DO HALO FIELD STARS AND GLOBULAR CLUSTERS BELONG TO THE SAME POPULATION?

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Obviously such transcendental issues as the helium content and age of the oldest stars depend on whether we are correct in our belief that the answer to this question is "yes." I hardly need say that over the past 40 years compelling affirmative arguments have been developed. Thus, for example, the solar motion of the common subdwarfs can be shown (e.g., Carney 1979) to be essentially identical with that of globular clusters (Kinman 1959) (Table 1), and the Fe-peak metallicities of giants and RR Lyraes in the halo field have been shown to be the same as those in clusters [see, e.g., recent reviews by Kraft (1979) and Freeman and Norris (1981)]. It is hard to believe that we would be incorrect in identifying the main sequence of a globular cluster with the main sequence defined by the trigonometric parallaxes, magnitudes and colors of subdwarfs having the same [Fe/H]. It might seem, therefore, that raising such an issue at this late date is equivalent to discussing a non-existent problem.

Table 1
Solar Motion

		Subdwarfs	Globular Clusters
$V(\mathrm{km\ s^{-1}})$		177 ± 12	168 ± 27
Apex	l	93° ± 5°	90° ± 8°
	b	0° ± 3°	−4° ± 8°

However, recent studies of NH, CH and CN band strengths in the spectra of old metal-poor stars have raised some disquieting notes. Thus in an extensive photometric study using DDO indices, the Victoria-CTIO group (Hesser, Hartwick and McClure 1976) found that, in comparing cluster and field giants of given Fe-peak metallicity, cluster giants showed a much wider variation of CN-band strengths than did field giants, when attention was confined to specific limited intervals of effective temperature and absolute magnitude. The study was necessarily limited

Richard M. West (ed.), Highlights of Astronomy, Vol. 6, 129–137.

https://doi.org/10.1017/S1539299600005049 Published online by Cambridge University Press

to clusters in the intermediately metal-poor (viz., ω Cen, M22) and "metal-rich" (viz., 47 Tuc, M71, NGC 6352) domains, since CN-bands become weak or vanishingly small in giants of the most metal-poor clusters (e.g., M92 and M15). Variations of CN strengths in ω Cen giants were perhaps to have been expected since [Fe/H] variations of more than 1 dex are known to exist in this cluster (Freeman and Rodgers 1977; Butler et al. 1978), but no Fe-peak variations are found in the other clusters, so the situation remains anomalous. Apparently some clusters in this metallicity domain exhibit a distribution of CN-strengths that is bimodal (Norris and Smith 1982); more about this later.

In giants of the most metal-poor domain, CN bands tend to disappear so that C and N abundances are better studied from the bands of CH (G-band) and NH (near λ3360). On the basis of their low resolution scanner spectra of extremely metal-poor giants, the Lick-KPNO group (Butler, Carbon, Kraft, Langer, Suntzeff, Trefzger) noticed quite early on (Carbon et al. 1977) that the NH-band strengths in some M92 giants greatly exceeded anything seen in the classical extremely metal-poor field giants that had been studied by Sneden (1974), viz., HD 2665, HD 2796, HD 6755, BD+52° 1601, HD 88609, HD 105546 and HD 122563: the matter is discussed in extenso by Carbon et al. (1982). An example of the kind of thing seen in the region of the NH bands is illustrated in Figure 1. The stars shown have the same [Fe/H]; M92, II-6 and IV-87 are subgiant branch stars with the same luminosity and temperature, but HD 2665 is about one-half magnitude brighter and 100°K cooler than the two M92 stars. (These changes have almost no effect on NH band strengths.)

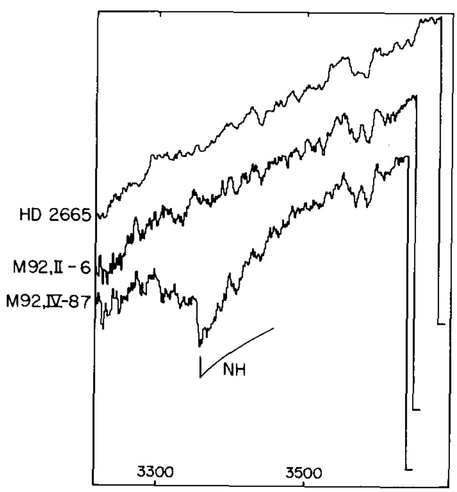

Figure 1. The region of the NH feature in the spectra of three metal-poor giants having [Fe/H] = -2.2. Vertical bars correspond to unit flux in the continuum near λ3600.

https://doi.org/10.1017/S1539299600005049 Published online by Cambridge University Press

Yet M92, IV-87 has a nitrogen abundance exceeding that in the other two stars by a factor of at least 10. Several other M92 subgiants have similarly strong NH bands. What is the origin of these extraordinary variations, and what significance does it have in terms of the question posed in the title of this talk?

Although it is quite likely the CN variations seen in the more metal-rich stars are driven by the same mechanism that is responsible for the NH and CH variations seen in the most metal-poor stars (Hesser 1982; Kraft et al. 1982), we shall not discuss all these halo populations together, but instead focus our attentions on the most metal-poor stars ([Fe/H] $\lesssim$ -1.4). In so doing, we avoid the (for our purposes) somewhat irrelevant current controversy over the [Fe/H] abundance scale at the high metallicity end of the globular cluster domain. At the same time, we take advantage of a Lick-KPNO C- and N-abundance survey of nearly 200 very metal-poor globular cluster and halo field giants. Although CN and CH strengths have been reliably measured on the DDO system for many globular cluster and halo field giants, an extensive catalog of C- and N-abundance determinations based on this material is not yet available.

From the Lick-KPNO survey C- and N-abundances, based on spectrum synthesis of CH and NH features, are available for nearly 120 giants in the classical metal-poor clusters M3, M13 (Suntzeff 1981), M15 (Trefzger et al. 1983) and M92 (Carbon et al. 1982). Fe-peak metallicities [Fe/H] and galactocentric distances R for these clusters are given in Table 2. Separation into Groups I and II retains the distinction associated with the RR Lyraes (Oosterhoff 1939), which also segregates the clusters by metallicity. The survey has also led to the derivation of C- and N-abundances for 64 halo field giants selected from Bond's (1980) objective prism survey. The mean galactocentric distance of the Bond sample is obviously only slightly smaller than that of the clusters, and the metallicity range is comparable ([Fe/H] $\lesssim$ -1.4).

Table 2
Metallicities and Galactocentric Distances
of the "Classical" Metal-Poor Clusters

	Cluster	[Fe/H]	R (kpc)
Group I	M3	-1.6	12.4
	M13	-1.6	9.1
Group II	M15	-2.1	10.3
	M92	-2.2	10.0

It is important to note that the cluster and field stars were observed with the same spectrographic equipment and were analyzed with the same abundance methodology; thus systematic abundance differences between cluster and field stars have been reduced to a minimum.

Turning first to the four clusters, we find that the abundances behave in a curious way. Our expectations, based on classical giant branch evolution (cf. Iben 1974) involving C $\rightarrow$ N processing and convective mixing, is that carbon should be modestly depleted and nitrogen modestly enhanced as evolutionary state advances. In one cluster (M3), these expectations are more-or-less fulfilled, but in the other clusters, the situation is much more complex. We summarize the results as follows:

1. In all clusters, there exist variations in [C/Fe] and [N/Fe] at any given point of the HR diagram. The smallest variations are found in M3.

2. In all clusters, <[C/Fe]> declines with advancing evolutionary state. In M13, M15, and M92 the depletion is considerably larger than is predicted by classical evolutionary theory.

3. In M3, <[N/Fe]> increases when <[C/Fe]> decreases, as expected. However, in the other clusters, <[N/Fe]> shows no measurable change (!).

4. In M15 and M92, some 25 percent of the stars have [N/Fe] $\gtrsim$ +1.0, and many stars in M13 also have rather high nitrogen abundances. These numbers are often higher than can be accounted for even if all the expected C were processed through to N.

These results, particularly (3) and (4), are puzzling and may imply the existence both of primordial overabundances as well as primordial variations in C and N and/or mixing by nonconventional mechanisms (cf. Suntzeff 1981; Carbon et al. 1982). Whatever these processes may be, of more immediate concern here is the result that clusters can be quite singular in their C- and N-abundance characteristics, even at the same [Fe/H]. This naturally leads to an inquiry concerning the C- and N-abundances in halo field giants having similar values of [Fe/H]. Would we expect to find that the distributions of [C/Fe] and [N/Fe] for these stars are some kind of ensemble average taken over the distributions in the clusters? Or would we find that the halo field stars imitate some cluster(s) and not others?

The matter was considered by Kraft et al. (1982) as part of the Lick-KPNO survey of 64 field giants (Bond 1980) mentioned earlier. Space limitations do not permit an extensive discussion of the details here, but the leading conclusions can be quoted. The samples in both the clusters and the halo field were limited to those stars hot enough (T_{eff} > 4500°K) that the influence of CO-formation on the derived carbon abundance could be ignored. Thus 54 field giants and about 115 cluster giants remained in the sample. The cluster stars were divided into Groups I and II according to whether [Fe/H] $\geq$ -2.0 or [Fe/H] < -2.0,

https://doi.org/10.1017/S1539299600005049 Published online by Cambridge University Press

respectively. Group I field star C- and N-abundance distributions are compared with Group I clusters (M3 and M13) in Figure 2; Group II field and cluster stars are compared in Figure 3.

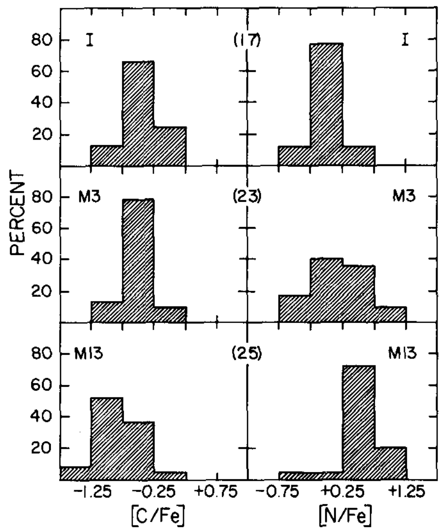

Figure 2. The distributions of [C/Fe] and [N/Fe] for giants of Group I, M3, and M13.

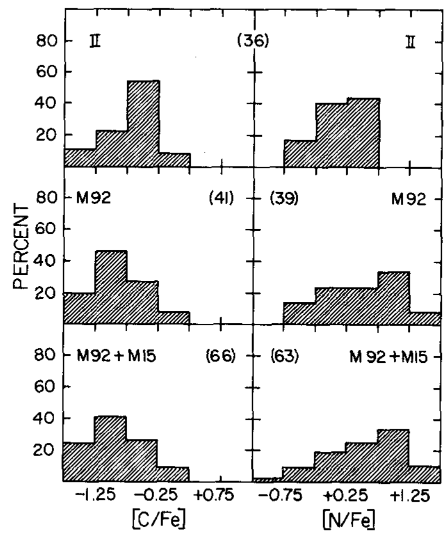

Figure 3. The distributions of [C/H] and [N/Fe] for giants in Group II, M92, and M92 and M15 taken together.

Inspection of the figures reveals the whole story. The Group I field giants show only modest C-depletions and N-enhancements, the distribution functions imitating M3 rather than M13. The Group II field giants also exhibit only modest C-depletions and N-enhancements; with regard to the C- and N-abundance distributions, the sample of Group II giants does not give the impression that it is drawn from the same parent population as the sample of stars observed in M15 and M92. Many M15 and M92 giants show much larger nitrogen enhancements and carbon depletions than do Group II field giants. For example, some 40% of M15 and M92 stars, 25 in all, have [N/Fe] > +0.75; the number of field stars with nitrogen abundance exceeding this value is zero. That these population differences are statistically real is supported at a high level of significance by appropriate statistical tests (cf. Kraft et al. 1982).

One naturally supposes at first that these differences are illusory -- perhaps they result from a flaw in the sampling procedure. For example, one might imagine that the cluster stars are simply in a more advanced evolutionary state than the field stars -- i.e., the

https://doi.org/10.1017/S1539299600005049 Published online by Cambridge University Press

former are, on the average, a little more luminous than the latter. It is easy to show, however, that since the field stars are sampled to a limiting apparent magnitude, they are, if anything, on the average more luminous than the cluster stars (Malmquist effect). Thus there is no very easy way around the conclusion that seems obvious, viz., that the most metal-poor solar vicinity halo giants are not representative of many of the giants seen in clusters such as M13, M15, and M92, this despite the fact that the halo giants and the clusters have similar metallicities and galactocentric distances. On the other hand, the distribution of C- and N-abundances seen in the field halo giants mimics quite closely what is found in M3 giants. Now it is interesting that, in a comparison of field subdwarfs with cluster main sequence stars, Carney (1982) was able to find an internally self-consistent picture of age, helium abundance and c-m diagram morphology only in the case of M3, but not in the case of M15, M92 and M13. If, then, the halo stars of the solar vicinity are to be regarded as sharing the fundamental properties of an M3-like population, can we exploit this identification in such a way as to improve our understanding of the origin of the local field halo stars? Possibly. But first, we must examine, on the basis of stellar evolutionary theory, ways in which the distributions of C- and N-abundances might differ between giants of M13, M15 and M92, on the one hand, and M3 and the field giants on the other.

Since M3 is a well-known "second parameter" cluster, i.e., since M3 has a red horizontal branch (HB) compared with M13 (which has the same [Fe/H]), one can inquire whether the physical mechanism that drives the second parameter effect also drives the difference in the C- and N-abundance distributions. It is clear that the second parameter effect cannot be driven directly by the CNO abundances themselves, as had once been thought (Hartwick and McClure 1972; Pilachowski et al. 1980) since Suntzeff (1981) has shown that the total C + N + O abundance in M3 is virtually the same as in M13. But following a calculation by Renzini (1977), Suntzeff (1981) and Norris (1981) independently suggested that internal stellar rotation could drive the second parameter effect. This follows from the rotationally-induced delay in the onset of the helium core flash as a star makes its first ascent of the red giant branch: rotation reduces the ratio of total mass to core mass at helium ignition and, as is well-known (Faulkner 1966), the resulting post-flash HB star takes up a position on the HB at a larger T_{eff} than is "normal." If then additional envelope mixing is also induced by higher stellar rotation (Sweigart and Mengel 1979), one would expect blue HB clusters such as M13, M15 and M92 to contain giants with more C-depletion and N-enchancement than one finds in red HB clusters such as M3, and presumably, if our earlier identification is correct, in the field giants as well. If significant envelope mixing is associated with some limiting value of stellar angular momentum, one might not be surprised to find clusters with bimodal CN strengths among giants; such clusters also have a (presumably) related bimodal distribution of HB population (Norris and Smith 1982).

Further evidence in support of the proposition that red HB's are to be associated with clusters in which the giants have modest C-depletions and N-enhancements is found in a recent study of giants in the classical second parameter clusters Pal 13 and NGC 7006 (Friel et al. 1983); in the case of NGC 7006, these results are in substantial agreement with the findings of Cohen and Frogel (1982), based on infrared magnitudes and colors. Thus it would seem that stellar rotation provides a mechanism which explains both the second parameter effect and the observed C- and N-abundance distributions. Since only rather modest amounts of additional angular momentum seem required, the rotational velocities needed are either below current levels of detection or else are confined to inaccessible internal regions of the stars. Thus rotation provides us with a serviceable deus ex machina, one that is conveniently (?) hidden from view.

It becomes, however, less convincing as a mechanism when we realize that the second parameter effect has a global characteristic. Some years ago, van den Bergh (1967) pointed out that clusters with red horizontal branches preferentially preferred the outer regions of the galaxy -- indeed Pal 13 and NGC 7006 are examples of such remote clusters. Since it is not so easy to understand how outer halo cluster giants "know" enough to rotate slowly simply on the basis of their location in the galaxy, one could well prefer a solution based, for example, on age (Searle and Zinn 1978). However, the possible relationship of the second parameter to C- and N-abundance distributions has only recently surfaced and could lead to somewhat different scenarios. For example, an idea put forward by Suntzeff (1982), a variation of the "clusters as survivors"-hypothesis of Fall and Rees (1977), has some attractive possibilities. In this picture, one imagines that the primordial (low-metallicity) clusters, in their relationship to gravitational encounters with the galaxy were of two kinds: loosely and tightly bound. In the latter, of which M13, M92, and M15 are surviving examples, the low mass stars we presently see as giants were contaminated with fresh triple-α carbon ejected from dying 3-10 $M_\odot$ cluster stars (Renzini and Voli 1981). Small initial enrichment of C would take place, with the result that after undergoing normal evolution as giants, these stars would show more spectacular overabundances of N. Such small initial enrichments of C do not violate the observed abundances of C (vis-a-vis N and O) in M13, M15, and M92 compared with M3; moreover, one finds that, using any reasonable stellar luminosity function, the amount of triple-α carbon produced and expelled from dying cluster stars is substantially more than is required.

Continuing with the picture, one hypothesizes that the stars of the loosely bound clusters, because of low stellar density, underwent little carbon contamination. The loose clusters dissolved and became the halo field stars we now see. Implicit in this picture is the view that the system of halo field stars is the relic of early clusters that must have contained about 100 times the mass of the present globular cluster system; moreover the outer halo clusters with red HB's presumably failed to dissolve because they had suffered few gravitational encounters with the galaxy. Consistent with the picture is the fact that M3, an inner halo second parameter cluster, survives as a cluster: if the tidal radius argument of Peterson (1974) is correct, M3 is virtually the only cluster pursuing a circular galactic orbit.

The Suntzeff scenario is described in more detail in Kraft et al. (1982) and attractively relates the C- and N-abundance distribution problem to the broader issues implicit in the formation of the galactic halo. It does not directly explain, however, why there is more mixing in stars with (slightly) enhanced carbon abundances and why such clusters should have blue HB's. Perhaps the enhanced carbon itself induces more mixing: even so, one seems to need an additional parameter such as age to distinguish loosely and tightly bound clusters. Finally, it is not clear why M3 itself did not undergo carbon contamination. Although it is true that M3 is not (at present) very dense compared with clusters such as M92 and M15 (cf. the compilation by Madore 1980), it is also true that M3 has almost the same density as M13, its second parameter counterpart.

We began this discussion by asking if globular cluster and halo field stars were essentially members of the same stellar population. We have seen that the distributions of C- and N-abundances in metal-poor giants are not the same in detail: the population of halo giants in the solar vicinity does not include some of the kinds of giants found in at least some well-known clusters of comparable metallicity. This probably has little or no effect on classical methods for determining the ages of the oldest stars. It turns out instead that these differences provide, rather unexpectedly, new clues to the understanding of the complex dynamical and chemical history of the galactic halo.

I am indebted to Jim Hesser and Nick Suntzeff for valuable conversations. This work was supported by NSF Contract AST 80-19431.

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