GLOBULAR CLUSTERS AND FIELD HALO STARS

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ABSTRACT. Recent work on the chemistry and kinematics of the field halo population stars is reviewed, including the metallicity distribution function, elemental abundance patterns, primordial abundances, and their relations with stellar kinematics. The important role played by these stars in determining the ages of the globular clusters is discussed. A comparison is made between the kinematic and chemical properties of the field and cluster stars to ascertain if they share a common history.

1. INTRODUCTION

Zinn and West (1984) list 34 globular clusters beyond the solar galactocentric distance but inside 25 kpc. Summing their integrated absolute magnitudes and upon adopting $M/L = 1.7\ M_\odot/L_\odot$, appropriate for both high- and low-concentration clusters (Illingworth 1976; Peterson and Latham 1986), we find the "local" plus "outer" halo clusters total about $10^7\ M_\odot$. If we integrate the Bahcall and Soneira (1984) model for the spheroid number density from 7 to 25 kpc, and assume a median stellar mass of $0.3\ M_\odot$, we find $1.7 \times 10^9\ M_\odot$ of field halo stars. They thus outnumber the cluster population by over 100 to 1, and (probably) have a much larger ratio in the number of independent origins sampled. The consequent proximity of the field stars has made them invaluable in the study of the more distant globular clusters and the stars they contain, and for the questions we hope the halo population can answer.

2. PROSPECTING FOR FIELD HALO STARS

Clusters are (usually) easy to recognize, but the more numerous field stars are hard to identify amidst the sea of field disk stars. They are distinguishable generally by low metallicities, high velocities, or both (see Sandage 1986a for the fascinating history). Norris (1986) has compiled from the literature a list of about 1200 objects with [Fe/H] < -0.6, and which have been identified without any kinematical biases. Complementing his work are the two recent studies of Lowell Proper Motion Catalogue stars, the first by Sandage (Sandage and Kowal 1986; Fouts and Sandage 1986; Sandage 1986b), and the second by Carney and Latham (1986c; hereafter CL). These surveys have strong

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kinematic biases but no metallicity biases. Together, they contain almost 1500 stars with $\mu \geq 0''.26$ yr^{-1}. Stock (1984, 1985) has identified high velocity stars independently of metallicity using objective prism radial velocities, but there has been little follow-up work.

3. AGES

Theory and observations of clusters yield age estimates for the halo population. Despite major successes (*c.f.*, VandenBerg, this meeting), more definitive results for the ages of the oldest stars and the relations between age, metallicity, and galactocentric distance will rely on improvements in the cluster distance scale. With accurate distances, we can rely only on the main sequence turn-off luminosity, not the convection-sensitive temperatures used in matching isochrones to color-magnitude diagrams. The otherwise unobservable helium abundance could then be inferred from the horizontal branch luminosity (§4.3).

Distances to clusters are currently estimated using isochrones (although the use of the surface temperatures as an extra parameter is undesirable), or "standard candles", which are calibrated using the nearer field stars. Assuming for the moment that field and cluster stars share common histories (see §6), there are three classes of standard candles. First, main sequence fitting has been utilized, with the calibration accomplished using the seven field stars with accurate trigonometric parallaxes ($\sigma_\pi/\pi < 0.2$), following Sandage (1970), Carney (1979, 1980), and Richer and Fahlman (1984), or by using larger samples of field stars and a statistical parallax (Carney 1979). HIPPARCOS and the Hubble Space Telescope will greatly improve the π_{trig} calibration, while the CL survey will soon provide a much-improved π_{stat} re-determination.

Second, RR Lyrae variables are valuable, for they are relatively bright and do not differ greatly in absolute magnitude. The goal, however, is to determine M_V to within $\pm 0^m.1$, and test whether M_V varies with metallicity. Currently, statistical parallax results (Strugnell, Reid, and Murray 1986; Hawley *et al.* 1986; Barnes and Hawley 1986) show $M_V \sim +0^m.80 \pm 0^m.15$, with no metallicity dependence, when reddening is treated in a consistent fashion. The lack of a relation between M_V and [Fe/H] does not agree with the cluster work of Sandage (1982) and his interpretation of the period-luminosity-amplitude relation he discovered. Baade-Wesselink analyses of field stars (*c.f.*, Burki and Meylan 1986; Jones *et al.* 1986, 1987) similarly do not show any strong M_V-[Fe/H] dependence, and, based on the work of Jones *et al.* (1986, 1987), $\langle M_V(RR)\rangle$ is probably close to $+0^m.90$. Such a faint absolute magnitude suggests even greater ages for the clusters than derived heretofore, and the lack of a metallicity dependence also implies a relation between cluster metallicity and age, with the more metal-rich clusters being much younger. These results, if correct, pose interesting tests for stellar evolution theory.

Third, a cluster white dwarf locus, if it can be well delineated by HST, will give us a composition-insensitive means to derive a distance. Once again, however, halo field white dwarfs must be used to calibrate the M_V *vs.* color index relations, lest we repeat Shapley's mistake in applying disk Cepheid absolute magnitudes to the Cepheids in globular clusters. Such work is underway.

In the future, cluster distances may yet be obtained directly, using the Baade-Wesselink method for the cluster variables, by comparing the internal cluster radial velocity and proper motion dispersions (*e.g.*, Cudworth and Peterson, this meeting), or even by direct trigonometric parallaxes using proposed space-based interferometers, which could in principle yield accurate results down to parallaxes of 5 to 10 microarcseconds.

4. CHEMICAL ABUNDANCES

4.1 The Metallicity Distribution Function

The metallicity distribution function, $\phi(Z)$, measures the history of the halo's chemical enrichment and the processing of gas through stars, and which may be compared with the predictions of models of galactic evolution, such as those of Hartwick (1976) and Searle (1979). Agreement was considered to generally be good, but Bond (1981) argued that while the observed $\phi(Z)$ agrees with the models at intermediate and higher metallicities, there is a significant lack of very low metallicity stars and clusters. He suggested that the halo population (or the low-mass part of it we can still sample at this epoch) began with a "basement" metallicity of [Fe/H] ~ -2.6. This is not consistent with Big Bang predictions unless the lower mass stars took longer to form than the stars of "Population III". Hartwick (1983) reanalyzed the cluster and field $\phi(Z)$ and concluded the data agreed with the models. Recently, Beers, Preston, and Shectman (1985; 1986) reported some results of their searches for extremely low metallicity stars. They have found several stars with [Fe/H] apparently between -3.0 and -4.0, and so have argued that the results agree well with simple models that predict dN/dZ ~ constant. The survey was biased against more metal-rich stars (they claim completeness below about [Fe/H] = -1.5), but as Howard Bond has pointed out, comparisons of their results with model predictions depend upon an accurate placement of this upper metallicity limit, beyond which their results are biased.

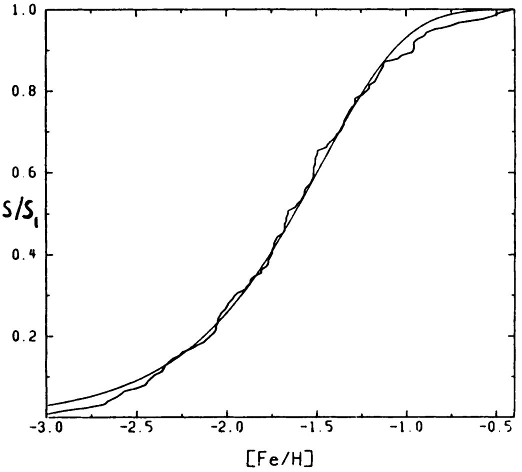

Fig. 1. The cumulative metallicity distribution function S/S_1 *vs.* [Fe/H] for a simple one-zone model with mean [Fe/H] = -1.5 (smooth curve), and CL stars $V < -220$ km sec^{-1}.

Basically, large samples are required to test the models, for if dN/dZ is constant, we expect stars with [Fe/H] = -4 to be 100 times less abundant than stars with [Fe/H] = -2. The CL survey is one such step, for it is large (almost 400 stars with [M/H] < -1), has no metallicity bias, and the metallicities are well determined since they are obtained from high-resolution (although low S/N) spectra. Figure 1 shows a comparison of the cumulative metallicity distribution function, S/S_1 (Hartwick 1976), for a simple model with [M/H] = -1.5, and a subset of CL stars (those with $V < -220$ km sec^{-1} = retrograde orbits) which are kinematically selected to be halo stars, done in collaboration with John Laird and Michael Rupen. Agreement is very good, which implies that simple one-zone models explain satisfactorily the chemical evolution of the bulk of the halo population.

4.2 Abundance Patterns

The proximity of the halo's field stars allows us to conduct high-S/N, high-resolution, spectroscopic studies of elemental abundance patterns. The larger number of available halo stars also means we may study lower metallicity objects than found in clusters. For example, clusters have [Fe/H] $\gtrsim$ -2.4, whereas the field stars extend to [Fe/H] ~ -4.0 (Carney and Peterson 1981; Bessell and Norris 1984; Peterson, Kurucz, and Carney 1986). Results for a sample of three dozen field red giants have been published by Luck and Bond (1985), and for field dwarfs by Peterson (1981), Magain (1985), and Francois (1986). Of course, there are many other studies involving smaller samples. Lambert (1986) has excellently reviewed the behavior of the light elements Na through Ca. Sneden (1986) has reviewed CNO abundances, while Spite and Spite (1985) have reviewed all known abundance results for halo stars, with the results divided into families of elements and production processes. The α-nuclei (Mg, Ca, Si) rise relative to iron as [Fe/H] declines from -0.2 to about -1.2, then level off down to -2.0. At extremely low metallicities, [α/Fe] may again rise as [Fe/H] declines. C, N, and O do not show equivalent behavior, which suggests they have different production sites and a time-variable rate of the importance of these sites. Briefly, [O/Fe] behaves like the α nuclei, while [N/Fe] is roughly constant (although the data are sparse at the lowest metallicities). [N/Fe] is abnormally high, however, in at least four cases (~ 5% of the sample), probably due to mass transfer or patchiness in the galactic nucleosynthesis processes (Bessell and Norris 1982; Laird 1985; Spite and Spite 1986). [C/Fe] ~ 0.0 down to [Fe/H] ~ -1.8, below which it appears to rise (Tomkin, Sneden, and Lambert 1985), perhaps due to an increasing contribution of explosive nucelosynthesis at the earliest epochs. Other signatures of explosive nucleosynthesis have been claimed in the "odd-even" [Al/Mg] vs. [Mg/H] results of Peterson (1981; but see also Arpigny and Magain 1983) and the very careful magnesium isotope abundance work of Tomkin and Lambert (1980) on HD 103095, and Lambert and McWilliam (1986) on ν Indi. The "odd-even' effect may also show breaks at [Fe/H] ~ -1.2 and -2.0 (Lambert 1986). A related but rather remarkable result for [Ni/Fe] has been claimed by Luck and Bond (1983, 1985). They found it, like [C/Fe], to be roughly solar until [Fe/H] ~ -2.0, below which it rises. The result remains disputed, however (Sneden and Parthsarathy 1983; Leep and Wallerstein 1981; Barbuy, Spite, and Spite 1985; Magain 1985; Peterson, Kurucz, and Carney 1986).

Based on very high S/N spectra of two very metal-poor field giants, Sneden and Parthsarathy (1983) and Sneden and Pilachowski (1985) found s-process elements deficient with respect to iron, as expected, but that the r-process elements-to-iron ratio is variable, perhaps suggesting the importance of "local" supernovae in the enrichment processes. This is reminiscent of the implications of the [N/Fe] variations. It would be very interesting to extend such work to more stars. With lower S/N, but a much larger sample, Luck and Bond (1985) have confirmed that [s-process/Fe] declines with [Fe/H], but only for [Fe/H] $\lesssim -1.5$.

In summary, there appears to have been a change in the nucleosynthesis patterns (including C, s-process, and possibly α-nuclei, oxygen, and Ni) that sets in at the epoch when [Fe/H] had risen to about -2.0, and then again (α-nuclei, oxygen, "odd-even" balance) at about -1.2, due to, perhaps, a change in the initial mass function (which governs the frequency of Type II supernovae) or the first appearance of Type I supernovae. The continued declining behavior of [O/Fe] and [α/Fe] as [Fe/H] rises until old disk metallicities are reached at [Fe/H] ~ -0.2 also suggests a change in the supernovae type, or, perhaps, relative rates, when the disk formed. More work should be undertaken, directed especially at the lowest metallicity stars to probe the earliest phases of nucleosynthesis and at the halo/disk transition, and at stars with extreme kinematical properties as a means of studying the history of nucleosynthesis throughout the Galaxy.

4.3 Primordial Abundances

Roger Cayrel will review later in this meeting the primordial abundances of the halo population, as determined almost entirely from spectroscopic studies of low metallicity field stars.

Perhaps the most impressive results have been those of the Spites (*c.f.*, Spite and Spite 1986 and references therein), who have measured lithium abundances in halo stars. Standard hot Big Bang models predict such low lithium abundances only if $\Omega \ll 1$.

Helium is an extremely important element, both for cosmology and age-dating of clusters, but it is very difficult to measure. The only direct measurements are for the planetary nebula K648 in the cluster M15 (Hawley and Miller 1978; Adams *et al.* 1984), and the three field halo planetaries 49+88°1 and 108-76°1 (Hawley and Miller 1978) and 61+41°1 (Barker and Cudworth 1984), all of which show normal helium abundances (*i.e.*, disk-like Y ~ 0.3) for these heavily-evolved objects. Indirect methods must be used for less-evolved stars. These rely on accurate luminosity determinations and stellar evolution theory. Zero-age horizontal-branch luminosities are functions primarily of the core mass and Y. Although M_{core} may be estimated via turn-off masses and mass-loss, ZAHB luminosities are not yet well enough determined (§3). On the other hand, main sequence luminosities are also affected by M, Y, Z, and age. Thus spectroscopy to determine Z and distance measures of lower-mass (*i.e.*, unevolved) stars can be utilized to estimate Y, if the masses are known. Although μ Cas has received much attention (Lippincott 1981; McCarthy 1984; Russell and Gatewood 1984; Pierce and Lavery 1985), it is an old disk star. CM Dra (Lacy 1977; Paczyński and Sienkiewicz 1984) is a much better candidate. Still, the derived helium abundances remain imprecise. By introducing another variable, T_{eff}, Y may be estimated by comparing field star L-T_{eff} data with model isochrones. While results are plausible ($Y = 0.23 \pm 0.04$ for $[O/Fe] = +0.6$: Carney 1979), use of T_{eff} introduces uncertainties that may be difficult to resolve. Halo star mass determinations thus remain an important goal, and field stars are the only possible sources. The CL survey has discovered a dozen metal-poor double-lined spectroscopic binaries, and perhaps one of them may yet prove useful for such mass determinations.

5. KINEMATICS

5.1 Θ_o

To determine space velocities in the Galaxy's non-rotating frame, we must remove the contributions to the perceived motions due to the solar peculiar velocity and especially that of the Local Standard of Rest's circular velocity, Θ_o. Gunn, Knapp, and Tremaine (1979) used 21 cm data to estimate $\Theta_o = 220$ km sec^{-1}. If this is approximately correct, stars near the Sun but with velocities of this order directed perpendicular to the LSR apex define a kinematically-selected non-rotating ensemble, which may also be used to estimate Θ_o. The CL survey includes 149 such stars, all of which are metal-poor, with a mean V velocity of -222 ± 8 km sec^{-1}. We will therefore adopt $\Theta_o = 220$ km sec^{-1}.

5.2 Kinematics *vs.* Metallicity

Eggen, Lynden-Bell, and Sandage (1962; hereafter ELS) pioneered such studies, finding clear trends between metallicity (inferred from the normalized ultraviolet excess, $\delta(U-B)_{0.6}$) and orbital eccentricity (projected onto the plane), as well as orbital angular momentum and the W velocity (*i.e.*, perpendicular to the disk). They concluded that the Galaxy's collapse and early metal-enrichment were very rapid, comparable to a free-fall or orbital timescale (few x 10^8 years). With the recent completion of major new surveys (Norris 1986; Sandage 1986; CL), the relationships between kinematics and metallicity may be re-addressed.

The fundamental ELS result, that projected orbital eccentricity, e, correlates with metallicity, has been challenged by Norris, Bessell, and Pickels (1984) and Norris (1986), who utilized kinematically unbiased surveys and found 15% to 20% of the metal-poor stars had $e < 0.4$. ELS found 0%. Sandage's (1986) new results, like those of ELS, rely on a kinematically-selected sample, again do not show a substantial number of low-eccentricity, low-metallicity stars, although the result is not zero, either. On the other hand, the similarly defined CL sample confirms Norris's result. Figure 2 shows their results as a plot of spectrocopically-derived metallicity *vs.* a three-dimensional orbital eccentricity, which was computed by Luis Aguilar by numerically integrating the U, V, and W velocities in a Bahcall and Soneira (1984) model Galactic potential. Two basic populations are seen, but the large range in eccentricities shown by the metal-poor dwarfs argues for a halo

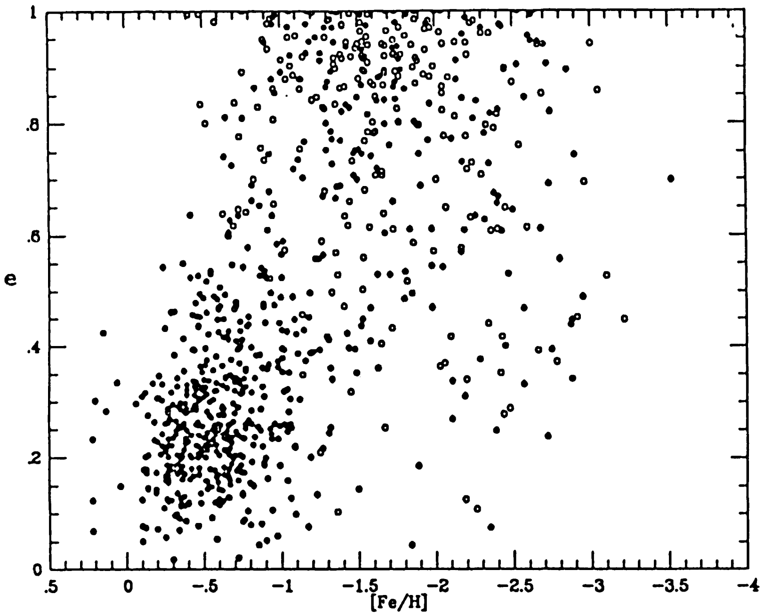

Fig. 2. The three-dimensional orbital eccentricity *vs.* spectroscopic [Fe/H] for stars in the CL survey.

formation and evolution timescale much longer than that espoused by ELS.

One may also compare the behavior of the mean U, V, and W velocities with mean metallicity. For brevity, we focus here upon only the second, as manifested by the mean rotational velocity, $<v_{rot}> = \Theta_o - <V>$, and compare it to metallicity. In Figure 3 we show the results of Norris (1986), Carney and Latham (1986a: 174 kinematically unbiased metal-poor red giants), Sandage (1986), and the CL survey. Although Sandage (1986) has argued that the metal-poor stars show a monotonic change of v_{rot} *vs.* [Fe/H], the figure suggests instead that a major change occurred when [Fe/H] had risen to about -1.4. It is provocative that this is also the time when the α nuclei, oxygen, the odd-even effect, and perhaps even the s-process element abundances relative to iron underwent a major change.

5.3 Kinematics *vs.* Distance

Field stars and clusters are excellent test particles with which to probe the Galaxy's mass distribution, using either velocity dispersions (*i.e.*, the velocity ellipsoid) or the total space velocity in the non-rotating rest-frame, $v_{RF} = [U^2 + (V + \Theta_o)^2 + W^2]^{\frac{1}{2}}$.

Velocity dispersions must be computed using kinematically unbiased samples. The local velocity ellipsoid for metal-poor stars has been derived by Norris (1986) using many data sources. He finds $\sigma_U = 131 \pm 6$,

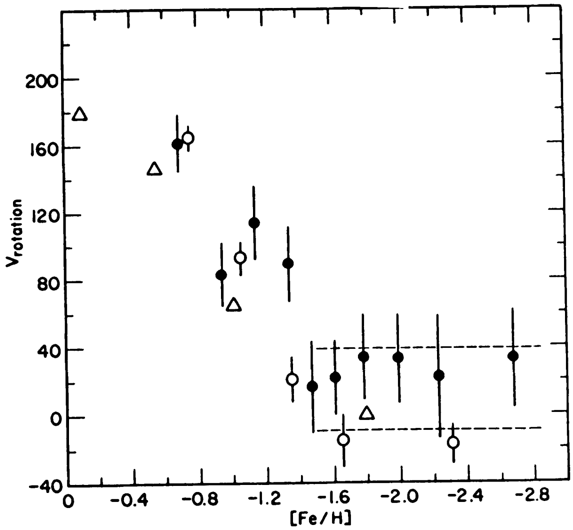

Fig. 3. The average rotational velocity binned in metallicity, with data taken from CL (o); Norris 1986 (o); Sandage 1986 (Δ); and Carney and Latham 1986a (dashed lines border the result for a sample of metal-poor red giants).

σ_V = 106 ± 6, and σ_W = 85 ± 4 km sec^{-1} (not including the red giant results of Carney and Latham 1986a, who found σ_R = 154 ± 18, σ_θ = 102 ± 27, and σ_Φ = 107 ± 15 km sec^{-1}). The local halo velocity ellipsoid is thus anisotropic.

There is a dispute as to how the halo velocity dispersion varies with distance. Ratnatunga and Freeman (1985) studied distant metal-poor giants and found a low velocity dispersion, 60 ± 8 km sec^{-1} toward the South Galactic Pole at a mean distance of 14 kpc. Norris (1986) discussed the problem, and his results showed that the velocity ellipsoid changes at large distances, but that the changes may be related to Galactocentric distance rather than height above/below the plane. Thus spherical polar rather than cyclindrical polar coordinates (as suggested by Ratnatunga and Freeman) are the natural frame. Further, the radial velocity studies of nearby and distant blue horizontal branch (*i.e.*, metal-poor) stars disagreed with the Ratnatunga and Freeman results (Pier 1984; Sommer-Larsen and Christensen 1985), although they supported the decline in the velocity dispersion with increasing Galactocentric distance.

Radial velocities of distant clusters (Hartwick and Sargent 1978; Lynden-Bell, Cannon, and Godwin 1983; Olszewski, Peterson, and Aaronson 1986) may be used to estimate the Galaxy's mass distribution, M(r), although assumptions must be made about the clusters' orbital shapes and the sample is small. By applying the local velocity ellipsoid to the outer halo clusters, Norris (1986) concluded M(r) ~ 3 x 10^{11} $M_\odot$ at r =

35 kpc, or about four times that contained within the LSR orbit.

Individual objects' rest frame velocities may also be used to set lower limits to the Galaxy's total mass, assuming they are bound to the Galaxy. If R15 (Hawkins 1983) proves to be an RR Lyrae at R_{GC} = 59 kpc with v_{rad} = -465 km sec^{-1}, the Galaxy's total mass must exceed 1.4 ± 0.2 x 10^{12} M_o. Carney and Latham (1986b) estimate the local value of the Galactic escape velocity to be $\geq$ 500 (and may exceed 550) km sec^{-1}, in which case (for θ_o = 220 km sec^{-1}) the Galaxy's total mass exceeds that within the LSR orbit by a factor of 5 (or 8).

6. DO CLUSTERS AND FIELD STARS SHARE A COMMON HISTORY?

One expects or hopes for an affirmative answer to this question, since much of our understanding of the Galactic halo and its history depends on the study of clusters, which we have seen comprise only a very small fraction of the total halo contents.

The age(s) of the field stars cannot be determined accurately, but differences of the order of 30% can be ruled out. Figure 1 of Sandage (1983) and Figure 5 of Sandage and Kowal (1986) shows the blue limit of local high ultraviolet excess (*i.e.*, metal-poor) proper motion stars resembles that of the turn-offs of comparably low-metallicity globular clusters ($B-V \leq 0\overset{m}{.}4$, $U-B \sim -0\overset{m}{.}2$). Figure 3 of Sandage (1983) shows a *V vs. B-V* diagram for SA 45, and that the blue limit again occurs at about $B-V \sim 0\overset{m}{.}35 - 0\overset{m}{.}40$.

The metallicity distributions of the field and the clusters differ somewhat. In Figure 4 we show S/S_1 *vs.* [Fe/H] for the field halo dwarfs of CL (with V < -220 km sec^{-1}) and the globulars beyond the solar orbit, with clusters' metallicities taken from Zinn (1985). The field contains more metal-poor stars as well as more metal-rich stars than the clusters, which implies that $\phi(Z)$ is broader for the former. A Kolmogorov-Smirnov test indicates an 81% chance that there are two different populations, which is suggestive, although not completely convincing. The metallicity scales have not been derived by exactly the same means. Peterson, Kurucz, and Carney (1986) have also suggested a possible downward revision in [Fe/H] for the lowest metallicity clusters.

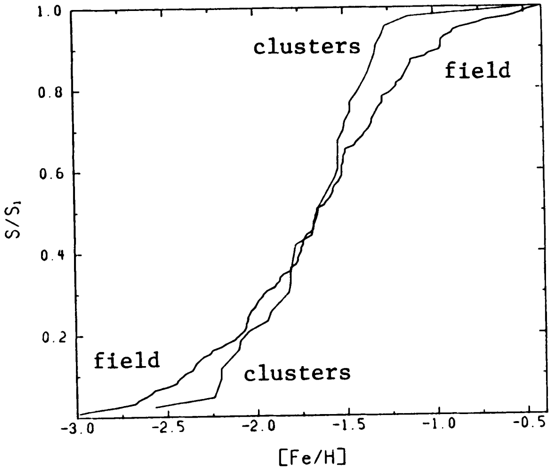

Fig. 4. Comparison of globular cluster and field star metallicity distributions.

The elemental abundance patterns agree fairly well. Kraft (1986) has discussed the field *vs.* cluster CNO abundances finding the same general enhancement of [O/Fe] in both groups. CN abundances are vulnerable to mixing-induced variations and will not be considered. The clusters appear to divide into oxygen-rich and oxygen-poor samples, however, whereas the field red giants show a continuous range. Again, this may be an artifact of the analyses. For the heavier elements, Table I below is a compilation for a few key elements: the light α-rich Mg and Ca, the odd-Z Na, the light and heavy s-process species Sr, Y, Zr; and Ba, and the r-process element Eu. Abundances derived from spectroscopic analyses of cluster giants were taken uncritically from several sources (Cohen 1978, 1979, 1981; Gratton 1982; Pilachowski, Sneden, and Wallerstein 1983; Pilachowski, Wallerstein, and Leep 1980; Pilachowski *et al*. 1982), and were divided into three groups on the basis of mean metallicity: [Fe/H] = -1.0 to -1.5 (NGC 2808, NGC 3201, NGC 4833, NGC 6752, M5, and M10; [Fe/H] = -1.5 to -2.0 (M3, M13, and M22); and [Fe/H] < -2.0 (NGC 6397, M92, and M15). I have restricted the field star comparisons to include only red giants, with data collected from the large survey of Luck and Bond (1985), supplemented by Leep and Wallerstein (1981), Gratton (1983), Sneden and Parthsarathy (1983), and Sneden and Pilachowski (1985). All together, 45 field stars are included. Agreement is, in general, quite good. The Eu results are very difficult to compare, since only one or two lines are usually available, only a few stars have been studied, and, as noted in §4.2, there may be local variations.

TABLE I.

Comparative Abundances of Clusters and Field Stars

	Clusters/Field Stars*		
<[Fe/H]> =	-1.20/-1.26	-1.63/-1.78	-2.25/-2.40
[Na/Fe] =	+0.1/[+0.2]	[+0.2]/-0.1	+0.25/[+0.1]
[Mg/Fe] =	+0.3/+0.4	+0.1/+0.4	[+0.1]/+0.4
[Ca/Fe] =	+0.3/+0.4	[+0.35]/+0.4	+0.45/+0.5
[Sr,Y,Zr/Fe] =	-0.2/-0.1	+0.3/-0.1	-0.2/-0.45
[Ba/Fe] =	-0.3/+0.1	-0.1/-0.2	-0.1/[-0.6]
[Eu/Fe] =	-0.3/[+0.8]**	+0.35‡/+0.34‡	.../-0.3

* Brackets indicate scatter larger than observational errors allow.
** Based on two stars, with [Eu/Fe] = +0.4 and +1.5.
‡ Based on only one star.

Finally, we compare cluster and field star kinematics, restricting the latter to include only those stars selected by means independent of kinematics. Table II repeats Norris's (1986) analysis of the motions of metal-poor ([Fe/H] < -1.2) clusters and field stars, and include Webbink's (this meeting) similar analysis of cluster kinematics. The

TABLE II.
The Field Star and Cluster Velocity Ellipsoids

	v_{rot}	σ_r	σ_θ	σ_ϕ	<e>	Reference
Clusters	40 ± 25	129 ± 19	131 ± 26	124 ± 19	0.48 ± 0.03	Norris
		119 ± 12	117 ± 19	95 ± 37		Webbink
Field	37 ± 11	129 ± 8	108 ± 13	96 ± 8	0.47 ± 0.05	Norris

eccentricity in the table is a three-dimensional one, not the projected value used by ELS. The two populations do not obviously different.

In summary, the field and cluster stars do not differ greatly in age, appear to share the same dynamical properties, but may have experienced somewhat different chemical enrichment histories.

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DISCUSSION

LATHAM: If the halo field stars have all originated from globular clusters, what do you expect for the frequency of binaries?

OSTRIKER: If the halo were produced primarily by dissolving globular clusters (an extreme possibility I do not believe) the close binary function would be higher in the field, since binaries are preferentially from clusters.

LAIRD: For the comparison of field dwarf and cluster metallicity distributions, there are 43 clusters and 36 stars used (since an additional kinematic criterion was applied to bias the sample toward outer halo stars. This mimics the selection of clusters with galactocentric radius > 7 kpc). There are about 3 stars of the 36 with [Fe/H] < -2.7.

STATLER: I'd like to clarify Jerry's answer concerning the fraction of binaries lost from clusters. This depends on how they are lost: if it is by evaporation through the tidal limit, the numbers of binaries will be very small. If tidal truncation is unimportant, then stars are lost by ejection from the center, and the fraction of those that are binaries can be anything up to 50%, this number being larger for harder binaries. A question then is: what are the orbital velocities of the binaries that you have observed?

SCHOMMER: Some 10 years ago, Kraft et al. found that $\Delta S = 2$ field RR Lyrae had a significantly different mean period than the $\Delta S = 2$ cluster variables. I believe the field <P> ~ $0^{d}45$, white <P> ~ $0^{d}55$ in the clusters. Is this still true?

CARNEY: Yes so far as I'm aware.

WALLERSTEIN: Surveys by Kraft and Saha find very few RR Lyraes with periods greater than 0.6 days in the globular clusters, especially the Oosterhoff II clusters. Also type II Cepheids are common in globular clusters but nearly absent from the halo. Since type II Cepheids are seen only in globulars with blue-horizontal branches, this indicates that the halo is a red horizontal-branch population.

CARNEY: There are quite a few local and distant field blue HB stars known (e.g., Pier 1984, Sommer-Larsen and Christensen 1985). It would be interesting to perform relative $1/V_{max}$ tests to test your idea.

HARRIS: At high galactic latitudes, the ratio of the numbers of Mira variables to numbers of RR Lyraes is higher than it is in clusters, and many of the Miras have periods longer than 250 days. Both facts are indicative of a more prominent metal-rich population in the halo field than in cluster, and are consistent with the few Population II Cepheids found in the halo field. Possibly a kinematically-selected sample is not fully sensitive to this population.

CARNEY: I don't see why a kinematically-selected sample would miss these stars. Our metallicity distribution does show more metal-rich stars as well as more metal-poor stars than in clusters. The metal-rich excess would help explain the Miras. I do not know, but would like to know, the kinematic properties of those Miras, however.

NORRIS: I was pleased to see that our results for V_{rot} vs. [Fe/H] agreed so well, especially at the low abundance end, in contrast with the recent result of Sandage. Would you care to comment on the difference between your and his results which are both based on kinematic samples?

CARNEY: Since our survey is a little deeper, we have a larger sample of higher velocity stars. We also have spectroscopic metallicities (and correspondingly somewhat better photometric parallaxes and hence kinematics); whereas Allan has relied only upon the ultraviolet excess, $\delta(U-B)_{0.6}$. We have also included reddening whereas he has not, although I believe its influence to be small. In any event, if there is a real population discontinuity, observationally-introduced scatter will transform it into a smooth trend. We, like you, see signs of a discontinuity.

PHILIP: I was interested in your statement that 22% of the halo stars were binaries. In my work on the early-type halo stars I have not run into any case of an A-type FHB star in a binary system What are the spectral types of your binary halo stars? Are there any A types among them?

CARNEY: Our stars are predominantly F, G, and K dwarfs, not post main-sequence stars, so our results don't apply directly to your objects. However, Dave Latham and I have commented (Astron. J. **91**, 60, 1986) that metal-poor field red giants also show a non-zero (> 10%) binary fraction, so I'd expect the field HB stars to contain some binaries, although the periods will probably exceed 100 days. Let me remind you the searches among the HB stars are not very complete, too. The field halo dwarf binary fraction was thought to be near zero for years until detailed studies such as ours were done.

PHILIP: Then it does seem to be true that there is no case yet known of a binary A-type Halo star.

COHEN: Since you mentioned planetary nebulae, I should say that Neugebauer, Soifer, Gillettt and I have found a new PN near the center of M 22 while checking up on an IRAS scan. It is probably impossible to get an He abundance from this object.

CARNEY: That is too bad.

ZINNECKER: When you discuss the metallicity distribution of halo field stars, there is the possibility that mixing in the interstellar gas of the protogalaxy is not complete. In other words: there may be a metallicity dispersion in the halo gas at any given time. Would that help to interpret the data? And one more question. There has been the suggestion in the literature that the halo gas would be polluted by supernova ejecta from massive star formation in the Virgo Cluster that preceded Pop II in our galaxy. Would anyone like to comment on this suggestion?

CARNEY: That may be part of it, but our sample is drawn from stars that originated throughout the galaxy and are only now nearby. I'd expect the clusters and field stars to then share the same spatially-averaged metallicity distribution function. Your second question was answered in a short note by George Wallerstein. Perhaps he will respond.

WALLERSTEIN: The suggestion that the first metals in our galaxy came as dust particles from Virgo does not fly, because the metals in extremely metal-poor stars do not correlate with those that are locked up in the interstellar dust.