IS THERE A COMPOSITION GRADIENT IN THE HALO?

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We define "metals" as consisting of the elements at and near the Fe-peak, and review several methods by which the metal-abundance gradient of stars in the halo can be obtained. In the inner halo (galactocentric distance $R \lesssim 8$ kpc), the Basel RGU photometry should allow the derivation of the shapes and dimensions of the iso-abundance contours. For the outer halo to $R \sim 30$ kpc, we review techniques based on Δs-measurements of RR Lyraes (Lick) and intermediate band-pass photometry of globular-cluster giants (Searle and Zinn, Palomar). Both methods suggest little change in mean [Fe/H] between 10 and 30 kpc; however, both may be biased against the discovery of very metal-poor objects. The conclusion that the outer halo has no abundance gradient may be somewhat premature.

Recent abundance analyses of the classical halo giant HD 122563 (Lambert, et al. 1974) and of giants in certain globular clusters (Cohen 1978; Carbon, et al. 1978) suggest that in old, metal-poor stars the relative abundances of the α-process and Fe-peak elements, and even of primary elements inter-alia are not the same as in the sun. Thus before we can speak of a "metal-abundance gradient in the halo", we need to decide which metals we mean. As a purely practical matter, optical observers require a metal-abundance "indicator" that can be measured with reasonable accuracy in faint cool stars of old stellar populations. Most current photometric techniques depend on the blocking of UV-flux produced by elements in and near the Fe-peak; thus in what follows, "metals" ≡ Fe-peak.

Nevertheless, a moderate decoupling of the C, O group from the Fe-peak is an interesting possibility. In both HD 122563 and the M15 planetary nebula (Hawley and Miller 1978) $[\frac{O}{H}] > [\frac{Fe}{H}]$ (recall the definition $[\frac{A}{H}] \equiv \log (\frac{A}{H})_* - \log (\frac{A}{H})_\odot$). In low mass stars, it is not easy to see how O can be produced by an evolutionary process, and a primordial overabundance of O may be required. Moreover, the strength of the CO-bands in M3 giants is greater than that of M13 giants, even though $[Fe/H]_{M3} < [Fe/H]_{M13}$ (Cohen, et al. 1978; Pilachowski 1978).

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In metal-poor clusters horizontal branch morphology critically depends on the C, O group whereas giant branch morphology depends largely on the Fe-peak (cf. Faulkner 1966, Renzini 1977); these results therefore may bear on the classical problem of the anomalously blue HB of M13 vis-a-vis M3.

Returning to the domain of Fe-peak metals, we now review several methods by which the halo gradient problem can be attacked. Space does not permit an exhaustive survey of techniques: what we describe is, however, representative.

A. Halo Field Dwarfs: Basel Three-color RGU System. The system (Becker 1972) discriminates metal-abundance in late-type (>F0) stars by means of the ultraviolet excess $\delta(U-G)$ at a given $(G-R)$ in a plot of $U-G$ vs $G-R$; $\delta(U-G)$ is similar to the more familiar $\delta(U-B)$ of the UBV system. When applied to dwarfs, $\delta(U-G)$ is defined to be 0.0 for metal-rich stars and reaches a value ~0.5 mag in stars with extreme metal deficiency. Compared with UBV the system has the advantage that $\frac{\delta(U-G)}{\delta[Fe/H]}$ is almost twice $\frac{\delta(U-B)}{\delta[Fe/H]}$, largely because B is affected more by blanketing than is G. This large UV-excess sensitivity is particularly favorable when one tries to detect metal-poor dwarfs in photographic Schmidt surveys (Steinlin 1973). The Basel investigators have studied $\delta(U-G)$ for stars as faint as V = 19 in six selected areas lying roughly in a plane containing the sun, the galactic nucleus, and the north galactic pole. The distribution of metal-abundance among dwarfs is thus studied to a distance some 8 kpc from the sun, and the shapes of the iso-abundance contours can be derived in principle for comparison with those predicted from galactic collapse models (cf., eg., Larson 1975, 1976). Preliminary results indicate that the "isochromes" of $\langle\delta(U-G)\rangle$ are flattened, corresponding fairly closely to the isodensity contours (Becker 1972) derived from the same surveys. The calibration of $\delta(U-G)$ in terms of [Fe/H] has not yet been carried out, so the precise conversion of "isochrome" to iso-abundance contour is not yet possible.

Since the mean $\delta(U-G)$-values are based on some 200 dwarfs in each field, the RGU system carries an enormous statistical weight when compared with other methods (described later), but also has some disadvantages. First, since it is applied to dwarfs, it does not penetrate into the outer halo. Second, since late-type giants exhibit a well-known gravity-induced UV-deficiency relative to dwarfs, one can confuse a metal-deficient giant of the distant halo with an ordinary nearby metal-rich dwarf. The Basel investigators statistically reduce the effect of this contamination by confining their attention to stars with $(G-R)$-colors corresponding to spectral types ~G5 and earlier. By thus limiting the sample to stars blueward of the Hayashi line for giants, they find only about one red horizontal branch "giant" per 100 main sequence stars, per unit volume of space. If the stellar density falloff goes as $\rho \sim R^{-3.5}$ (Kinman, et al. 1966; Harris 1976), giant star contamination should be quite negligible. We turn next to methods of deriving metal abundances more applicable to the outer halo ($R > 8$ kpc).

B. RR Lyrae Stars

Recent work (McDonald 1976; Butler, et al. 1978) bolsters the long-held view that, except for the most metal-rich objects ($\Delta s \leq 2$), RR Lyraes are standard candles with $\langle M_V \rangle = +0.6$. Since they are also F-type stars, objects in which the sources of opacity are well understood, their metal abundances can be reliably estimated. Butler's (1975a) calibration of Preston's (1959) Δs-index, based on the Ca II (K) and hydrogen lines, leads to $[Fe/H] = -0.16\ \Delta s - 0.23$. Thus measurements of Δs in halo RR Lyraes provides an ideal means of mapping the halo abundance gradient. Fortunately, extensive surveys made with the Lick astrograph have discovered RR Lyraes near the north galactic pole (NGP) and in several other galactic star fields (Kinman, et al. 1965, 1966) to a magnitude limit near $m_{pg} = 18.5$ (about 30 kpc). Since 1975, measurements of Δs for stars in three of these fields, including the NGP, have been made with the Wampler-Robinson (1972) scanner (IDS) operated at the cassegrain focus of the Lick 3-m (Shane) reflector. Although Δs measurements, generally numbering at least two per star, continue, a preliminary idea of the results can now be stated. As one proceeds above the plane to a distance of about 10 kpc, [Fe/H] on the average declines to a value somewhat smaller than that for RR Lyrae itself; beyond 10 kpc there is little evidence for a gradient, although there is large scatter. Certainly, stars with moderately high metallicity ($[Fe/H] \sim -1$) exist even at a distance of 20 kpc above the plane.

However, before we can naîvely embrace the evident conclusion that no abundance gradient exists in the halo between 10 and 30 kpc, we must examine two selection effects that discriminate against the discovery of very metal-poor RR Lyraes (By "very metal-poor", we mean $[Fe/H] < [Fe/H]_{M92} = -2.2 \pm 0.2$. M92 has the lowest well-known metal abundance among globular clusters). First, as is well-known (cf. Faulkner 1966, Iben 1974), a decline in metals leads to a bluer and bluer "mapping" of the horizontal branch; thus stellar populations with very low metals may skip the region of RR Lyrae production altogether. If we examine the distribution with [Fe/H] of RR Lyraes on the solar vicinity (Butler 1975), we find no stars with [Fe/H] significantly lower than M92. On the other hand, the giant HD 122563 has $[Fe/H] = -2.7$, a value reliably established (Wallerstein, et al. 1963), to be 0.5 dex lower than M92, and the existence of two giants with $[Fe/H] \lesssim -3.0$ has been reported (Bessell 1977). (Lick ITS observations easily show the weakening of metal features in HD 122563 compared with giants of the same T_{eff} in M92.) The number of stars involved is too small to permit definitive conclusions, but the material suggests that RR Lyraes may not in fact be generated in populations with very low metals.

A second selection effect is purely observational. Preston's (1959) work established that Δs is positively correlated with period amongst Bailey a's, but the amplitude of the light curve is in turn negatively correlated with period. This means, on the average, that the stars with lowest metal abundances tend statistically to have the largest periods and smallest light amplitudes. Kinman et al. (1966b) estimated that in the NGP, the sample of Bailey a's with $\Delta m \geq 0.75$ mag is complete to $m_{pg} = 17.0$, corresponding to a distance of 17 kpc. Since this Δm corresponds to [Fe/H] ~ -1.8, it seems likely that beyond 17 kpc, a significant fraction of metal-poor stars may be lost by the survey.

C. Giant Stars in Globular Clusters.

The fact that metal-rich globular clusters such as 47 Tuc and NGC 6171 ($[\frac{Fe}{H}] > -1.0$) are confined to a region in and near the galactic nuclear bulge, whereas metal-poor clusters are found in all parts of the galaxy has been known for some time (e.g., Morgan 1956, Kinman 1959, Arp 1965, Harris 1976, Fig. 5 and 6). What is not so clear is whether in the outer halo beyond the domain of metal-rich clusters $R \gtrsim 8$ kpc), an abundance gradient exists amongst the metal-poor clusters themselves. Several studies (Bell 1976, Canterna and Schommer 1978, Cowley et al. 1978) indicate surprisingly high metallicities ($>[Fe/H]_{M92}$) for a number of remote halo clusters and satellite subsystems (e.g. Draco) of the Galaxy. In a recent comprehensive paper, Searle and Zinn (1978) hereafter "SZ") addressed the halo abundance gradient question, and drew "the tentative conclusion that for $R > 8$ kpc, the distribution over abundance of halo globular clusters is independent of galactocentric distance". Although we suspect that this conclusion is probably valid, we believe the authors are also correct in emphasizing the word "tentative". The main problem is that the method employed by Searle and Zinn is not able to discriminate very well, within the quoted errors, between metal-poor clusters having, for example, [Fe/H] = -2.0 and [Fe/H] = -2.5. The question we raise, therefore, is whether the apparent cut-off in cluster metal deficiency near [Fe/H] ~ -2.0 simply reflects an artifact of the method of analysis; whether a few clusters, for example NGC 5053 and NGC 2419 have been assigned metal abundances that are too large; and whether the apparent absence of a gradient might result from a combination of this lack of discrimination and the fact that the galactic halo contains very few clusters with galactocentric distances $R > 20$ kpc. (We do not quarrel with the conclusion that several remote clusters, e.g., NGC 7006, in fact have [Fe/H] considerably larger than -2.0)

Our point becomes clearer when we examine the SZ method in more detail. Space does not permit an extensive review, but the essential points can be recovered from a study of Fig. 1, in which we plot the energy distributions F_ν expressed in magnitudes, averaged over 160 A intervals, for various metal poor stars, following exactly the treatment by SZ. The energy distributions are plotted against $\psi(\lambda)$, where $\psi = 1.30\ \lambda^{-1} - 0.60$ or $0.75\ \lambda^{-1} + 0.65$, according as $\lambda^{-1} \leq 2.29$ or > 2.29. Note that, as a function of $\psi(\lambda)$ (or $1/\lambda$) the energy distributions are virtually straight lines between λ8000 and 5000 A. The slope of this straight line, i.e., the increase in magnitude between

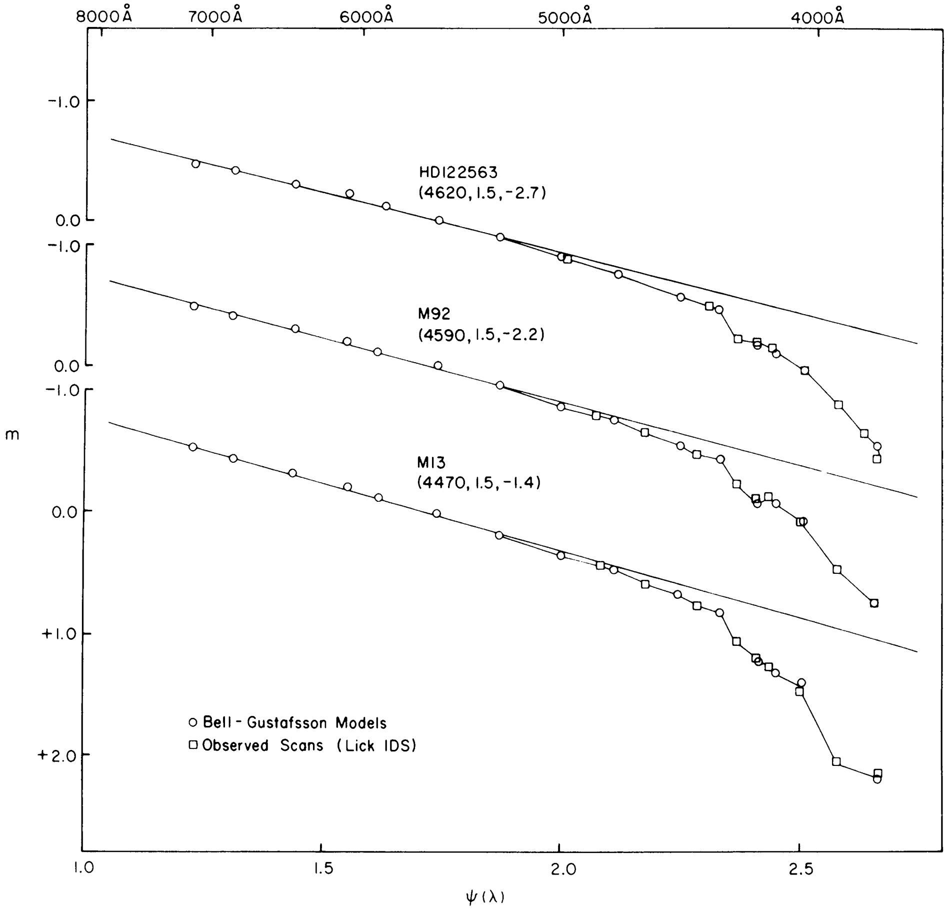

Figure 1. Theoretical and observed scanner fluxes F_ν for metal-poor stars. The latter, averaged over 160 A intervals, are normalized to the former, averaged over 50 A intervals, at λ4850 A; the numbers in parentheses refer to models with parameters (T_{eff}, log g, [Fe/H]).

λ8000 and 5000 A, denoted by ψ_o, depends on the intrinsic energy distribution of the star and on interstellar reddening; however, since the transformation given above is based on the Whitford reddening law (Miller and Mathews 1972) areas between the straight line, extrapolated shortward of $\lambda^{-1} = 2.29$, and the observed stellar flux m_λ, are reddening independent. Such areas, integrated over 160 A intervals and denoted by Q(λ), thus measure the intrinsic spectrum of the star.

In the SZ-method, some dozen red giants typically are scanned in each cluster, the Q(λ) are measured for each star at several wavelengths

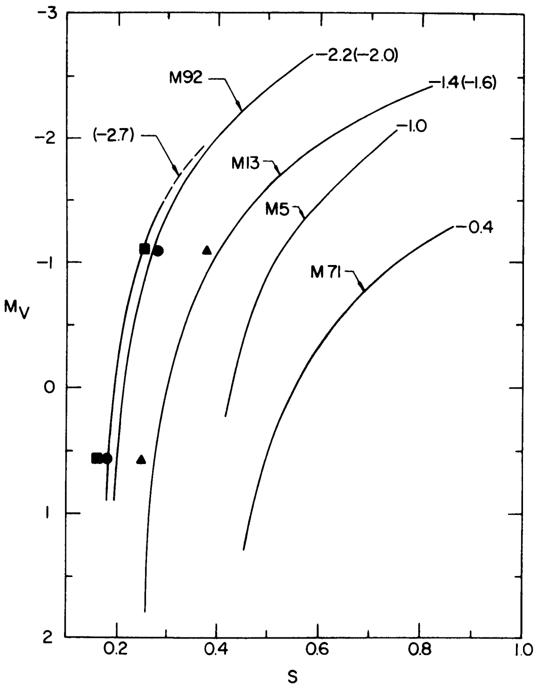

Figure 2. The variation of S with M_V in several globular clusters, after Searle and Zinn (1978). The location of a fictitious cluster with [Fe/H] = -2.7 is shown; filled symbols, reading from left to right, refer to models with [Fe/H] = -2.7, -2.2, and -1.4.

between λ5160 and λ3880, and a weighted mean of these Q's, denoted by S, is formed (the reader is referred to SZ for details). For each cluster star M_V is plotted as a function of S; this is illustrated in Fig. 2, which is adapted from the SZ paper (we do not show the individual observations). A particular S-value, denoted by ⟨S⟩, is read out at the convenient luminosity M_V = -1 for all clusters; typically the s.d. in ⟨S⟩ for a well-observed cluster is ± 0.02. The tight correlation of ⟨S⟩ with [Fe/H] determined from RR Lyraes (Butler 1975) provides the basic calibration of cluster abundances.

Consider now a fictitious cluster having [Fe/H] 0.5 dex smaller than that of M92 (for which we adopt [Fe/H] = -2.2). Where would a cluster lie in Fig. 2 if its [Fe/H] were -2.7? We can calculate this with the help of the theoretical scanner fluxes recently computed by Bell and Gustafsson (1978, hereafter "BG") for giants having a range of values of T_{eff}, log g, and [Fe/H]. The idea is that we start with the theoretical energy distribution corresponding to some M92 giant with M_V near -1, calculate S from this distribution, and then ask how S is changed if [Fe/H] is reduced by 0.5 dex and M_V is held constant.

In order to make the calculation, we must do two things. First, we must compare the theoretical with observed energy distributions, since the Bell and Gustafsson theoretical scanner fluxes do not include some wave-length intervals needed to calculate the Q(λ)'s (and therefore S). And second, we must find the change in location of the Hayashi line when [Fe/H] is changed from -2.2 to -2.7. We adopt for this purpose the interior model calculations of Sweigart and Gross (1978, hereafter "SG"). We begin with a real star, HD 122563, for which $(B-V)^\circ = 0.90$ and $[Fe/H] = -2.7$, and ask where it would lie in the HR diagram of a cluster having $[Fe/H] = -2.7$ if the turn-off mass (therefore age) and helium abundance were the same as M92. From the BG models, we find that the star has T_{eff} near 4600°K, and for a change in metals of 0.5 dex, it will be hotter than its M92 counterpart by 30°K (cf. SG), a change corresponding to 0.015 in $(B-V)^\circ$. Thus the M92 counterpart has $(B-V)^\circ = 0.915$ and $T_{eff} = 4590$°K (BG); whence T_{eff} (HD 122563) = 4620°K. For an M92 modulus of 14.5 (Sandage 1970) this puts HD 122563 at $M_V = -1.15$ ($\log g = 1.5$); the "real" stars of interest in M92 are therefore objects such as IV-10 and IV-79.

In Figure 1, we show theoretical scanner fluxes (BG) averaged over 50A intervals, for a star having (T_{eff}, log g, [Fe/H]) = 4620°K, +1.5, -2.7), compared with Lick IDS Scanner fluxes for HD 122563, with $\Delta\lambda = 160$ A (corresponding to the SZ resolution). The agreement between theory and observation is remarkably good (The Lick IDS data also agree very well with those of Christensen (1978) for the same star.). One is therefore encouraged to believe that the Q(λ) can be derived for the "theoretical" star having parameters (4620°K, +1.5, -2.7) using the real energy distribution of HD 122563 interpolated at the appropriate wavelengths. Similarly, in the second panel of Figure 1, we show a comparison between the theoretical model with parameters (4590°K, +1.5, -2.2) and the mean energy distribution of M92 IV-10 and IV-79 also derived from Lick IDS scans. A summary of values of ψ_0 and Q(λ) are given in Table 1. The main point is this: when we calculate S for these two energy distributions, we find S(-2.7) = 0.267 (for HD 122563) and S(-2.2) = 0.280 (for the mean of IV-10 and IV-79 in M92); that is, within the error (±0.02) quoted by SZ, the values of S are indistinguishable. Thus we conclude that, with the SZ method, one cannot distinguish a cluster with metal abundance [Fe/H] = -2.2 from one with [Fe/H] 0.5 dex smaller.

The reason for this lack of sensitivity is not hard to find. As one removes metals from a solar abundance giant, the spectrum changes rapidly until [Fe/H] reaches a value near -2, at which point the metal lines are mostly very weak; after that, the spectrum changes slowly and response is confined largely to the region of H and K and the Fe features immediately shortward. Indeed of the Q's, only Q(3880) shows much sensitivity when $[Fe/H] < -2.0$. But Q(3880) is the least "error-free" of the Q's, and besides, its effect tends to be lost when it is averaged

Table 1

"Star" (ref.)	$(B-V)^{\circ}$	ψ_o	Q (4520)	Q (4360)	Q (4040)	Q (3880)	S
(4620,-1.5,-2.7) (present)	0.90	0.98	0.12	0.30	0.43	0.66	0.267
(4590,-1.5,-2.2) (present)	0.915	1.02	0.10	0.33	0.45	0.76	0.280
M92, IV-10 (SZ)	0.935	1.02	0.14	0.23	0.46	0.92	0.28
(4470,-1.5,-1.4) (present)	1.01	1.07	0.14	0.34	0.59	1.10	0.38
M13, A1 (SZ)	1.02	1.07	0.16	0.37	0.61	1.31	0.39

with the other Q's to find S. The Lick scanner observations with resolution 12 Å, easily reveal the differences between HD 122563 and M92, IV-10 or IV-79 at and near H and K; these differences are suppressed at the 160 A resolution employed by SZ.

One may object in our treatment that the absolute magnitude of HD 122563 is unknown: it is true that we know directly only its abscissa in the HR diagram. Nevertheless, we are concerned with its spectrum only as an interpolation device to obtain the Q(λ)'s within a family of theoretical scanner fluxes; this interpolation will be valid if T_{eff} and log g for HD 122563 are close to those of the M92 stars (viz. 4590°, +1.5) used in the comparison. Now the BG-models show that (U-B) is quite sensitive to log g when $T_{eff} \sim 4500°K$ mostly because of the change in relative influence of Rayleigh scattering on the opacity. For M92 IV-79, $(U-B)^{\circ} = 0.40$ (Cathey 1974) whereas for HD 122563, $(U-B)^{\circ} = 0.38$; this difference corresponds to a change of less than 0.1 dex in log g, which is completely negligible.

As a further check on our conclusions, we calculate S in the same way for a star at $M_V = -1.15$ in a theoretical cluster having M13 abundances. We are concerned only with the difference Δ[Fe/H] between M92 and M13, although the [Fe/H]-value for M13 is somewhat controversial. We summarize in Table 2 the values of Δ[Fe/H] (sense M13 minus M92) given in the literature (Cohen, et al. found [Fe/H] = -2.4 for M92). We adopt Δ[Fe/H] = +0.8, although our conclusion would be little changed for a value as small as +0.6. From SG, we find that the Hayashi line moves to $T_{eff} = 4470°K$; the corresponding BG-model, with Lick scanner flux points, is shown in the bottom panel of Fig. 1; observational details are given in Table 1. The calculated value of S ($M_V = -1.15$) is 0.38. The S-values at $M_V = -1.15$ for the three abundances

Table 2

Method	Ref.	Δ[Fe/H]
Δs (RR Lyraes)	Butler (1975)	+1.1
Echelle, high res. spectro.	Cohen, et al. (1978) Cohen (1978)	+0.8
High res. spectro.	Wallerstein & Helfer (1966)	+0.7
DDO photometry	Hartwick, *et al*. (1977) Bell (1976)	+0.6
	Adopted	+0.8

(Fe/H) = -2.7, -2.2, -1.4) are shown in Fig. 2; except for a slight systematic displacement to the left, the points match the observed clusters well. We have carried out a similar set of calculations at M_V = +0.6. The fit to the "observed" curves is again good; the curve labelled (-2.7) is drawn between the two computed points. The extrapolation to higher luminosities is uncertain, since BG do not compute scanner fluxes for the combination (4000°K, 0.75, -3.0). Examination of their table of theoretical colors suggests, however, that the dashed curve might actually cross over the curve for [Fe/H] = -2.2 as M_V decreases, owing to the influence of Rayleigh scattering.

We conclude by commenting on the use, as an abundance parameter, of $(B-V)_{o,g}$, the unreddened color of the giant branch at its junction with the horizontal branch; this color is achieved near M_V = +0.6. It is well-known that $(B-V)_{o,g}$ is correlated with [Fe/H] in the range -2 < [Fe/H] < 0 (cf. Butler 1975b). But how sensitive is it to abundance changes near [Fe/H] = -2 and lower? $(B-V)_{o,g}$ for metal-poor clusters (Sandage, *et al*. (1977) ranges from 0.67 for NGC 5053 to 0.72 for M68 and M53 and equals 0.69 ± 0.02 for M92; the errors are estimated to range from ± 0.02 to ± 0.05 in the best determined cases. But as we have seen above, if we change our BG model from (5000, 2.25, -2.2) (for M92) to (5030, 2.25, -2.7) (for a fictitious cluster with metals reduced by 0.5 dex), $(B-V)_{o,g}$ changes from 0.71 to 0.685, i.e., $\Delta(B-V)_{o,g}$ = 0.025. Since $\Delta(B-V)_{o,g}$ is of the same order as the typical errors in $(B-V)_{o,g}$, it follows that the isolation of very metal-poor clusters by this technique is also somewhat problematical.

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DISCUSSION

Peimbert: 1. I agree that from your data there seems to be no abundance gradient in the halo perpendicular to the plane in the solar vicinity. What can be said about regions closer to the galactic center?

2. Can you comment on the state of CNO abundance determinations?

Kraft: 1. Rodgers found evidence for an abundance gradient in a small sample of RR Lyraes nearer the galactic nucleus. I do not remember now the numerical values, but they would need changing to judge by recent work of Bell and Manduca.

2. Bell, Deming, Laird, and myself have obtained high-dispersion (KPNO 4-M echelle) spectra of many field RR Lyrae stars near maximum light--a phase at which the temperature is high enough to permit analysis of atomic lines of the CNO group. The RR Lyraes studied cover the entire range 0 > [Fe/H] > -2. We have found that moderately substantial carbon over-deficiencies are the rules, and not the exception. Our oxygen analysis involves computation of non-LTE level populations for a model oxygen atom, and is not finished. Preliminary computations indicate slight oxygen *under*-deficiencies in the most iron-poor stars; results for the iron-rich stars should be available soon. Nitrogen abundances can be determined only for the most iron-rich RR Lyraes, and for those [N/H] $\sim$ 0.

Lesh: Do you find a difference in metal abundance between the RR Lyrae stars in globular clusters and those in the disk population, corresponding to the difference in helium abundance between these two groups that you have postulated on other grounds? Would you expect the difference in helium abundance to entail a difference in metal abundance?

Kraft: Yes, in the sense that halo RR Lyraes have [Fe/H] in the range -1 to -2 or so, whereas old disk RR Lyraes have [Fe/H] $\gtrsim$ -0.7. But this is *opposite* to the sense of my proposal that He in the disk RR Lyraes is actually *lower* than in the RR Lyraes of halo globular clusters. This is, of course, opposite to the generally accepted theoretical picture of chemical evolution in the Galaxy. But *direct* observational determinations of the He abundance are, of course, lacking.

Bok: How far out in z do you go with your RR Lyrae variables? If the RR Lyraes you have are well-mixed perpendicular to the galactic plane, then one would not expect differences in metal abundances for the group.

Kraft: The most distant stars are 25 or 30 kpc above the plane. The question is whether over such a large distance one expects complete mixing in [Fe/H]. Galactic collapse models suggest that a gradient should exist; the present work provides a direct observational test.

Butler: Regarding the question, "What do we do now?", I would like to return to Manduca and Bell, who have recently computed synthetic spectra for RR Lyrae stars, and have shown that synthetic ΔS values are in agreement with observed values for RR Lyrae stars of known calcium abundance. Because it is clear that we are in need of a metal abundance parameter which can be measured efficiently, and one which remains sensitive to abundance in extremely metal-poor G and K-giants, it would certainly be useful to experiment (computationally) with new ΔS-like parameters in which IR colors replace hydrogen lines in removing the temperature dependence of K-line strength. It is my guess that the K-line would remain measurable in a middle G-giant as metal-poor as [Ca/H] = -4.