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# BLANKETING DIFFERENCES AMONG GLOBULAR CLUSTER GIANTS

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## ABSTRACT

Intermediate-band observations of differential blanketing in giants in $\omega$ Cen are analyzed by the methods of Searle and Zinn to obtain the general abundance parameter $S$ and thence [Fe/H]. In the sample observed, the range of [Fe/H] is $-1.8$ to $-0.8$, in accord with the spread in composition of the bulk of the RR Lyrae stars. The effects of back warming by CO blanketing are investigated through study of $[S, (B-V)_0]$-relations. It is found that CO is correlated dichotomously with Fe/H for most clusters. M5 shows variable CO for a given Fe/H, while in $\omega$ Cen, Fe correlates with CO monotonically. Conjectures regarding variable mass functions are made in this context.

*Subject headings:* clusters: globular — spectrophotometry — stars: abundances — stars: late-type

### I. INTRODUCTION

Following the observation of the color-luminosity array of the brighter stars in the globular cluster $\omega$ Cen by Woolley *et al.* (1961), it was suggested by Iben (1974) and Schmidt and van den Berg (1974) that the wide giant branch was caused by chemical inhomogeneity in the cluster, leading to significant differential blanketing in the $B-V$ colors.

Subsequently, Freeman and Rodgers (1975) observed the spectra of RR Lyrae stars in $\omega$ Cen and found that the value of [Ca/H] varied from star to star over the range $-0.3$ to $-1.9$. A reanalysis by Manduca and Bell (1978) of these data gives $[Ca/H] = -1.0$ to $-1.9$. The major source of uncertainty in the lower value arises from the uncertainty in the size of the appropriate interstellar K-line correction. A more extensive discussion by Butler, Dickens, and Epps (1978) of the [Ca/H] abundances of the RR Lyrae stars confirmed the heterogeneity of the compositions of the horizontal-branch stars in $\omega$ Cen. Freeman and Rodgers (1975) argued that since it is difficult to imagine how elements such as calcium could be synthesized in evolving coeval stars in $\omega$ Cen, the inhomogeneity was likely to be primordial in nature. Mallia (1976), Norris and Bessell (1975), Bessell and Norris (1976), and Norris (1979) intensively studied the variations in CN and CH in the cluster giant-branch stars and have recently shown that the band strengths of CN are related to the strengths of lines of Fe I, Sr II, and Ca II. It appears that the line and band strength enhancement in *some* giants is general, and not confined to those features which appear stronger as a result of the process of synthesis and subsequent mixing in stars of mass $\sim 0.8\ M_\odot$. This result does not exlude the possibility of enhancement of *s*-process elements such as Ba in stars (e.g., ROB 371) observed by Dickens and Bell (1976).

Searle and Zinn (1978) have described a technique which, using intermediate-bandwidth spectrophotometry, defines a differential blanketing parameter, measured over the wavelength range 5000–3800 Å, compared with a de-reddened pseudocontinuum in the wavelength range 7500–5000 Å. The de-reddening is accomplished by a wavelength rather than flux transformation, based on the Whitford reddening law. Searle and Zinn's individual, contiguous blanketing values $Q(\lambda)$ are integrated over the blue wavelength region ($\lambda < 5000$ Å) to form $S$. $S$ is a function of the stellar temperature as well as a function of the integrated differential line and band blanketing. Searle and Zinn use the convenient display method of plotting $M_V$ (based on an assumed brightness of the horizontal branch of $M_V = +0.6$) against $S$. Since $S$ is a function of both temperature and blanketing, the giant branches of different clusters are separated into discrete sequences in the $(M_V, S)$-plane as a result of the different effective temperatures of stars of different composition at the Hayashi limit and of differential blanketing. These two effects are in lockstep, so a unique sequence results for a homogeneous giant branch. In this way Searle and Zinn were able to rank globular clusters in composition to further their studies of the distribution of abundances of the galactic halo. In a comparison of the $S$ values for individual clusters at $M_V = -1$ with the values of [Fe/H] deduced by Butler (1975) from Ca and H blanketing in globular cluster horizontal-branch stars, Searle and Zinn found a correlation between $S$ and [Fe/H] of the form $Fe/H = 3.73S - 3.05$.

In this paper we continue to address the question of the primordiality of the by now well-established inhomogeneity of the stars of $\omega$ Cen. We use the techniques of Searle and Zinn to establish the nature of the breadth of the giant branch in $\omega$ Cen. The integrated differential blanketing measured by $S$ is dominated by elements formed by a $\alpha$-process and $e$-process synthesis. If $S$ is found to differ from star to star and if each blanketing value $Q(\lambda)$ correlates with $S$ and if the range in $S$ is consistent with the range in [Ca/H] found in the horizontal-branch stars and if $\delta S/\delta(B-V)_0$ is consistent with that found from clusters of widely differing abundance, we will take these to indicate that the composition variations in $\omega$ Cen are primordial. There is direct evidence against such a view. Cannon and Stewart (1979) have done photometry of the main-sequence turnoff of $\omega$ Cen and place an upper limit of 0.04 mag on the rms scatter of the width of the main sequence due to differential blanketing compared with an expected value of about 0.1 mag (see, e.g., Melbourne 1960). Further work on the main sequence of $\omega$ Cen is being done with SEC TV photometric calibration by E. B. Newell and some of the authors.

## II. OBSERVATIONS

The observations were made at the 1.9 m telescope of Mount Stromlo with the 32-channel spectrophotometer (Rodgers *et al.* 1973). This instrument differs from the Hale Observatory device in having channels of 184 Å width compared with the 160 Å width available to Searle and Zinn. However, $S$ is the sum of the blanketing $Q(\lambda)$'s of contiguous bands blueward of 5000 Å; so if common stars of known absolute energy distribution are used by the Hale observers and us (which was the case), then no intermediate standards are required and our values of $S$ are directly comparable to the Searle and Zinn data. The observations and reductions to absolute energy distributions used standard procedures. Crowding was avoided in the choice of program stars, and sky positions were selected by inspection of long-exposure photographs.

## III. RESULTS

A typical energy distribution of an $\omega$ Cen star is shown in Figure 1, in which the flux per unit frequency interval, expressed as a magnitude $M$, is plotted against $\psi$, which is defined by

$$\psi = 1.30\lambda^{-1} - 0.60 \quad \lambda^{-1} \leq 2.29\,,$$

$$\psi = 0.75\lambda^{-1} + 0.65 \quad \lambda^{-1} > 2.29\,.$$

A least-squares straight line is fitted to the spectrum over the wavelength interval 7500–5000 Å. A parameter $Q(\lambda_i)$ is then defined for each channel by subtracting from the observed magnitude the value given by the best-fit line. Searle and Zinn refer to plots of $Q(\psi)$ against $\psi$ as "intrinsic spectra" since they represent a flux distribution that is independent of reddening. Such plots constitute the basis for their investigations.

Searle and Zinn employ, as a parameter that is taken to be characteristic of an individual cluster, a weighted mean value of $Q$ determined over the wavelength region 4920–3800 Å which is termed $S$. Formally,

$$S = \sum_i w_i Q(\lambda_i) \Big/ \sum w_i\,,$$

where $w_i$ is the channel bandwidth.

We show in Figure 2 some representative spectra of stars, in the $(Q, \psi)$-plane. In Table 1 we list the values of $Q(\psi)$ for the $\omega$ Cen stars observed by us together with their "gradients" $\phi$. The stars in Table 1 were observed only once. From the data, the original energy distributions of the $\omega$ Cen giants can be recovered. The value of $S$ obtained for each star is also given in Table 1. In Figure 3 we show the giant branches in the $(M_V, S)$-plane for the clusters observed by Searle and Zinn together with the data for $\omega$ Cen. Since it is crucial to our argument that the scatter in the $\omega$ Cen data be real, we must defend our estimates of the errors. We have derived these estimates in the following way. We first compute the uncertainties in our data arising from photon statistics of star and sky from each channel. We then allow this error to enter

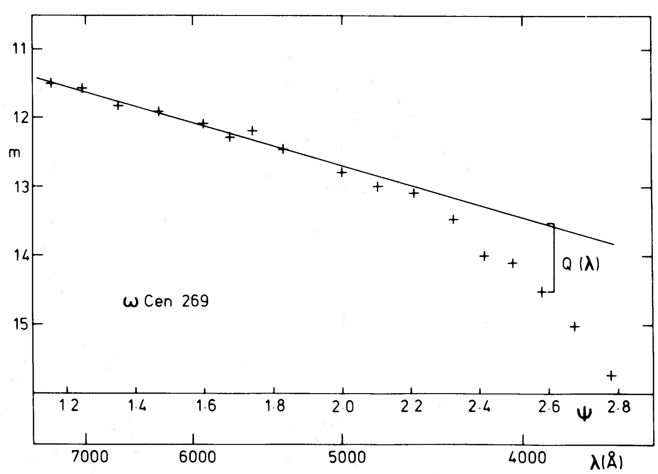


FIG. 1.—The observed spectral flux distribution of the $\omega$ Cen star ROB 269. The definition of the parameter $Q(\lambda)$ is illustrated.

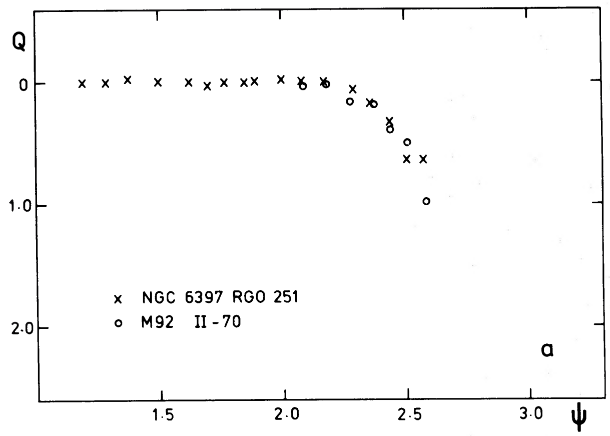


FIG. 2*a*

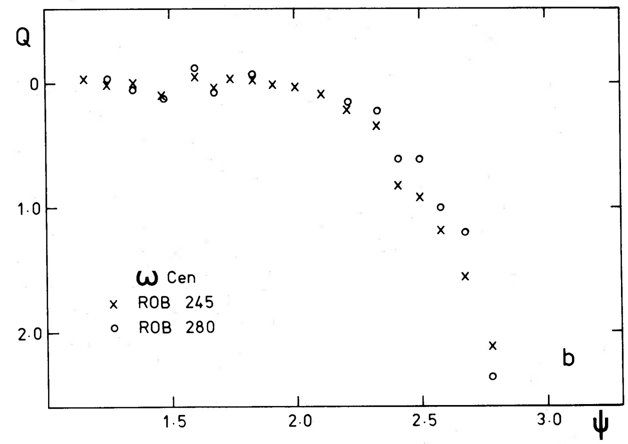


FIG. 2*b*

FIG. 2.—Representative spectra of giants in ω Cen, in the ($Q$, $\psi$)-plane. Comparison is shown of ω Cen stars ROB 245 ($M_V = -1.67$, $S = 0.55$) and ROB 280 ($M_V = -1.58$, $S = 0.41$).

with appropriate weight into the least-squares solution for $\phi$. In the determination of $Q$ the photon statistics are sufficiently good that the error in the integrated flux between 5000 and 3800 Å is about one-third that due to any systematic error in the gradient $\phi$. In real terms, typical random errors in each channel are 0.01 mag, with possible systematic errors of 0.05 mag due partly to sky conditions and partly to instabilities in our pulse-counting equipment on bright equatorial standards. The final result is that $S$ has a typical error of $\pm 0.06$ mag, of which 0.01 mag is due to lack of photons. We show these computed errors as bars in Figure 3. The estimates of $M_V$ used in the compilation of Figure 2 are based on the photometry of ω Cen giants by Cannon and Stobie (1973), which gives $V$ and a distance modulus $(m - M)_{app} = 13.9$, with $E(B - V) = 0.10$ from Newell, Rodgers, and Searle (1969). We see that there appears to be for the ω Cen giants a range of $S$ at nearly constant $M_V$, which exceeds our claimed errors.

In Figure 4 we plot the values of $(B - V)_0$ on the giant branch, at $M_V = -1.0$, against $S$ at the same luminosity as that of the Searle-Zinn observations. A tight relationship exists, which can be represented by $S = (1.20 \pm 0.04)(B - V)_0 - (0.82 \pm 0.05)$, reflecting the effects of composition both on the position of the Hayashi track and on differential blanketing in $B$ and $V$. In Figure 5 we show the same plot for the ω Cen stars. The $B - V$ data listed in Table 1 and used in Figure 5 are from the Woolley *et al.* (1961) photometry of ω Cen corrected to the system of Cannon and Stobie (1973) in the range $12 < V < 13$: our estimate of the errors of the individual nonphotoelectric colors is $\pm 0.08$, and the systematic error is $\pm 0.02$, with six stars common to the two photometries. A less well defined relation can be seen, which is represented by

TABLE 1

SCANNER OBSERVATIONS OF ω CENTAURI GIANTS

| Star | V | B-V | Ψ | Q(5000) | Q(4808) | Q(4623) | Q(4439) | Q(4255) | Q(4071) | Q(3886) | S | ΔS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 245 | 12.23 | 1.34 | 1.49 | 0.03 | 0.09 | 0.22 | 0.35 | 0.83 | 0.92 | 1.19 | 0.55 | 0.06 |
| 251 | 12.25 | 1.33 | 1.50 | 0.04 | 0.09 | 0.36 | 0.40 | 0.77 | 0.70 | 0.6 | 0.46 | 0.06 |
| 252 | 12.25 | 1.14 | 1.50 | 0.03 | 0.06 | 0.20 | 0.34 | 0.60 | 0.48 | 0.48 | 0.34 | 0.06 |
| 269 | 12.35 | 1.22 | 1.46 | 0.08 | 0.13 | 0.16 | 0.19 | 0.69 | 0.67 | 0.97 | 0.43 | 0.10 |
| 279 | 12.32 | 1.38 | 1.42 | 0.06 | 0.11 | 0.37 | 0.53 | 1.02 | 0.88 | 0.88 | 0.59 | 0.06 |
| 280 | 12.32 | 1.34 | 1.45 | 0.03 | 0.08 | 0.15 | 0.22 | 0.61 | 0.61 | 1.0 | 0.41 | 0.07 |
| 312 | 12.44 | 1.30 | 1.48 | 0.04 | 0.06 | 0.17 | 0.30 | 0.77 | 0.69 | 0.86 | 0.44 | 0.06 |
| 325 | 12.46 | 1.15 | 1.46 | 0.03 | 0.07 | 0.15 | 0.23 | 0.56 | 0.61 | 0.91 | 0.39 | 0.06 |
| 351 | 12.50 | 1.17 | 1.41 | 0.04 | 0.10 | 0.23 | 0.37 | 0.52 | 0.50 | 0.62 | 0.37 | 0.06 |
| 359 | 12.50 | 1.29 | 1.33 | 0.02 | 0.10 | 0.22 | 0.35 | 0.83 | 0.75 | 0.83 | 0.48 | 0.06 |
| 370 | 12.53 | 1.25 | 1.32 | 0.03 | 0.09 | 0.20 | 0.32 | 0.72 | 0.68 | 1.12 | 0.48 | 0.05 |
| 378 | 12.58 | 1.29 | 1.41 | 0.04 | 0.08 | 0.22 | 0.35 | 0.68 | 0.82 | 0.90 | 0.47 | 0.07 |
| 379 | 12.62 | 1.19 | 1.38 | 0.04 | 0.10 | 0.42 | 0.37 | 0.69 | 0.65 | 0.91 | 0.50 | 0.07 |
| 381 | 12.58 | 1.21 | 1.47 | 0.03 | 0.09 | 0.23 | 0.38 | 0.70 | 0.61 | 0.64 | 0.41 | 0.05 |
| 389 | 12.60 | 1.23 | 1.34 | 0.09 | 0.13 | 0.17 | 0.29 | 0.77 | 0.73 | 1.12 | 0.49 | 0.10 |
| 400 | 12.62 | 1.31 | 1.37 | 0.05 | 0.13 | 0.24 | 0.36 | 0.75 | 0.79 | 1.19 | 0.54 | 0.06 |
| 402 | 12.68 | 1.07 | 1.31 | 0.02 | 0.09 | 0.21 | 0.32 | 0.44 | 0.39 | 0.47 | 0.30 | 0.05 |
| 418 | 12.70 | 1.10 | 1.32 | 0.06 | 0.23 | 0.28 | 0.34 | 0.64 | 0.63 | 0.60 | 0.43 | 0.14 |
| 484 | 12.78 | 1.20 | 1.23 | 0.05 | 0.07 | 0.19 | 0.27 | 0.64 | 0.56 | 0.81 | 0.39 | 0.06 |

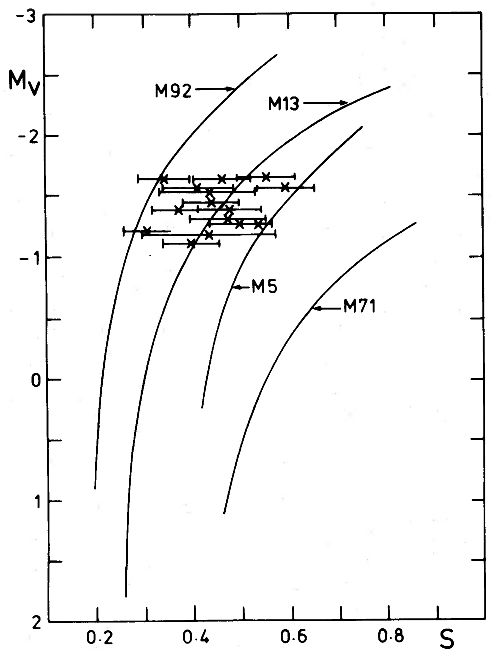


FIG. 3.—Fourteen of the observed $\omega$ Cen giants are depicted in an $(M_V, S)$-plane, thereby illustrating the variations in blanketing among them. For comparison, the loci defined by the much tighter sequences of four of the clusters observed by Searle and Zinn are shown. Some data from Table 1 are omitted for clarity.

$S = (0.95 \pm 0.06)(B - V)_0 - (0.62 \pm 0.07)$, as a least-squares fit. In Figure 5 we plot the mean relation for the Searle-Zinn data together with that for the $\omega$ Cen data.

We believe that, considering the adduced errors for $S$ for the $\omega$ Cen stars, these relations are identical in slope. Searle and Zinn considered the calibration of $S$ in terms of stellar composition. The best relation between composition and $S$ was found to be $[\mathrm{Fe/H}] = 3.73\langle S \rangle - 3.05$, where $\langle S \rangle$ is taken at $M_V = -1.0$. On this basis we deduce that the range of [Fe/H] in the $\omega$ Cen giants which we have observed is from $-1.8$ to $-0.8$. Butler, Dickens, and Epps (1978) give a range of $-1.7$ to $-0.8$ "predicted" from the color-luminosity array and a total abundance range for the RR Lyrae stars of $-2.0$ to $-1.1$. These estimates are all affected by selection, but their gratifying agreement, we believe, confirms that the chemical inhomogeneity of $\omega$ Cen (i) extends to the common metals involved in differential blanketing, and (ii) evinces itself throughout the color-luminosity array of bright evolved stars.

Butler *et al.* comment that the giants in $\omega$ Cen are, as a group, 0.04 mag too red in $(B - V)_0$ for their average [Fe/H] value. Figure 5 shows the same result. That this appears in the $[\langle S \rangle, (B - V)_0]$-plane indicates that the effect is not due to differential blanketing by lines or bands in the wavelength regions covered by the $\langle S \rangle$ and $(B - V)_0$ observations. For example, an enhancement of CN bands in the spectra of two otherwise identical stars will move points in Figure 5 along the loci defined by general abundance changes since the dominant band systems with heads at 3883 and 4215 Å fall in the $B$ and $Q(\lambda)$ bands. Norris (1979) has shown that in $\omega$ Cen CN is correlated with [Fe/H], and Persson and Frogel (1979) have shown that CO (i) is correlated with [Fe/H] and (ii) has a steeper dependence on [Fe/H] than in other clusters. To explain Figure 5 and Figure 6 (see below), we require a mechanism which affects the relative near-infrared and blue fluxes determining $\langle S \rangle$ for a given $(B - V)_0$, or vice versa. Gustafsson *et al.* (1975) have described red giant model atmospheres with differing temperature structures resulting from enhancement of C, N, and O. CO provides surface cooling and CN back warming. The effects of such enhancements on the contribution functions and the fluxes are difficult to estimate; nevertheless, examination of the fluxes of

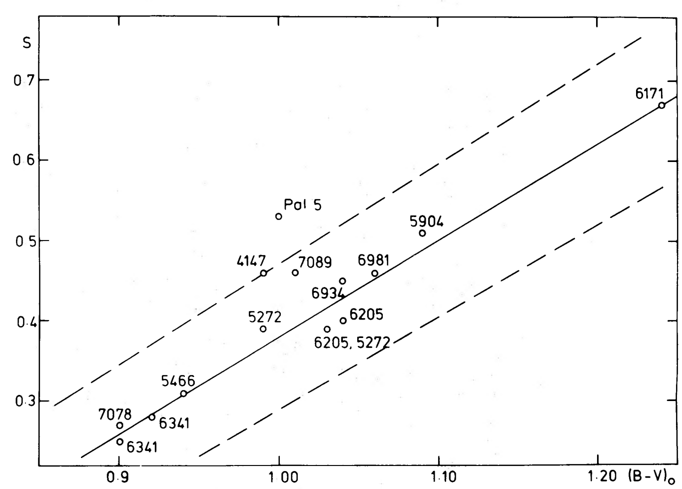


FIG. 4.—An $[S, (B - V)_0]$-plane for giants in the magnitude range $M_V = -1.0 \pm 0.06$ in the clusters studied by Searle and Zinn. Each cluster is denoted by its NGC number, and several of them are represented twice. A least-squares best fit is shown by the solid line, and the limiting error lines are shown dashed.

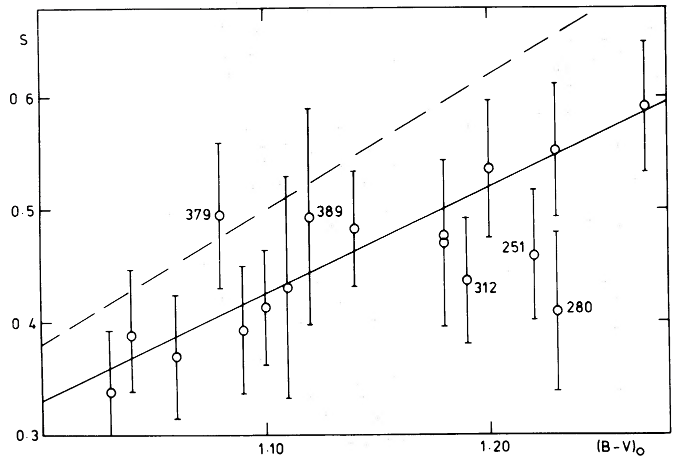


FIG. 5.—The $[S, (B-V)_0]$-plane for the $\omega$ Cen giants. The solid line is that of a least-squares best fit, and the dashed line represents the best-fit line from Fig. 4. The numbered points were excluded from the best-fit calculation.

much less appropriate models of Population I supergiants (Bell and Rodgers 1969) suggests that CN enhancement can cause at least part of the differential blanketing effects in Figure 5. We appreciate the unsatisfactory nature of this perforce empirical approach. However, if our hypothesis that CNO variations influence the temperature distributions in cluster giants is correct, then it is possible that if we examine stars of a different luminosity, the relative effects of $H^-$ and Rayleigh scattering opacities, particularly for the more metal-weak clusters, will be altered sufficiently that the effect of different temperature distributions will be enhanced. We examine $S$ taken at $M_V = -1.5 \pm 0.1$ and $(B-V)_0$. The data are plotted in Figure 6. The relation is dichotomous. We first note that M3 and M13 fall in different groups in the diagram. Persson and Frogel (1979), Cohen, Frogel, and Persson (1978), and Pilachowski (1978) have observed that CO in M13 is weak relative to that in M3. We propose that this effect has altered the temperature distribution in the M3 giants so that relative to M13, $(B-V)_0$ is redder for a given $S$. Implications about the CO abundances from Figure 6 can be checked against direct observations for several clusters. Figure 6 predicts that M5 is inhomogeneous in CO and/or CN, and Pilachowski has observed this to be the case. Figure 6 indicates that M92 is weak in CO in addition to having a low value of Fe/H, and this also has been found to be the case by Pilachowski. We predict that NGC 5024 and NGC 6299 will be found by infrared observers to be CO strong. Our prediction that M10 is inhomogeneous in CO is not supported by the infrared observations of three stars by Pilachowski. Hesser, Hartwick, and McClure (1977) have nevertheless noted variations in CN strengths in stars in this cluster. The role of CO or CNO as a second parameter (not counting age) may be examined if our interpretation of Figure 6 is correct. There is a little indication that the

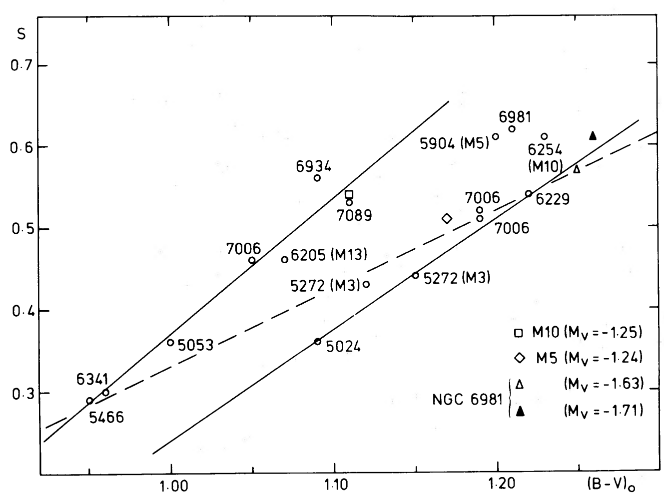


FIG. 6.—An $[S, (B-V)_0]$-plane analogous to Fig. 4, but now drawn for giants in the magnitude range $M_V = -1.5 \pm 0.1$. Several stars outside this range are also included, in order to illustrate the behavior of M10, M5, and NGC 6981 better.

sequences of Figure 6 correlate with horizontal-branch morphology. A few specific cases are worth discussion. We note that M13 (weak in CO) has a bluer horizontal branch than M3 (strong in CO). The interesting cluster NGC 7006 has a red horizontal branch and has some giants strong in CO and, according to Hartwick and McClure (1972), has at least four giants with strong CN, possibly indicative of high CO. Figure 6 indicates at least two stars which are CO strong and one which is weak. Nevertheless, NGC 5024, which we claim to be CO strong, has a blue horizontal branch. We argue that the combined effects of CO strength, metal abundance, and possible CO inhomogeneity in a given cluster make it very difficult to establish, quite apart from consideration of mass loss, age, rotation, etc., whether CO is a *dominant* factor in horizontal-branch morphology.

We plot the mean line for the $\omega$ Cen stars in Figure 6. We find that, in their ubiquitously abnormal fashion, they are CO weak when metal weak and CO strong when metal strong and that their behavior in Figure 6 is in accord with the conclusions reached by Persson and Frogel (1979).

## IV. CONCLUSIONS

The present observations of $S$ indicate a range of [Fe/H] in the giant-branch stars of $\omega$ Cen of about 1 dex. They provide supplementary evidence for a different global (CNO, metal)-relation for these stars from that found in giants in other clusters.

There is evidence in the $[S, (B-V)_0]$-relation that CO influences the temperature structure in the outer layers of the atmosphere. If this is so, there is evidence for (i) a dichotomous distribution of CO in globular clusters superposed on the general Fe–CO correlation, and (ii) a heterogeneity in CO in clusters in which, unlike $\omega$ Cen, Fe is inhomogeneous. The CO dichotomy appears to us to be most likely due to primordial processes rather than mixing since $\omega$ Cen shows the same range of CO, compared with the variation in [Fe/H], as that shown by the globular clusters at large. Further, there is a variety of evidence that in $\omega$ Cen, 47 Tuc, and other clusters (Freeman 1979) the inhomogeneities are radially distributed. We therefore believe that the range in CNO is largely primordial in origin.

A possible cause of the inhomogeneities is a variation in the mass function of the stars formed during cluster collapse. While Arnett (1978) concludes that relative chemical yields are rather insensitive to the adopted mass function, he nevertheless demonstrates that typical nucleosynthesis sources are massive ($\mathfrak{M} \approx 40\,\mathfrak{M}_\odot$) and that in the mass range 3–48 $\mathfrak{M}_\odot$ there is a clear enhancement of the yield of O relative to C of about 100. This result, *inter alia*, is confirmed by Weaver, Zimmerman, and Woosley (1978) in their calculation of the presupernova composition of stars of 15 and 25 $\mathfrak{M}_\odot$. It is also possible, according to Iben and Truran (1978), for enrichment of $^{13}$C and $^{14}$N to be accomplished by thermal pulsing of intermediate-mass objects while $^{12}$C and the progeny of $^{22}$Ne can be synthesized and distributed by stars of both intermediate and high mass. It seems likely then that differential mass functions for $\mathfrak{M} > 3\,\mathfrak{M}_\odot$ can be responsible for chemical inhomogeneities within clusters. In $\omega$ Cen an excess of O could account for the increased CO which accompanies enrichment of the *e*-process elements by the formation of a generation of massive ($\sim 30\,\mathfrak{M}_\odot$) stars. Only about 40 $\mathfrak{M}_\odot$ of Fe is required to enrich $\omega$ Cen to the observed amount. Small numbers of massive stars are required, and a sochastic enrichment of gas in the collapsing cluster probably occurred.

The spatial distribution of enhancement around each supernova determined the currently observed number distribution of metallicity. An alternative view of the composition distribution function of $\omega$ Cen is that it developed during cluster collapse as a result of the formation of successive generations of massive stars in which the mass function stayed essentially constant.

For clusters other than $\omega$ Cen, we suppose that little or no *e*-process enrichment of the collapsing gas took place. However, in clusters such as M5, intermediate-mass star formation with consequent C and O (but not Fe) enrichment led to the observed inhomogeneities. For most clusters it appears that the protocluster gas was enriched by stars that were less massive in general than those formed during the collapse of $\omega$ Cen.

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