDICES

Model (T_{eff}/log g/[A/H])	$B-V$	m_{CN}	m_{HK}	m_{Ca}	m_G	m_{Fe}
6000/3.0/−0.5	0.466	0.181	0.217	−0.107	−0.029	−0.036
6000/3.0/−1.0	0.434	0.131	0.131	−0.120	−0.069	−0.046
6000/3.0/−2.0	0.403	0.086	0.035	−0.121	−0.104	−0.057
6000/3.75/−0.5	0.486	0.223	0.197	−0.085	+0.019	−0.018
6000/3.75/−1.0	0.455	0.152	0.129	−0.097	−0.026	−0.033
6000/3.75/−2.0	0.420	0.085	0.036	−0.099	−0.082	−0.048
6000/4.5/−0.5	0.512	0.289	0.200	−0.054	+0.065	+0.001
5500/3.0/−0.5	0.613	0.361	0.305	−0.005	+0.131	+0.033
5500/3.0/−1.0	0.574	0.225	0.220	−0.032	+0.087	+0.011
5500/3.0/−2.0	0.520	0.110	0.087	−0.046	−0.009	−0.020
5500/3.75/−0.5	0.626	0.430	0.270	+0.013	+0.161	+0.051
5500/3.75/−1.0	0.593	0.288	0.214	−0.013	+0.129	+0.031
5500/3.75/−2.0	0.542	0.131	0.098	−0.026	+0.031	−0.009
5500/4.5/−0.5	0.645	0.517	0.271	+0.043	+0.187	+0.066
5250/3.0/−1.0	0.656	0.371	0.299	+0.017	+0.176	+0.050
5250/3.0/−2.0	0.606	0.166	0.149	−0.009	+0.072	+0.003
5250/3.75/−0.5	0.701	0.588	0.308	+0.072	+0.219	+0.087
5250/3.75/−1.0	0.668	0.418	0.259	+0.029	+0.192	+0.066

TABLE 6

ABUNDANCES DEDUCED FOR ω CENTAURI STARS

Star	Visual Inspection	M_v, m_{HK}	m_{HK}, $B-V$	M_V, m_{Ca}	M_V, m_G	M_V, m_{CN}
11-32[a]	−1.8	−2.1	< −2.0	−1.0	−1.5	−2.0
11-45[a]	−1.2	−0.9	−1.6	−1.0	−0.8	−0.9
11-57	−1.5	−2.0	−2.0	−1.7	−2.0	−1.5
12-01[a]	...	−0.7	−0.4	−0.6	−0.7	−0.6
12-42	−1.5	−1.4	...	−1.6	−1.4:	−1.2
12-49	−1.5:	−1.8	−1.6	−1.0	−1.5	−1.8
13-04	< −1.5	−1.4	−2.2	−1.0	−1.0	−1.3
13-23	−1.5	−1.5	−2.0	−1.3	−1.4	−1.4
13-35[a]	−0.7	−1.2	−1.3	−0.8	−1.2	−0.8
13-53	−1.3	−1.4	−1.9	−0.7	...	...
21-17	−1.8	−1.5	−2.0	−1.2	−1.1	−1.5
21-49[a]	−1.7:	−1.0	−2.0	−0.7	−0.8	−1.0
21-52	−1.0	−0.7	> −0.5	−0.7	−0.9	−1.0
22-25[a]	−1.0	−1.6	−1.5	−2.2	−1.6	−1.3
22-28[a]	−1.0	−1.7	−1.6:	−1.9	−1.5	−1.4
22-35[a]	−1.6	−2.0	−2.0	−2.2	−1.7	−2.0
22-52	−1.5	< −2.0	−2.0	−1.8:	−2.0	−1.5
23-42	−0.8	−1.5	−1.9	−1.5	−1.4	−1.4
32-48	−1.5	−1.4	−2.0	−1.0	−1.3	−1.3

[a] Noisy spectrum (usually, taken under cloudy conditions).

the stars according to abundance groups assigned from Figure 6, e.g., $[M/H] \leq -1.5$, $-1.5 < [M/H] < -1.0$, and $[M/H] \geq -1.0$. (Note that if the observed m_{HK} values had not been reduced by the 0.07 mag zero-point shift discussed in note 7, none of the ω Cen stars would have been more metal-poor than $[M/H] = -1.5$, a result contradicting the abundances deduced for giants by Bell and Gustafsson 1983 and for RR Lyraes by Manduca and Bell 1978.)[8]

The distribution of stars in the M_V, m_{Ca} diagram (Fig. 8) is similar to the previous two diagrams. By contrast, the m_{Ca}, $B-V$ relation and deviations therefrom shown in Figure 9 are essentially independent of abundance, a circumstance we may use to reassess the correctness of our earlier error estimates. If we assert that all stars should lie along this line, the standard deviation for the measurements (neglecting the error in $B-V$)

[8] In principle, interpretation of our sky-subtracted spectra should be free of the effects of the interstellar K line. For completeness we note that from measurements of hot stars, Freeman and Rodgers (1975) have inferred an equivalent width of 1.2 Å for the interstellar K line toward ω Cen. This value is quite high compared to estimates for other clusters (Butler 1975) and may be partly due to background light from unresolved stars (Greenstein 1968). Consequently, it seems likely that the Freeman and Rodgers value is an upper limit to the true interstellar K-line contribution. *If* our simultaneous measurement and subsequent subtraction of the sky had failed completely, the effects of the interstellar K line could be estimated as follows. The pseudo-equivalent width of the K line in CS 13-53 is 7 Å. Assuming this psuedo-equivalent width can be treated as a line on the square-root portion of the curve of growth, reduction of this equivalent width by 1.2 Å would correspond to an abundance shift of 0.1 dex. In stars with weaker stellar K lines (such as CS 13-23), failure to correct for the interstellar component could lead to an overestimate of the abundance of that star by 0.2 or 0.3 dex, depending on the radial velocity of the interstellar gas and the exact contribution to the "interstellar" line by background starlight.

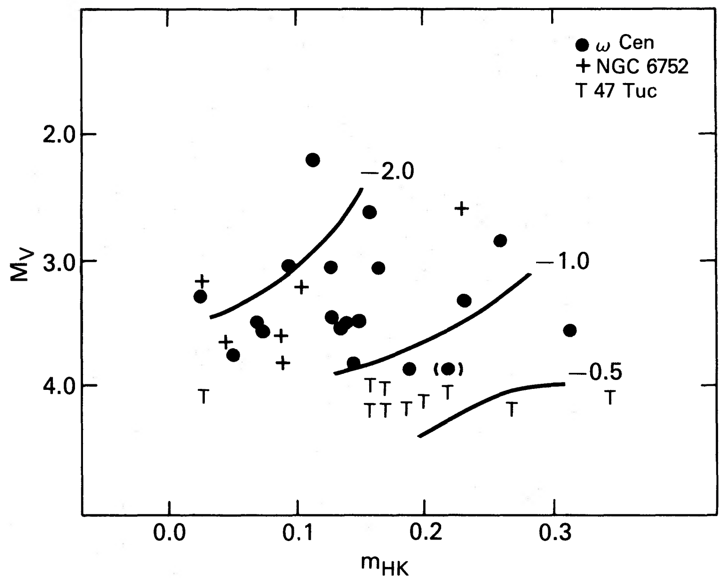

FIG. 6.—The M_V, m_{HK} diagram is shown for stars in ω Cen (radial velocity members), NGC 6752 and 47 Tuc. The lines are computed from synthetic spectra with T_{eff} = 6000 K, 5500 K, and 5250 K, and the gravities have been obtained from the isochrones plotted in Fig. 6. Note that the observed m_{HK} indices have been reduced by 0.07 mag. (The symbol for star CS 12-01, for which the data are particularly noisy, is placed in parentheses in this and the succeeding plots.)

is 0.04, suggesting that the 0.01 mag value quoted in Table 4 is somewhat small. The ± 0.03 mag estimated error in Cannon and Stewart's (1981) $B-V$ values would translate into ± 0.015 uncertainty in m_{Ca}, which is still about twice the Table 4 estimate.

The M_V, m_G; M_V, m_{CN}; and M_V, m_{Fe} diagrams form Figures 10–12. We have not applied any zero-point shift to the m_G data but have reduced all the observed m_{CN} values by 0.14 (the NGC 6752 data required a correction of 0.20 mag). It can be seen that in general the positions of the stars in these diagrams are quite consistent: stars which have a low metal abundance, as deduced from M_V, m_{HK} (Fig. 6), also have weak CN, a weak G band, and weak Fe. Note, however, that CS 13-35 has an exceptionally strong CN feature (cf. Paper I).

A number of stars, e.g. CS 13-04, CS 11-32, and CS 21-17, appear to have quite strong G bands, as judged from m_G. While this result may very well be correct, the carbon overabundances will not be as high as a direct comparison of abundances from M_V, m_{HK} and M_V, m_G would imply. We also note that [M/H] from M_V, m_G is as metal-poor as [M/H] from M_V,

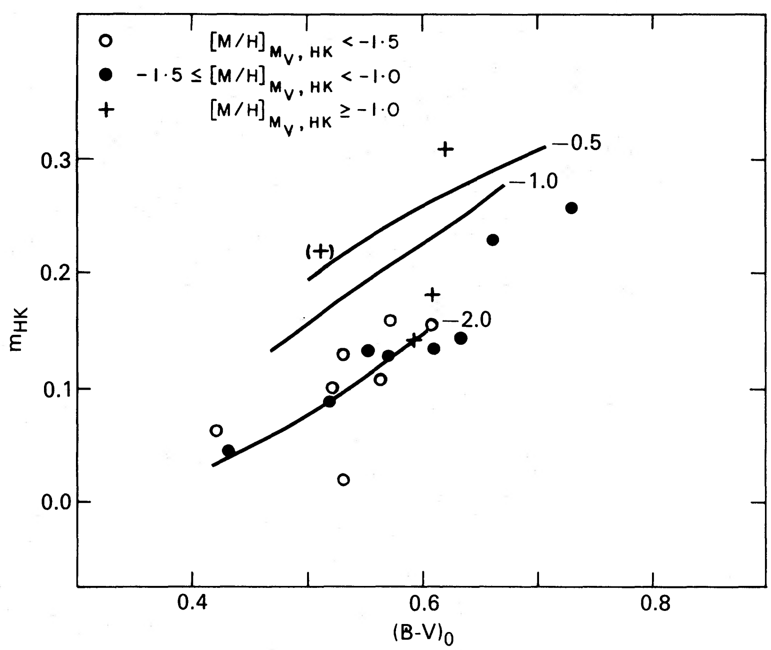

FIG. 7.—The m_{HK}, $B-V$ diagram is shown for ω Cen radial velocity members; as in the proceding figure, the observed m_{HK} indices have been reduced by 0.07 mag. The lines are deduced from synthetic spectra as described in the text and Fig. 6. In this and succeeding diagrams (except Fig. 16), symbols are used to distinguish stars by three broad metallicity groups assigned from the M_V, m_{HK} diagram (Fig. 6).

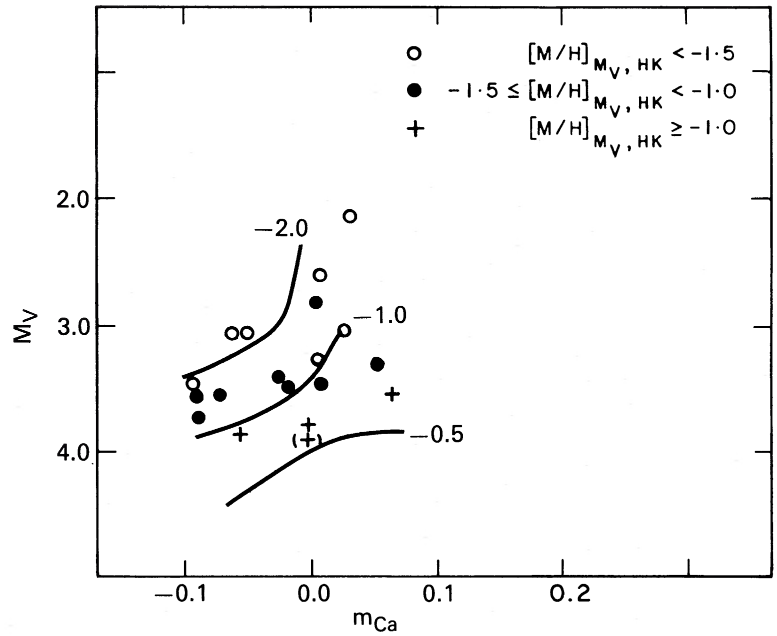

FIG. 8.—The M_V, m_{Ca} diagram for ω Cen radial velocity members. The lines are computed from synthetic spectra. The observed m_{Ca} indices have been reduced by 0.07 mag, as described in the text.

m_{HK} for only two stars. This is of course dependent on the zero-point shifts.

Bearing in mind Suntzeff's (1980) successful application of a similar m_{HK} index to globular cluster giants, and noting that our giant-branch models can reproduce his observations, we will adopt for subsequent use those abundances inferred from the M_V, m_{HK} diagram. Fortunately, as we have seen, those abundances are generally in agreement with those derived from most of the other diagrams (see Table 6 and Figs. 8, 10, 11, and 12). As noted earlier, we attach less weight to the results from the m_{HK}, $B-V$ diagram owing to their relative sensitivity to small errors in the observed $B-V$ colors: an error of 0.04 in $B-V$ corresponds to 0.4 in [M/H] for a metal-rich star. Moreover, errors in reddening cause a systematic error in the m_{HK}, $B-V$ abundances. Similarly, visual comparison of observed and computed spectra, using color to indicate the appropriate model temperature, appears to give results somewhat less precise than those found from the numerical indices and which are also dependent to some extent upon errors in $B-V$. The abundances estimated from visual inspection compared with those given by the m_{HK}, $B-V$ and M_V, m_{HK} diagrams respectively are shown in Figures 13 and 14. In the latter diagram the scatter is relatively large, but the overall trend is one of agreement, while in Figure 13 the scatter is small but the abundances from m_{HK}, $B-V$ are systematically smaller by ~ 0.4 in [M/H].

Finally we summarize the metallicity findings of the previous

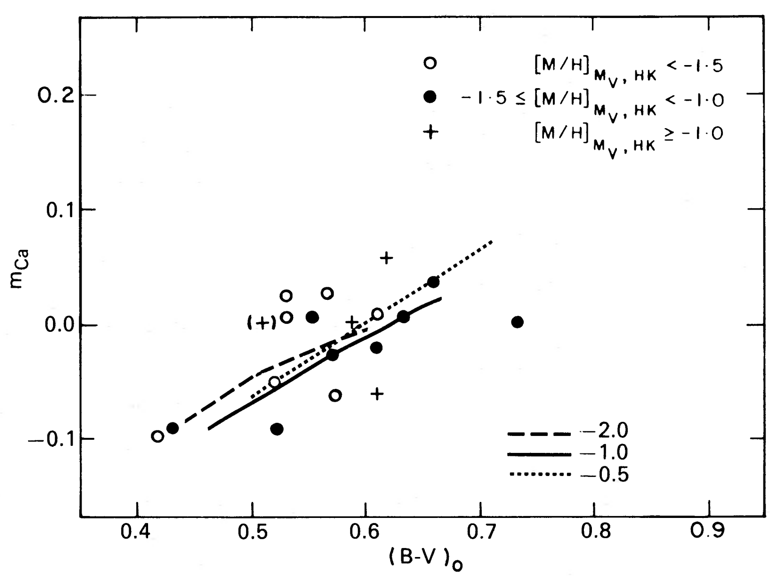

FIG. 9.—The m_{Ca}, $B-V$ diagram for ω Cen radial velocity members, where, as in the preceeding figure, the observed m_{Ca} indices have been reduced by 0.07 mag before plotting and the lines are derived from synthetic spectra.

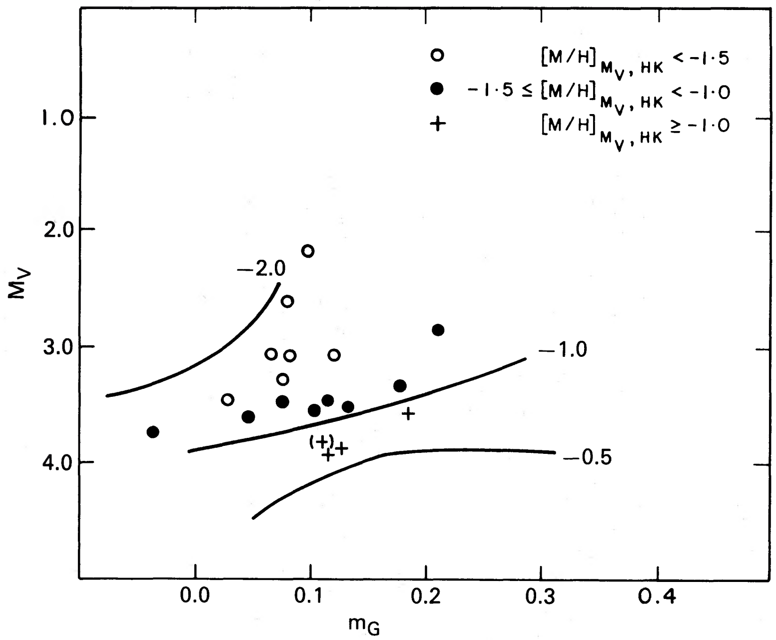

FIG. 10.—The M_V, m_G diagram for ω Cen radial velocity members (otherwise as in the previous figures)

sections in Figure 15, which is an updated version of Figure 8 from Bell and Gustafsson (1983). In this figure the abundance histograms for bright giant stars, RR Lyrae stars, and the faint giant/subgiant stars are compared. Stars in all three groups share similarities in their distributions, including a lack of marked skewness or of bimodality. The combined analyses of Paper I and this paper make it clear that many of the anomalies observed among ω Cen's giants have their origin during, or *immediately* after, the main-sequence evolutionary stage.

c) The Age of ω Centauri

The CMD for the turn-off region stars which we regard as cluster members is given as Figure 16, with stars in NGC 6752 and 47 Tuc also being plotted to illustrate the difference between ω Cen and more normal globulars of widely differing metallicity. $Y = 0.20$ isochrones for 15 and 18×10^9 yr and for abundances of [M/H] $= -2.2$, -1.2, and -0.7 from VandenBerg (1983) are also superposed. The scatter exhibited by the ω Cen stars in the figure is much greater than the estimated

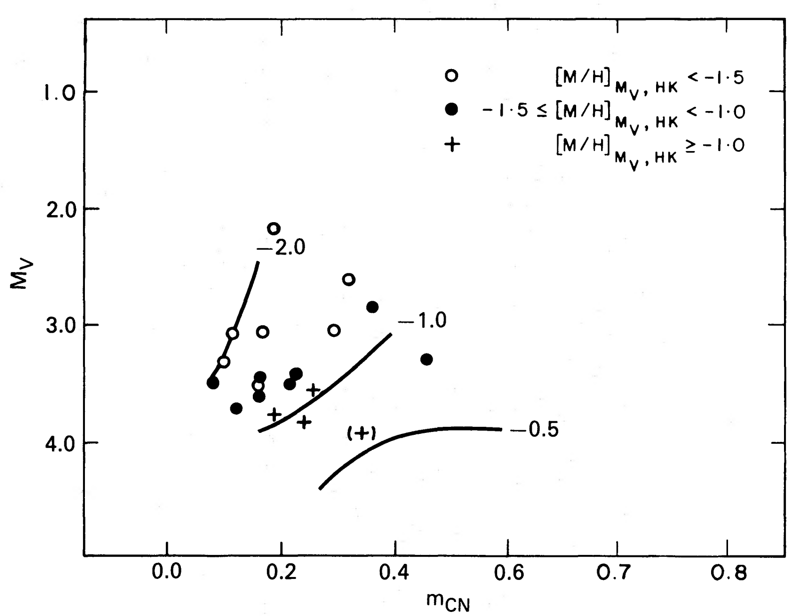

FIG. 11.—The M_V, m_{CN} diagram for ω Cen radial velocity members, as in previous figures except that the observed m_{CN} indices have been reduced by 0.14 mag before plotting, as described in the text.

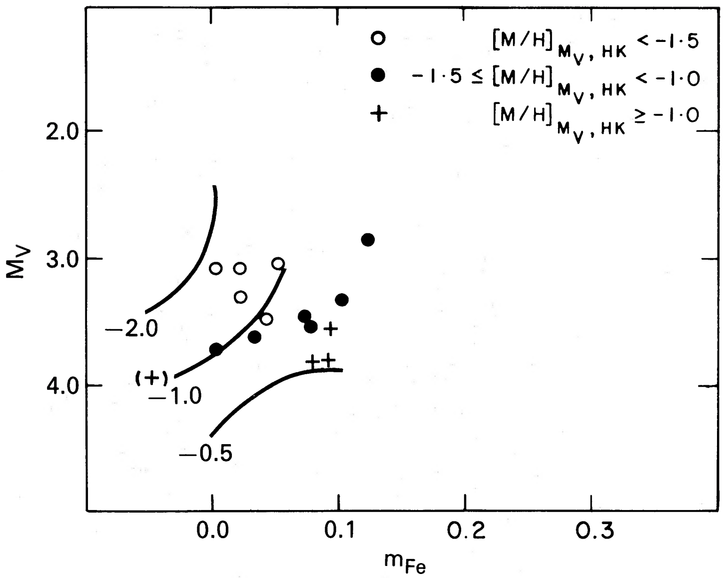

FIG. 12.—The M_V, m_{Fe} diagram for ω Cen radial velocity members (otherwise as in the previous figures)

errors of the photometry. (Cannon and Stewart 1981 quote ± 0.03 mag in $B-V$ for stars with $V < 17.5$). While a range of color is inherent to globular cluster subgiant branches, we believe that much of the dispersion in this diagram could be caused by the greater than 1 dex abundance spread in the cluster stars, as the comparison with the other two clusters also suggests. Before proceeding with an age determination from this figure it is necessary to incorporate the abundances of the individual stars in order to search for systematic effects.

In Figure 17 we show the CMD for the ω Cen cluster members once again separated into the three different abundance groups introduced earlier together with the same isochrones illustrated in Figure 16. Now it is apparent that the more luminous stars are the more metal-poor ones and that the less luminous stars are the metal-rich ones. Allowance for the different abundances of the cluster stars, and the previous elimination of radial velocity nonmembers, greatly reduce the uncertainty in the age determination. With $E(B-V) = 0.14$, $(m - M)_0$, $V = 13.5$, and $Y = 0.20$, we can estimate that, *independent of metal abundance*, the ω Cen stars have an age of about 18×10^9 yr, which is consistent with the value of 15–18×10^9 yr deduced by VandenBerg (1983) for a number of globular clusters.

The role of the adopted abundances in the above age derivation requires further elucidation. As stated earlier, we have preferred abundances from the M_V, m_{HK} diagram, which we also remarked are generally in agreement with abundances inferred from other indices. However, in deducing abundances

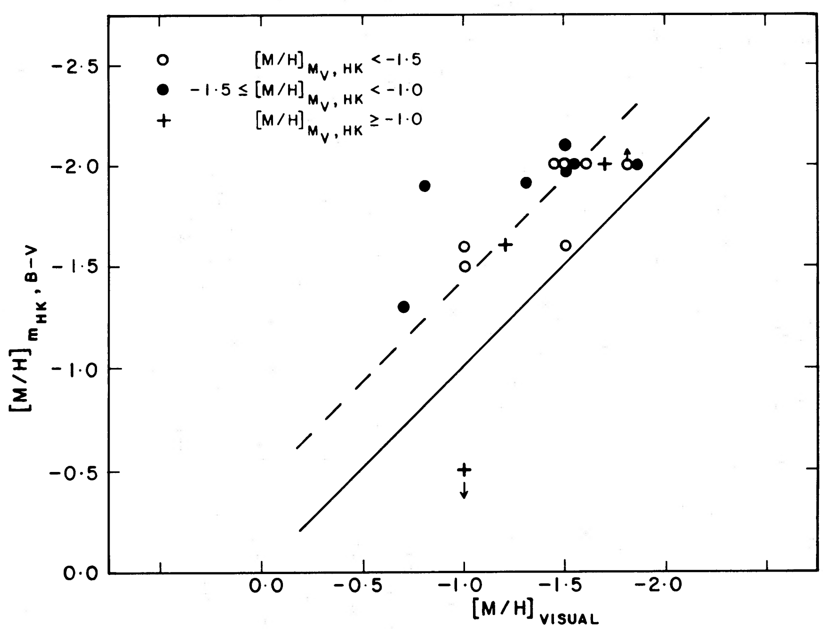

FIG. 13.—Comparison of the [M/H] values estimated from the visual comparison of observed and synthetic spectra (§ IV*b*) and those estimated from the m_{HK}, $B-V$ diagram (Fig. 7). Both the 45° line and one shifted by $\sim$0.4 dex are included; see text.

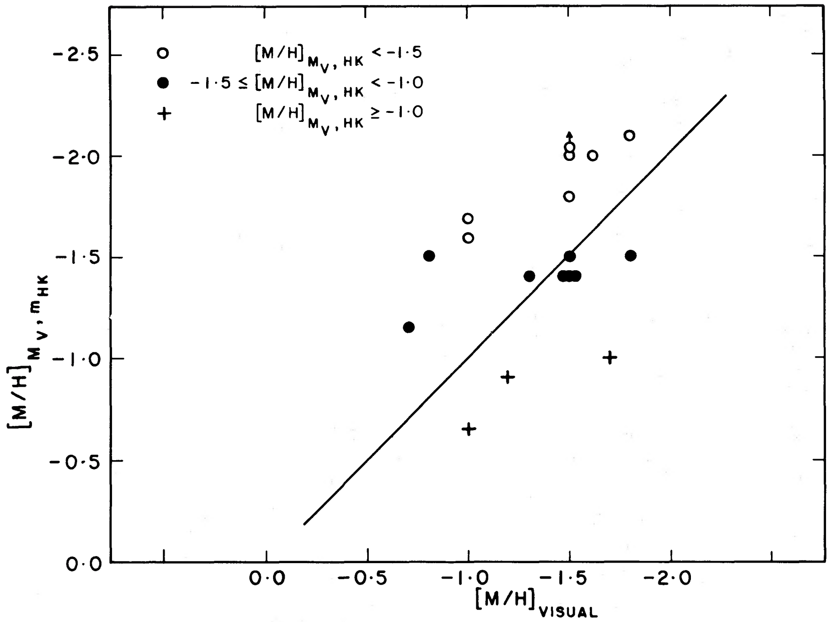

FIG. 14.—Comparison of the [M/H] values estimated from the visual comparison of observed and synthetic spectra (§ IV*b*) and those estimated from the M_V, m_{HK} diagram (Fig. 6). A 45° line is shown for reference; see text.

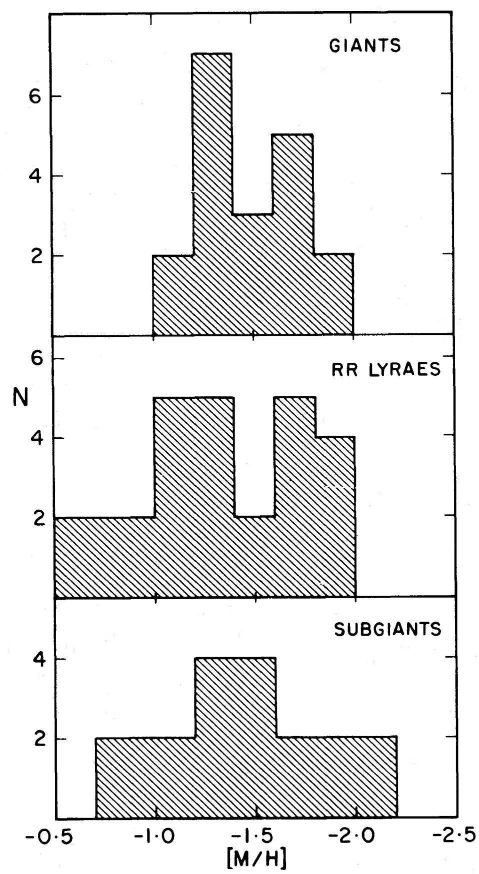

FIG. 15.—A histogram of abundances inferred from bright gaints, RR Lyrae stars, and our sample of faint subgiants and giants; see text.

from M_V, m_{HK}, we have assumed that the stars all have the same age. This has allowed us to obtain the gravities from the evolutionary tracks, but, fortunately, it is not as circular an argument as it first seems. It signifies that we cannot detect ω Cen stars with $[M/H] > -0.5$ and ages greater than 18×10^9 yr because the stars we have observed are not faint enough(!). It also leads us to inquire whether we could obtain the correct abundance for a very young metal-rich star or a very old metal poor star. If we have a star with $[M/H] = -2.2$, $B-V = 0.5$, and $M_V \approx 3.5$ (corresponding to an age greater than 20×10^9 yr), it will have a surface gravity, log g, only 0.1 greater than that of an 18×10^9 yr old star of the same color. This range in gravity will not affect m_{HK}, judging from the data in Table 5. However, when plotted in an M_V, m_{HK} diagram, the fainter M_V will cause the measured [M/H] to appear 0.3 dex greater than it actually is. The converse will be true for a young, metal-rich star—the abundance will be found to be lower than it actually is. We can therefore say that coeval star formation is *consistent* with all our data, and we believe we can exclude the possibility of a large age spread with the metal-rich stars being significantly younger. It would be of considerable interest to extend the observations to stars another magnitude fainter where the geometry of the evolutionary tracks is quite different, in order to see if the same conclusions hold.

Finally, we note that: (1) VandenBerg (1983) does not give isochrones for 18×10^9 yr and $Y = 0.30$, but the isochrones for 15×10^9 yr for $Y = 0.20$ and 0.30 virtually coincide in the M_V, $B-V$ region which we have used, so that uncertainty in the appropriate helium abundance would probably not affect these age estimates very much. (2) VandenBerg compared his isochrones with the observations for ω Cen stars over the range $2.5 < M_V < 5.5$. While we have relied only on stars with $3 < M_V < 4$, we have the advantage of knowing that our stars are almost certainly cluster members (which, as emphasized in § III, is not a trivial problem for ω Cen). (3) In order to center the main-sequence data with the isochrones we have adopted $M_V(HB) = 0.6$, whereas VandenBerg adopted $M_V(HB) = 0.3$.

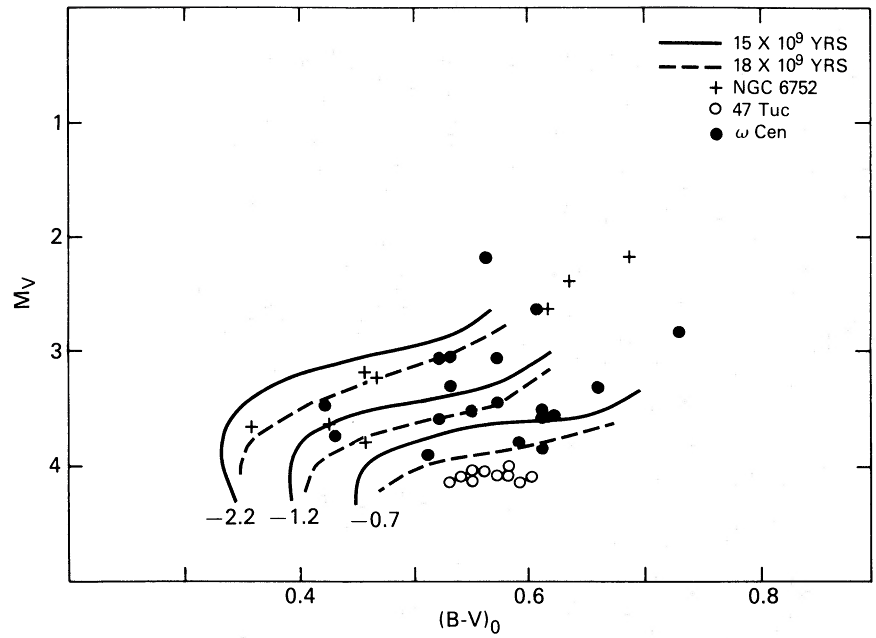

FIG. 16.—The CMD of the ω Cen stars found to be members on the basis of radial velocity data is compared with the $Y = 0.2$ isochrones of VandenBerg (1983). Stars which we have previously observed in NGC 6752 ([M/H] ≈ -1.5) and 47 Tuc ([M/H] ≈ -0.8) are also plotted to indicate the range spanned by the parameters governing the ω Cen subgiants.

VI. CONCLUSIONS

We have obtained spectra for a large proportion of a sample of faint ($16.0 < V < 17.8$) giant and subgiant stars lying just above the main-sequence turnoff point in ω Cen. The radial velocities give a good criterion for cluster membership, and we find that about three-quarters of the bluer stars but less than a quarter of the redder stars are members of the cluster. Consequently, interpretations of photometric data of faint stars in terms of a range of abundances must be viewed with caution if membership information for individual stars in the sample is lacking.

Abundance information has been extracted from our spectra via several comparisons with synthetic spectra. Among the confirmed members there is a $B-V$ range of ~ 0.2 mag at a given value of M_v and metallicities differing by a factor of 10, which is very similar to the well-established range of abundances seen in the more highly evolved red giant and RR Lyrae stars. We find correlations between color, temperature, and

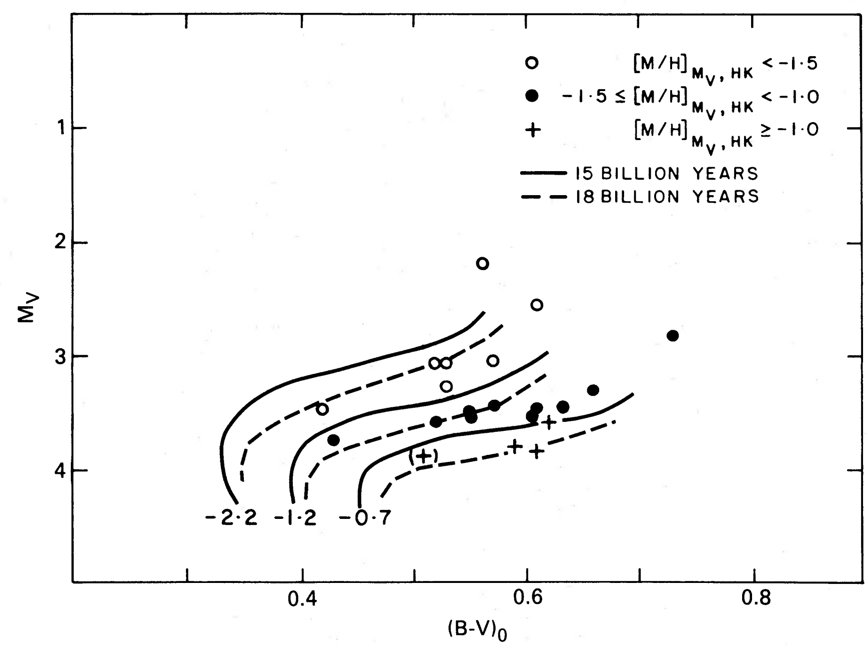

FIG. 17.—The CMD for the ω Cen stars is compared with the same VandenBerg (1983) isochrones shown in the preceding figure. After sorting the stars into the three abundance groups, $[M/H] < -1.5$, $-1.5 < [M/H] < -1.0$, and $[M/H] > -1.0$, it is seen that stars within each group tend to lie near an 18×10^9 yr isochrone.

abundance similar to those seen in earlier studies of brighter ω Cen stars, but we also find examples of stars of similar color exhibiting quite different abundances. The latter effect appears to be well explained in terms of theoretical isochrones. Using recent tracks by VandenBerg (1983), it seems that the CMD and several plots of spectral line indices against luminosity and color can be simultaneously well fitted by theoretical relations in which all the ω Cen stars have approximately the same age, around 18×10^9 yr, although the data cannot rule out an age spread of up to 10%.

These new data confirm that the abundance spread seen among the highly evolved stars persists at least down to the top of the main sequence. It is highly speculative to say much about the pattern of abundance variations on the basis of such a small sample of stars and with still relatively imprecise data, but the simplest interpretation is that the slightly evolved subgiants show not only the same range ($-2.0 < [M/H] < -0.5$) as the bright giants, but a similarly uniform distribution within this range. Also, there are no very striking abundance anomalies among the few species which we have observed. In general the abundances of Ca, Fe, C, and N appear to vary together, although, as we found in Paper I, there may be overabundances of N and underabundances of C as with the brighter giants.

Four possible mechanisms for establishing a large abundance range in ω Cen were discussed in Paper I. The fact that this paper demonstrates that the range is present among stars just beyond the turnoff perhaps strengthens the argument given there for a primordial mechanism. There is certainly no evidence for a sudden onset of abundance anomalies at some point as stars evolve up the giant branch, as is required, for example, in the Sweigart and Mengel (1979) mechanism. If the latter is operative, any abundance variations would involve only CNO and would be expected to occur only in stars more luminous than we have observed ($M_V < -0.5$). Some sort of accretion mechanism involving mass transfer in binaries could be involved. Since about half the ω Cen stars have enhanced abundances and since there is still no direct evidence for any binary stars in ω Cen, the binary hypothesis does not seem attractive. However, some recent studies of Galactic X-ray sources, as well as of binary frequencies among metal-poor field stars, may bear on the ω Cen problem. For instance, Hertz and Grindlay's (1983) reanalysis of Hartwick, Cowley, and Grindlay's (1982) *Einstein* IPC data for ω Cen has identified five point sources within the cluster. They argue that the sources have $\lesssim 1\ M_\odot$ and that the X-rays are generated by accretion onto a white dwarf in a compact binary system. Optical identifications are urgently needed to evaluate the correctness of their hypothesis. ω Cen contains CH stars, which are believed to be the Population II analogs of Population I Ba II stars, and McClure (1984*a*, *b*) has shown from precision radial velocity observations that virtually all field stars of the Ba II and CH categories that he has observed have radial velocity variations indicative of binary companions. Furthermore, Stryker, *et al.* (1985) have found the incidence of binaries among field F and G subdwarfs to be $\sim 30\%$, which is higher than heretofore believed and now similar to that found for Population I stars. In view of the several lines of evidence indicating that binaries are rare in globular clusters in general (Trimble 1980; but see also Harris and McClure 1983), the relevance of the field star studies to the ω Cen problem will only become clear after detailed searches for spectroscopic binaries have been carried out in ω Cen itself. A more general accretion mechanism, whereby individual stars accrete from intracluster gas, may also be operating in ω Cen, but the similarities of the range of abundances for faint subgiants and bright giants then seems somewhat surprising.

Until more work is done on the alternatives, particularly the binary hypothesis, it seems that a primordial abundance spread is left as the most likely explanation for the ω Cen observations, although it is not very satisfying to say that ω Cen happens to have been born from much less homogeneous material than most other globulars. Perhaps, as Freeman and Norris (1981) have suggested, ω Cen is (or was) massive enough to behave like many galaxies, and by having retained processed material from a very early generation of stars was able to set up an abundance gradient within itself.

Our analysis is based upon moderate-resolution spectra of generally quite modest signal-to-noise ratio taken for a membership survey (and then often under cloudy conditions). Nevertheless these spectra provide a guide as to just how much could be learned about this important, anomalous cluster from somewhat better spectra of a larger sample of upper main-sequence, turnoff, and subgiant stars. Such spectra are within reach of aperture plate spectrographs equipped with modern detectors on 4 m class telescopes, and would serve to verify and extend our conclusions.

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