

## Galactic Metal-Poor Halo

Most of the gas, stars and clusters in our Milky Way Galaxy are distributed in its rotating, metal-rich, gas-rich and flattened disk and in the more slowly rotating, metal-rich and gas-poor bulge. The Galaxy's halo is roughly spheroidal in shape, and extends, with decreasing density, out to distances comparable with those of the Magellanic Clouds and the dwarf spheroidal galaxies that have been collected around the Galaxy. Aside from its roughly spheroidal distribution, the most salient general properties of the halo are its low metallicity relative to the bulk of the Galaxy's stars, its lack of a gaseous counterpart, unlike the Galactic disk, and its great age. The kinematics of the stellar halo is closely coupled to the spheroidal distribution. Solar neighborhood disk stars move at a speed of about  $220 \text{ km s}^{-1}$  toward a point in the plane and  $90^\circ$  from the Galactic center. Stars belonging to the spheroidal halo do not share such ordered motion, and thus appear to have 'high velocities' relative to the Sun. Their orbital energies are often comparable with those of the disk stars but they are directed differently, often on orbits that have a smaller component of rotation or angular momentum. Following the original description by Baade in 1944, the disk stars are often called POPULATION I while the metal-poor halo stars belong to POPULATION II.

GLOBULAR CLUSTERS are the most readily identifiable component of the Galactic halo. Roughly 150 are known and most, but not all, occupy a spheroidal distribution, have radial velocities that are much larger than expected for disk-like rotation, and are metal poor. Figure 1 shows the distributions of the metal abundances,  $[\text{Fe}/\text{H}]$  ( $\equiv \log[n(\text{Fe})/n(\text{H})]_\star - \log[n(\text{Fe})/n(\text{H})]_\odot$ ). Figure 2 shows the distribution of clusters' distances from the Galactic plane as a function of  $[\text{Fe}/\text{H}]$ . Two 'populations' of globular clusters exist: one belonging to the metal-weak halo, and a more metal-rich one that is a disk, possibly a 'thick disk' population (see GALACTIC THICK DISK). Field stars show very similar behaviors in metallicity and kinematics.

Globular cluster masses range from a few hundred  $M_\odot$  (AM-4) to several million  $M_\odot$  ( $\omega$  Centauri = NGC 5139). Despite their large masses, globular clusters contribute only a small fraction ( $\approx 2\%$ ) to the total mass of the metal-poor stellar halo. Field stars dominate the mass. The total mass of the metal-poor stellar halo may be estimated using the density of such field stars in the solar neighborhood ( $\approx 0.2\text{--}0.5\%$  of the disk stars) and the cumulative distribution of the mass in globular clusters as a function of Galactocentric distance. In field star and cluster stellar mass, the metal-poor halo amounts to only about  $10^9 M_\odot$ , about 1% of the Galaxy's total stellar mass.

Despite its minor contribution to the Galaxy's stellar mass budget, the halo has been studied extensively to answer a wide variety of questions. In 1918, Shapley exploited the positions and approximate distances to globular clusters to identify the direction of and distance to the Galactic center,  $R_{\text{GC}}$ . Globular clusters and the halo population 'standard candle' RR LYRAE VARIABLES are

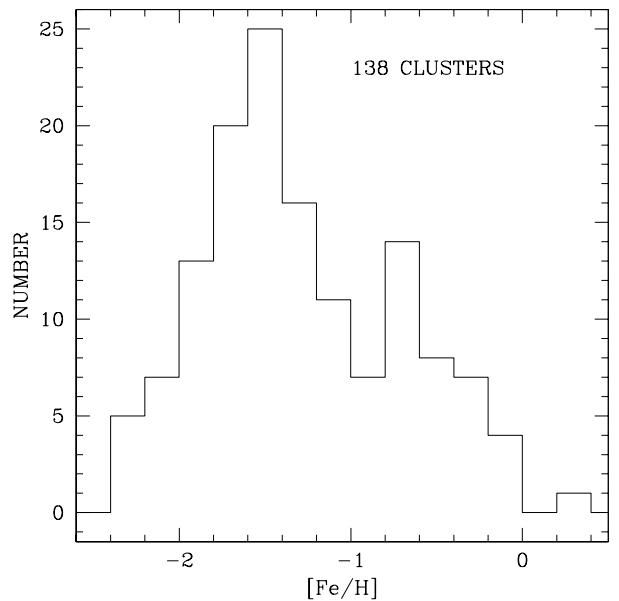


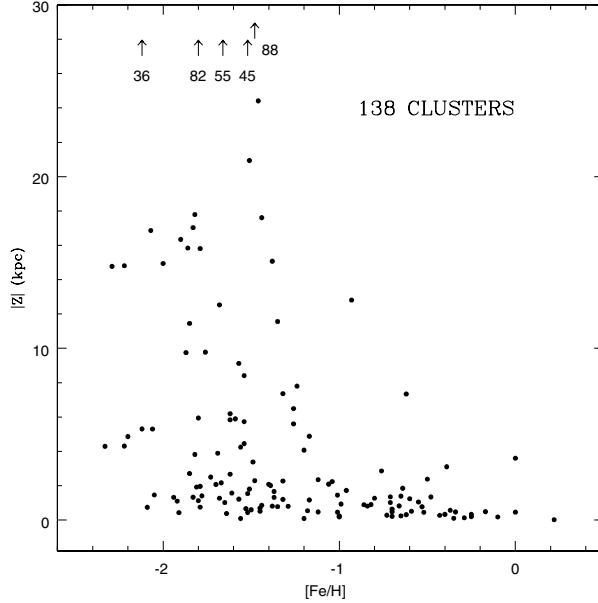
Figure 1. The distribution of  $[\text{Fe}/\text{H}]$  values for globular clusters.

still used to measure  $R_{\text{GC}}$ . The recognizability of globular clusters and RR Lyraes and their large range in  $R_{\text{GC}}$  provide good 'test particles' to map out the Galaxy's gravitational potential and discern the distribution of both the stars and the DARK MATTER. Most work on the halo population, however, arises from our desire to understand the Galaxy's formation process and its early history, and, in fact, to discern the chemical abundances produced by the BIG BANG since it appears that the first stars to be formed in our Galaxy lie in the Galactic halo. What were the abundances of those earliest stars? How did they change and how rapidly? How did the Galaxy form and evolve?

### Chemical abundances

Figure 1 employs  $[\text{Fe}/\text{H}]$  as the measure of 'metallicity'. For brighter field stars and the brightest stars in globular clusters, this may be determined by employing high-resolution, high-signal-to-noise spectroscopy to measure line strengths. In conjunction with atomic line parameters and an appropriate model stellar atmosphere, one may derive element-to-hydrogen abundance ratios such as  $[\text{Fe}/\text{H}]$ . The process is often iterative, involving tests to make certain that the derived abundances do not depend on the lower energy levels of the atomic transitions (to check the model's effective temperature), on the line strengths (to assess the effects of turbulent line broadening) and on gravity-sensitive and gravity-insensitive lines. The technique is often referred to as a 'fine analysis' or a 'curve of growth' analysis.

Because of long exposure times, such analyses of field and cluster stars are not always employed to estimate  $[\text{Fe}/\text{H}]$  values. Instead, metallicity 'indicators' are calibrated using results available from such analyses

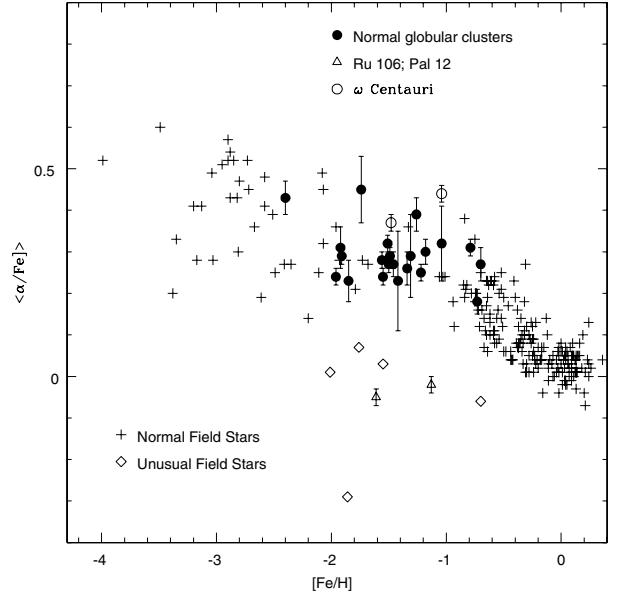


**Figure 2.** The distance from the plane of globular clusters as a function of [Fe/H].

and then exploited to study larger and/or fainter samples of stars or clusters. Lower-dispersion spectra are easier and faster to obtain than high-dispersion spectra, and one technique that exploits this method is called  $\Delta S$  since it employs a measured apparent difference in spectral type. In RR Lyrae variables, one measures the spectral type using the hydrogen lines and compares that with that defined from the 3933 Å line of Ca II. The difference is an indicator of the calcium abundance. A similar method, called  $W'$ , exploits the three strong lines of Ca II at 8498, 8542 and 8662 Å and is used to estimate [Fe/H] (assuming a constant or at least monotonic relation between [Ca/H] and [Fe/H]) for red giant stars in globular clusters. One may also employ photometric methods. As [Fe/H] increases, both the predicted and the observed colors of stars along the red giant branch become redder, and thus the red giant branch color is a good metallicity indicator. Quantitatively, one measures the dereddened  $B - V$  or  $V - I$  color indices at the magnitude level of a cluster's horizontal branch. The resultant values,  $(B - V)_{0,g}$  and  $(V - I)_{0,g}$ , are calibrated using [Fe/H] values available for a well-studied subsample of clusters.

High-resolution spectroscopy of metal-poor halo stars is valuable for measuring the abundances of elements other than iron to study the chemical evolution in the early Galaxy and, in fact, those produced by the Big Bang. Five results are especially noteworthy.

(1) Figure 1 shows two roughly Gaussian distributions of [Fe/H]. Simple models may explain such behavior. In brief, a gaseous system with an initial metallicity,  $[Fe/H]_{init}$ , produces stars, some of which explode as supernovae, and the metallicity of the gas rises. Low-mass,



**Figure 3.** The behavior of Mg, Si and Ca abundances relative to iron as a function of [Fe/H] for field and cluster stars.

long-lived stars then preserve the record of this enrichment process. The fraction of stars with higher metallicities rises until roughly 50% of the gas has been converted into stars or expelled from the system. At that point, the metallicity continues to rise, but the fraction of stars with higher metallicities diminishes owing to the decreasing gas supply, eventually reaching  $[Fe/H]_{final}$  when all the gas is gone. The low mean metallicity of the halo is thought to arise because most of the gas was expelled from the halo before significant supernova-induced enrichment could occur. This gas may have formed much of the Galaxy's bulge. Figure 1 also suggests that two separate chemical evolution histories have been involved in the production of the metal-poor halo and the moderately metal-poor thick disk.

(2) Globular clusters are fairly massive systems, yet only one,  $\omega$  Centauri, shows clear signs of metallicity variations that might be due to self-enrichment during the formation of the cluster. Since the colors of red giant branch stars depend on [Fe/H], the failure to detect spreads in colors of clusters' red giant branch stars implies a lack of significant self-enrichment. Given the small total mass in any one globular cluster, this may not be surprising. Some primordial variations in selected elements have been claimed, however.

(3) The abundances of the ' $\alpha$ ' elements, oxygen, magnesium, silicon, calcium and titanium appear to be enhanced relative to iron by a factor of between 2 and 3 in metal-poor stars and clusters. Figure 3 shows the behavior of elements other than oxygen in field and in clusters, from which it is clear that  $\langle \alpha/Fe \rangle \approx +0.4$  for  $[Fe/H] < -1.0$ . The cause is thought to be the dominance of type II SUPERNOVAE, which are the explosive deaths of

massive, and short-lived, stars. Models predict that such stars will produce all the elements, from helium to carbon and oxygen through the iron peak and beyond into the neutron capture domain. The decline in [ $\alpha'/\text{Fe}$ ] is thought to arise from the later appearance of type IA supernovae, thought to be due to the deflagration–detonation of white dwarfs that exceed the Chandrasekher mass limit owing to mass transfer. Their ejecta should be very rich in iron-peak elements and relatively deficient in lighter elements. Thus figure 3 may be the signature of the initial type II events, followed later ( $\approx 10^9$  yr) by a mixture of type Ia and type II supernovae. Oxygen is the most abundant heavy element, but, unfortunately, disputes continue about the trend of [O/Fe] versus [Fe/H]. Analyses of OH lines in the ultraviolet suggest that [O/Fe] increases linearly as [Fe/H] declines, but analyses of O I in main sequence stars and of [O I] in red giants show the same behavior as in figure 3.

(4) Neutron capture elements, including those manufactured in the S-process and the R-process, can reveal the relative importance of these processes and, hence, the relative contributions to nucleosynthesis in the young Galaxy by the stars responsible for these processes. The s-process may arise largely in the late evolutionary stages of intermediate-mass stars, while the r-process is thought to occur within type II supernovae. As in the case of the ' $\alpha'$  elements, changing ratios of s-process and r-process abundances indicate changing relative contributions by asymptotic giant branch stars and supernovae. If the models are correct, r-process production should dominate the first several hundred million years of chemical evolution. Further, some of the r-process elements, such as thorium, are radioactive and, in principle, may have their abundances measured in stars, enabling their ages to be determined.

(5) The most metal-poor stars formed out of material enriched only slightly from stellar evolution and supernovae and a more easily detectable contribution from the big bang. Lithium, beryllium and boron are especially interesting since their production ratios are determined by the baryon density, its smoothness and the effects of cosmic rays. In almost all metal-poor stars that do not have deep convection zones that could carry lithium to deeper layers where it can be destroyed by proton capture, the lithium abundances appear to be constant, about a factor of 10 below the current interstellar medium value, and indicative of a low baryon density universe. There are, however, some puzzling exceptions, including a few metal-poor stars with little or no detectable lithium and a few others with enhanced lithium abundances.

### Distances and motions

Radial velocities of stars in the field and in clusters may be measured directly using stellar spectroscopy and the Doppler effect. Tangential velocities may be determined only if a star's PROPER MOTION and distance are both measured since  $v_{\tan} = 4.74 \mu d$ , where  $\mu$  is the proper motion in arcsec per year and  $d$  is the distance in parsecs. If all these are known, one may determine velocities in the

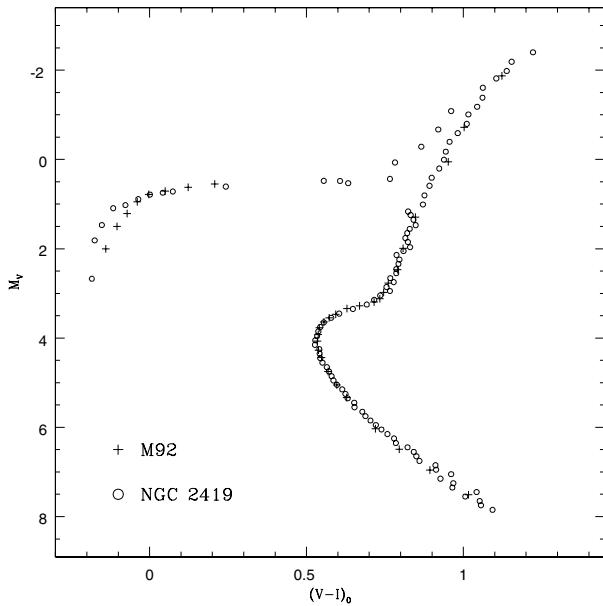
Galactic frame. In the solar neighborhood, these are called  $U$ ,  $V$  and  $W$ , and are directed toward ( $\ell = 180^\circ$ ;  $b = 0^\circ$ ), ( $\ell = 90^\circ$ ;  $b = 0^\circ$ ) and ( $b = 90^\circ$ ), respectively. With a model Galactic gravitational potential, Galactic orbits may be estimated, including apogalacticon,  $R_{\text{apo}}$ , perigalacticon,  $R_{\text{peri}}$ , and maximum distance from the Galactic plane,  $Z_{\max}$ . Stars and clusters at different  $R_{\text{GC}}$  may be handled similarly, but  $\Pi$ ,  $\Theta$  and  $Z$  replace  $U$ ,  $V$  and  $W$ , retaining the same (local) vector orientations. Three-dimensional motions have been measured for over 30 globular clusters and over 1000 metal-poor field stars.

The distance scale for metal-poor stars remains a controversial but crucial topic. Distances to stars help to determine their velocities as well as their absolute magnitudes. The former are necessary in studies of relations between kinematics versus chemistry that provide insight into the Galaxy's dynamical history. The latter are vital because it is the luminosity of the main sequence turn-off that is used to estimate the relative and absolute ages of globular clusters.

Trigonometric PARALLAXES have been measured for a significant number of metal-poor main sequence stars, and such data may be used to calibrate relations between absolute magnitude, color and metallicity. These may in turn be used to estimate distances to those globular clusters with high-precision photometry of their faint main sequence stars. Another 'standard candle' is the RR Lyrae variable. It appears that  $M_V(\text{RR}) = 0.20[\text{Fe}/\text{H}] + 0.8$ , although the zero point is uncertain by about 0.2 mag. Measurement of horizontal branch magnitudes, corrected for reddening, thus enables measurement of cluster distances. In fact, using the relation for  $M_V(\text{RR})$  and measuring the apparent  $V$  magnitude of the main sequence turn-off yields the  $M_V$  value for the turn-off, independent of reddening.

### Ages

Two lines of evidence suggest that the most metal-poor stars and clusters with  $[\text{Fe}/\text{H}] < -2.0$  have the same age to the limit of our abilities to measure them. First, spectroscopic evidence indicates that the r-process dominates over the s-process in such systems, suggesting that intermediate-mass stars had not yet polluted the interstellar medium, and implying that the age differences probably do not exceed  $10^9$  yr. Figure 3 also suggests a similar timescale in that supernovae of type II dominated the production of iron. Second, evidence favoring common ages comes from color–magnitude diagrams. Recent ground-based and space-based observations have extended the comparisons to large distances, including NGC 2419 with  $R_{\text{GC}} = 90$  kpc. Figure 4 shows that this cluster is indistinguishable in age from M92, which lies only 9 kpc from the Galactic center, and is similar in age to several other low-metallicity ( $[\text{Fe}/\text{H}] < -2.0$ ) clusters with  $R_{\text{GC}}$  values ranging from 6 to 9 kpc. Again, the maximum age spreads are roughly a billion years or less. Analyses of field star ages using Strömgren photometry also show no sign of age differences among the most metal-poor stars.



**Figure 4.** Superposed color-magnitude diagrams of the middle halo globular cluster M92 and the distant cluster NGC 2419, taken from Harris *et al* (1997).

The next important chronological questions are whether the metal-poor and metal-rich field stars and clusters differ in age and whether this difference is a function of their location in the Galaxy. The age differences imply the speed at which the metal-poor halo was chemically enriched, and differences in initial densities of the young Galaxy's central, middle and outer halo may have produced differences in the rate at which stars and clusters formed and the rate at which the metallicity enrichment proceeded. At large  $R_{\text{GC}} (> 80 \text{ kpc})$ , it appears that intermediate-metallicity clusters, with  $[\text{Fe}/\text{H}] \approx -1.5$ , are of order  $2 \times 10^9 \text{ yr}$  younger than comparable metallicity clusters with  $R_{\text{GC}}$  values of 6–12 kpc. The implication is that the metallicity enrichment proceeded more slowly in the outer halo. Thus the differences in gas density between the outer and middle halo may have been an important factor in the Galaxy's evolutionary rates. We do not yet know whether these trends of equal ages at the lowest metallicities and smaller age spreads continue into the innermost halo ( $R_{\text{GC}} < 3 \text{ kpc}$ ).

The age spread among the intermediate-metallicity and relatively metal-rich ( $[\text{Fe}/\text{H}] \approx -1$ ) clusters in the middle halo remains a matter of debate. Field stars appear to show age spread at such intermediate metallicities. There are clear examples of significant age differences among clusters, the pair NGC 288 and NGC 362 being one of the best examples. Another pair of unusually young clusters is Ruprecht 106 and Palomar 12, which appear to be several billion years younger than average. In fact, the  $[\alpha/\text{Fe}]$  ratios for these clusters are close to solar and, hence, very low for their  $[\text{Fe}/\text{H}]$  values, as shown in figure 3. Their behavior may be explained

by very young ages (but then the question is why are they so metal poor?) or by an origin perhaps quite different from that of the bulk of the metal-poor globular clusters. In any case, there seems little doubt that *some* globular clusters are younger than average, but how many and by how much? To attempt to detect smaller age differences than possible from the main sequence regime, shown in figure 4, attention has turned to the HORIZONTAL BRANCH STARS, identified in the figure as those stars with  $M_V \approx +0.5 \text{ mag}$ . Theory predicts that, for intermediate-metallicity clusters, younger clusters might be distinguished from older clusters by the distribution of stars along the horizontal branch: redder indicates younger ages. NGC 362, with a red horizontal branch, is indeed younger than NGC 288, which has a very blue horizontal branch. The problem is actually quite complex, and this 'second parameter', the color of the horizontal branch compared with those of other clusters with similar  $[\text{Fe}/\text{H}]$  values (the 'first parameter'), may also be affected by stellar interactions in dense environments. Indeed, some clusters, such as NGC 2808 and NGC 6229, show bimodal horizontal branches yet no signs of two epochs of star formation. What can be said is that *some* clusters with intermediate metallicities in the middle halo are younger than average.

The absolute ages of the Galaxy's oldest globular clusters are of great interest but two key problems remain. First, if star formation began first in the Galaxy's central regions, the oldest clusters, those with low  $[\text{Fe}/\text{H}]$  values but lying close to the Galactic center, have not yet been studied. Of greater concern, however, is the dichotomy in results for  $M_V(\text{RR})$  that has arisen from the Hipparcos satellite's trigonometric parallaxes. Absolute magnitudes for field metal-metal main sequence stars have been used to estimate distances and main sequence turn-off luminosities for comparably metal-poor globular clusters. Ages range between 12 and 14 billion yr. However, the  $M_V(\text{RR})$  values derived are brighter than those of field RR Lyrae variables obtained with Hipparcos. On the other hand, the detection of thorium (and other r-process elements) in the spectra of some metal-poor field stars, most notably CS22892-052, has enabled estimates of stellar ages from radioactive decay. Values near 14 billion yr appear favored.

### Formation and evolution of the halo

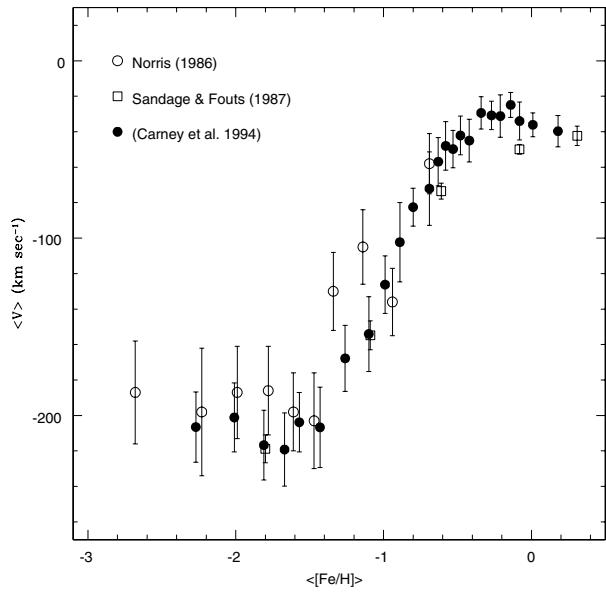
Early work on the chemical abundances, velocities and ages of what we now call the metal-poor halo field stars and clusters culminated in a classic paper by Eggen *et al* (1962). They derived  $U$ ,  $V$  and  $W$  velocities for 221 field dwarf stars selected from two catalogs: one of nearby stars and one of stars with large proper motions (hence a good source of high-velocity stars). They estimated metallicities from the 'ultraviolet excess',  $\delta(U-B)_{0.6}$ , which in essence is an indicator of the degree of heavy element line blanketing in the near ultraviolet. The velocities were combined with a model Galactic gravitational potential to estimate the stars' orbital eccentricities, and the most important result

was that the orbital eccentricity correlated well with the metallicity. The orbital eccentricities of the most metal-poor stars were found to be uniformly high, indicating that the stars were formed on plunging orbits. Assuming metallicity is a proxy for time, the conclusion was that the Galaxy began to form stars while it was still in a state of collapse. The large spherical halo could then be explained as the earliest stage of the Galaxy, following which it rapidly collapsed and settled into a disk configuration. The process was rapid because the plunging orbits implied a nearly free-fall timescale, of order  $2 \times 10^8$  yr, and it was a coherent process since the study did not reveal stars with low metallicities (the oldest stars) with disk-like orbits or stars with high metallicities (the more recently formed stars) with high-velocity halo-like orbits.

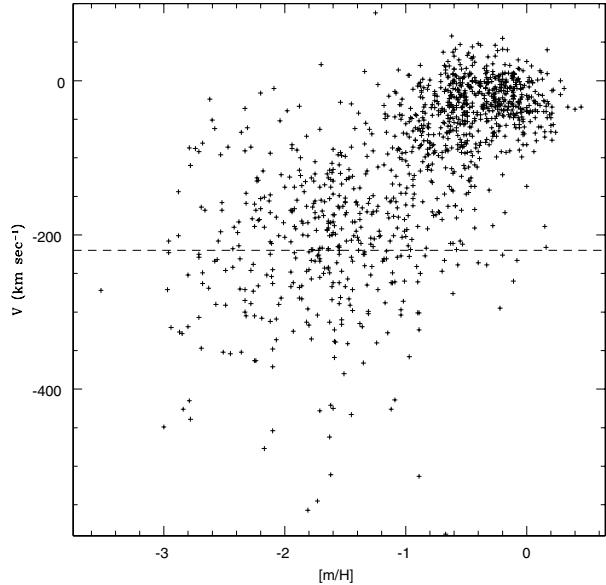
The first major challenge for the rapid-coherent collapse model was the study of Galactic globular clusters by Searle and Zinn (1978). One key point of the collapse model is that globular clusters should all have the same age, at least to within our abilities to measure them. Searle and Zinn noted that clusters with large  $R_{GC}$  tend to have redder than average horizontal branch colors. If the ‘second parameter’ is age (which appears to be true for the most distant clusters), then the process was not as rapid as originally believed. A slower, coherent contraction would still be a reasonable interpretation of the data, except that in such a case enough time would have passed to permit the remaining gas to be enriched by supernovae. As the gas contracted to form the disk, one would then expect the innermost stars and clusters to have higher metallicities since star formation should have continued longer. A radial gradient in metallicity would have been established, but Searle and Zinn failed to find any evidence of such a gradient for  $R_{GC}$  values larger than about 8 kpc. Based on their cluster data, they proposed that the halo was formed out of ‘protogalactic fragments’, each with an individual metallicity enrichment history. The assemblage of these fragments would then have resulted in a dynamically hot halo whose field stars and globular clusters have a range in ages yet no metallicity gradient owing to the random, ‘incoherent’ nature of the process. Additional support for the ‘incoherent’ model came from studies of field stars. Kinematically biased studies of stars selected only from proper motion catalogs (the ‘Carney–Latham’ sample) and stars selected without kinematical bias by Norris revealed a lack of correlation between metallicity and kinematics, as shown in figures 5 and 6.

An obvious argument favoring an accretion origin for some, perhaps most, of the halo was the discovery of the SAGITTARIUS DWARF GALAXY by Ibata *et al* (1994). This is a large dwarf galaxy on close approach to our Galaxy. In an astronomically short time, it will shed many stars, including its four globular clusters (M54, Terzan 7, Terzan 8 and Arp 2), into the Galaxy’s halo. Several other signs point to the importance of accretion as a source of some of the halo’s stars and clusters.

First, if the evolution of the halo into the disk was a coherent process, the halo should possess modest net



**Figure 5.** Average velocities  $V$  as a function of  $[Fe/H]$  using equal bin sizes from kinematically biased (Sandage and Fouts 1987; Carney *et al* 1994) and unbiased (Norris 1986) samples of field stars.



**Figure 6.** The velocity  $V$  versus  $[m/H]$  from Carney *et al* (1994). The dashed line divides prograde and retrograde Galactic orbital motion.

prograde rotation. Figures 5 and 6 show that if the local Galactic rotational velocity,  $\Theta_0$ , is  $220 \text{ km s}^{-1}$ , then the net halo rotation is very small. Further, Majewski (and others) have found that stars 5 kpc or more from the plane may possess net retrograde rotation. This suggests that at least some fraction of the halo’s stars did not participate in the

coherent Galaxy formation process. Other studies have suggested that globular clusters with horizontal branch colors implying younger-than-average ages also show signs for retrograde rotation. The evidence is weak given the one-dimensional velocity information and the small sample sizes, however.

Another possible signature of independent origin and evolution is chemistry. If two gas clouds produce stars at similar rates and with similar mass functions, the supernova enrichment history should be the same, and in consequence identical trends of  $[\alpha'/\text{Fe}]$  versus  $[\text{Fe}/\text{H}]$  should result. However, if one cloud forms stars more slowly, the appearance of the effects from the type Ia supernovae should first appear when the mean metallicity is still 'stuck' at a lower value, perhaps much lower than seen in the Galaxy at  $[\text{Fe}/\text{H}] \approx -1$ . Ruprecht 106 and Palomar 12, identified in figure 3, could be explained by delayed star formation in a small 'fragment' or dwarf galaxy that was accreted by the Galaxy. A small number of field stars have also been found with unusually low  $[\alpha'/\text{Fe}]$  ratios, the most extreme being BD+80245. An interesting additional feature of these stars is that they are generally very high velocity, with orbits that carry them out to  $R_{\text{GC}} = 20\text{--}40$  kpc. Ruprecht 106 and Palomar 12 also lie at fairly large distances,  $R_{\text{GC}} = 17$  and 14 kpc, respectively. On the other hand, not all stars with such large apogalacticon values or clusters with such large distances have unusual abundance ratios. Studies of such systems appear to more frequently find the enhanced  $[\alpha'/\text{Fe}]$  values typical of middle halo stars and clusters.

Another avenue to explore for signs of accretion is the idea that disintegrating satellite galaxies would leave behind a stream of stars (and gas, if they possess any). The MAGELLANIC STREAM is an example of a spoor that is apparently induced by the Galaxy's tidal effects on the MAGELLANIC CLOUDS. (Note this also indicates that the Clouds are also doomed to merge with the Galaxy.) The Magellanic stream traces almost an entire great circle on the sky, and the stream also passes near the positions of the Draco and Ursa Minor dwarf spheroidal galaxies. Another such great circle includes the Fornax, Leo I, Leo II and Sculptor dwarf galaxies, as well as a number of Galactic globular clusters. Another search technique recognizes that each distant dwarf galaxy or globular cluster in orbit about the Galaxy has an orbital pole and that, in the absence of three-dimensional motions, the pole occupies a point along a great circle in the sky. Intersections of such great circles suggest common orbital poles and have been used to identify possible streams. However, until accurate proper motions become available for more globular clusters and the distant dwarf spheroidal galaxies, the reality of these common origins for some such systems must remain speculative. Finally, common origins for larger numbers of objects but with all three components of velocity known may show up in the form of velocity 'substructure'. A dynamically hot population such as the halo should have stars well dispersed in velocity space. Observed 'clumpings' of stars at high

velocities indicate either that the halo is not well mixed kinematically or that these clumps arose because of tidal destruction of small stellar ensembles by the Galaxy's tidal forces.

Even if the evidence cited above supports accretion of proto-Galactic 'fragments' or dwarf galaxies, this does not necessarily rule out that many of the metal-poor, high-velocity stars were part of a coherent formation process, as outlined by Eggen *et al.* While some subsets of globular clusters may show net retrograde rotation, others show prograde rotation. While some globular clusters may be younger than average, many appear to be coeval with other clusters of similar metallicity. Some globular clusters and field stars, especially with large  $R_{\text{GC}}$  or  $R_{\text{apo}}$  values, have unusual  $[\alpha'/\text{Fe}]$  values, but most do not, even clusters like NGC 7006 ( $R_{\text{GC}} \approx 35$  kpc) and numerous extreme-velocity field stars. Furthermore, metal-poor stars close to the Galactic plane show not only prograde rotation but signs of a radial metallicity gradient, as do subsets of globular clusters. Both processes, coherent evolution plus accretion, have almost certainly contributed to the formation of our Galaxy's metal-poor halo, but a much larger and more complete census will be required to determine the relative numbers of natives and immigrants.

#### Bibliography

The original division of the local stellar neighborhood into 'high velocity' and 'low velocity' was made by

Oort 1926 *Groningen Obs. Publ.* 40

This was followed much later by the recognition that some stars are extremely deficient in heavy element abundances:

Aller 1960 *Astron. J.* **65** 399

Aller and Greenstein 1960 *Astrophys. J. Suppl.* **5** 139

Baschek 1959 *Z. Astrophys.* **48** 95

Chamberlain and Aller 1951 *Astrophys. J.* **114** 52

The  $\Delta S$  calibration calibration may be found in

Clementini *et al* 1995 *Astron. J.* **110** 2319

Fernley and Barnes 1996 *Astron. Astrophys.* **312** 197

$W'$  is discussed by

Da Costa and Armandroff 1995 *Astron. J.* **109** 2553

An excellent discussion of chemical evolution models is provided in

Pagel *Nucleosynthesis and Chemical Evolution of Galaxies*

The halo-bulge connection is summarized by

Wyse and Gilmore 1992 *Astron. J.* **104** 144

$[\alpha'/\text{Fe}]$  is discussed at length by

Wheeler *et al* 1989 *Ann. Rev. Astron. Astrophys.* **27** 279

while light element abundances reflective of the big bang are discussed by

Boesgaard and Steigman 1985 *Ann. Rev. Astron. Astrophys.* **23** 319

and the Type II *versus* Type Ia supernovae effects are illustrated by

Wyse and Gilmore 1988 *Astron. J.* **95** 1404

Globular cluster space velocities may be found in

Dinescu *et al* 1997 *Astron. J.* **114** 1014

Dinescu *et al* 1999 *Astron. J.* **117** 277

Odenkirchen *et al* 1997 *New Astron.* **2** 477

Good examples of the relative contributions of s-process versus r-process elements as a function of metallicity are presented by

Gratton and Sneden 1994 *Astron. Astrophys.* **287** 927

Krishnaswamy-Gilroy *et al* 1988 *Astrophys. J.* **327** 298

Ages of metal-poor field stars were derived by

Marquez and Schuster 1994 *Astron. Astrophys. Suppl.* **108** 341

The relative ages of the most metal-poor clusters are summarized well by

Harris *et al* 1997 *Astron. J.* **114** 1030

Stetson *et al* 1996 *Publ. Astron. Soc. Pac.* **108** 560

The distant intermediate metallicity clusters are discussed by

Stetson *et al* 1999 *Astron. J.* **117** 247

The age difference between NGC 288 and NGC 362 is summarized by

Sarajedini *et al* 1997 *Publ. Astron. Soc. Pac.* **109** 1321

The ‘second parameter’ as a possible age indicator is presented by

Lee *et al* 1994 *Astrophys. J.* **423** 248

Radioactive dating of field stars is described by

Cowan *et al* 1997 *Astrophys. J.* **480** 246

Some of the key papers dealing with the origin of the halo are

Eggen, Lynden-Bell and Sandage 1962 *Astrophys. J.* **136** 762  
Searle and Zinn 1978 *Astrophys. J.* **225** 357

They lay out the basic arguments in favor of a rapid, coherent collapse of the halo prior to the formation of the disk (Eggen *et al*) and an alternative involving independent evolution of ‘proto-Galactic fragments’ during or following the formation of the Galaxy. Thorough

summaries of globular cluster kinematics, including early versions of figures 1 and 2, are in

Da Costa and Armandroff 1995 *Astron. J.* **109** 2533

Zinn 1985 *Astrophys. J.* **293** 424

The latest results from the ‘Carney–Latham’ sample are discussed

Carney *et al* 1996 *Astron. J.* **112** 668

while the work by Norris may be found in

Norris 1986 *Astrophys. J. Suppl.* **61** 667

The possibility that stars far from the plane are on retrograde orbits was first raised by

Majewski 1992 *Astrophys. J. Suppl.* **78** 87

The discovery paper of the Sagittarius dwarf galaxy is

Ibata, Gilmore and Irwin 1994 *Nature* **370** 194

Good examples of searching for accretion patterns by lining up objects on great circles on the sky are summarized by

Fusi Pecci *et al* 1995 *Astron. J.* **110** 1664

and the use of orbital poles is given by

Lynden-Bell and Lynden-Bell 1995 *Mon. Not. R. Astron. Soc.* **275** 429

Velocity ‘substructure’ is discussed well by

Majewski *et al* 1994 *Astrophys. J. Lett.* **427** L37

Bruce W Carney