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Field Halo Stars: the Globular Cluster Connection*

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Abstract. High resolution and high signal-to-noise spectra of about 20 metal-poor stars have been analysed. The correlations between the relative abundances of 16 elements have been studied, with a special emphasis on the neutron-capture ones.

This analysis reveals the existence of two sub-populations of field halo stars, namely Pop IIa and Pop IIb. They differ by the behaviour of the s-process elements versus the α and r-process elements.

A scenario for the formation of these stars is presented, which closely relates the origin of field halo stars to the evolution of globular clusters. According to this scenario, the two sub-populations originate from two different stages in the globular cluster's chemical evolution.

1. Introduction

In traditional spectroscopic analyses of metal-poor stars, the mean abundance ratio of the chemical elements is discussed as a function of the overall metallicity, usually measured by the iron abundance [Fe/H]. The results are then compared to predictions from models of nucleosynthesis and chemical evolution of the Galaxy, and they are used to provide constraints on the sites and mechanisms for element synthesis. Unfortunately, these abundance ratios show rather considerable star-to-star scatter, therefore providing only weak constraints on the models.

With the improvement of observing and spectroscopic analysis techniques, it is now possible to reduce considerably the observational uncertainties in the abundance determinations, therefore decreasing the scatter in the abundance ratios. If the data are of sufficient quality, the remaining scatter is then mostly a genuine cosmic scatter which can be measured and analysed. We can investigate the cosmic scatter in relative abundances at a given metallicity and identify abundance correlations between several elements. Since the elements which are strongly correlated together have very likely been synthesized by the same nucleosynthetic processes in the same kinds of objects, we now have a new and efficient tool for identifying the sites and mechanisms of element synthesis at different stages of the galactic evolution. This new tool leads us to propose a scenario for the formation of field halo stars which links them to the globular clusters evolution.

2. Quality of the spectroscopic data

We have analysed a sample of about 20 dwarf and subgiant stars with [Fe/H] ~ -1, i.e. one tenth of the solar metallicity. This metallicity is generally assumed to correspond to the most metal-rich part of the halo of our Galaxy. The spectra were obtained with the Coudé Echelle Spectrometer (CES) fed by the 1.4m Coudé Auxiliary Telescope (CAT) at the European Southern Observatory (La Silla, Chile). Four spectral regions, chosen to contain lines of neutron-capture elements, were observed. The spectral resolution is of the order of 65 000 and the signal-to-noise ratio in the continuum is ~ 250 for each spectrum. In order to reduce the analysis uncertainties, the lines were chosen to have similar dependences on the stellar atmospheric parameters (effective temperature, surface gravity, microturbulence velocity, overall metallicity) whenever possible. Moreover, the analysis was carried out differentially inside the sample, i.e., each star was compared to all other stars in the sample.

The sample of stars, together with some key abundance ratios and the total velocity with respect to the Local Standard at Rest, are presented in Table 1.

Following the traditional abundance analyses (e.g. Magain 1989, Edvardsson et al. 1993) we would show for example [Ti/Fe] as a function of [Fe/H]. The 1σ scatter in that plot for our sample amounts to 0.08 dex (20%). Is

* Based on observations carried out at the European Southern Observatory (La Silla, Chile)

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Table 1. Basic observational data, abundance ratios and total space velocity.

HD	b-y	[Fe/H]	[Ti/Fe]	[Y/Fe]	V(LSR)
22879	0.366	-0.892	+0.325	-0.033	131.4
25704	0.371	-0.894	+0.349	-0.174	132.2
59984	0.355	-0.755	+0.217	-0.195	52.2
61902	0.329	-0.727	+0.168	-0.264	87.0
63077	0.372	-0.831	+0.355	-0.070	152.1
63598	0.366	-0.856	+0.349	0.005	90.0
76932	0.360	-0.910	+0.332	0.045	120.9
78747	0.383	-0.730	+0.362	-0.050	29.5
79601	0.378	-0.668	+0.342	-0.151	42.0
97320	0.337	-1.220	+0.308	-0.150	91.0
111971	0.353	-0.737	+0.139	-0.218	31.9
126793	0.373	-0.800	+0.354	-0.102	10.8
134169	0.368	-0.804	+0.277	-0.193	40.8
152924	0.318	-0.708	+0.263	-0.196	45.0
189558	0.385	-1.129	+0.325	0.117	148.9
196892	0.346	-1.031	+0.342	0.048	126.2
199289	0.368	-1.074	+0.326	-0.138	72.5
203608	0.326	-0.677	+0.120	-0.223	51.0
215257	0.357	-0.804	+0.123	-0.309	77.5

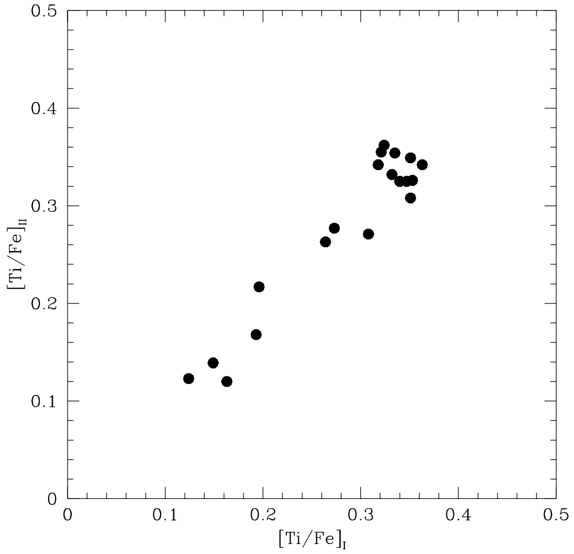

Fig. 1. Comparison of the values of [Ti/Fe] deduced from neutral lines, [Ti/Fe]$_{I}$, with those deduced from ionized lines, [Ti/Fe]$_{II}$

this scatter real or is it due to observational and/or analysis uncertainties? To answer this question we compare in Fig. 1 the values of [Ti/Fe] deduced from neutral lines with the ones deduced from lines of the singly ionized species. We can see a very nice correlation between those two values, with a scatter of only 0.026 dex (6%). Since the neutral and ionized lines have different dependences on the stellar atmospheric parameters, this shows that the scatter in element abundances due to analysis uncertainties does not exceed 6%. Therefore, the scatter in the abundance of Ti relative to Fe is real cosmic scatter. We will now investigate the cosmic scatter in the relative abundances of the other chemical elements.

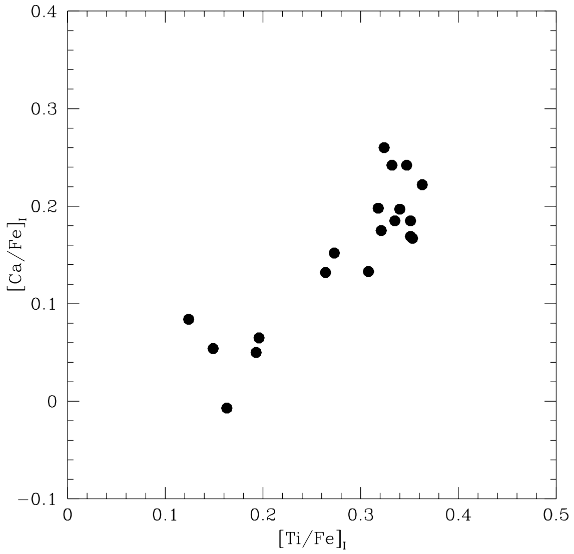

Fig. 2. Plot of [Ca/Fe] versus [Ti/Fe]

3. Highlights of the abundance correlations

We find a close correlation between [Mg/Fe], [Ca/Fe] and [Ti/Fe], as illustrated in Fig. 2. This indicates that the so-called α-elements were synthesized by the same process in the same objects. We find a similar correlation between the abundances of Cr, Ni and Fe relative to Ti, indicating a common origin for these iron-peak elements.

We have also carried out this analysis for the neutron-capture elements, because we wanted to identify the sites and mechanisms for the synthesis of these elements in a relatively early phase of the galactic evolution. A first hint was put forward by Zhao and Magain (1991) who found that the elements Y and Zr are better correlated with Ti than with Fe. They suggested that this indicates that massive stars played a dominant role in the early nucleosynthesis of Y and Zr. Our results confirm their findings. For example, while the scatter of [Y/Fe] amounts to 0.12 dex (30%), the scatter of [Y/Ti] is only 0.07 dex (18%). Our new data allow us to go further than just compare the scatters, as shown in Fig. 3 where the values of [Y/Fe] versus [Ti/Fe] are plotted for each star in our sample. We see that [Y/Fe] is indeed correlated with [Ti/Fe], but this correlation is not simple. We can see two separate behaviours. For one subsample of the stars, the value of [Ti/Fe] increases with increasing [Y/Fe], while for the other subsample [Ti/Fe] is constant (and maximum) while [Y/Fe] increases. We find similar results when any of the elements Sr, Y and Zr is compared to any of the α-elements.

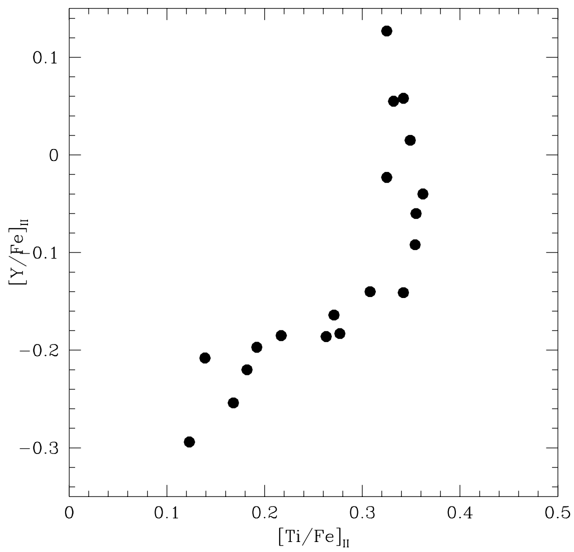

Fig. 3. Plot of [Y/Fe] versus [Ti/Fe]

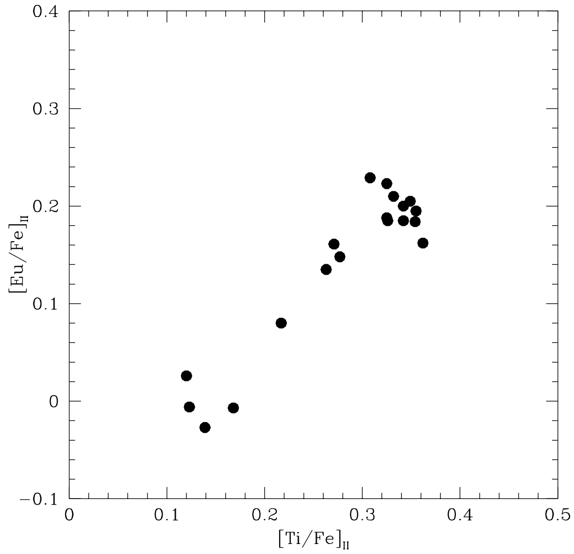

Fig. 4. Plot of [Eu/Fe] versus [Ti/Fe]

A very clean result is presented in Fig. 4, where the abundance of the prototypical r-process element Eu is compared to the Ti abundance. The correlation is nearly perfect. It allows us to conclude that, in general, the r-process element Eu is synthesized in the same objects as the α-elements, i.e. most probably in the supernova explosion of massive stars, confirming the generally accepted scenario. We notice the absence of a vertical feature similar to the one obtained for [Y/Fe]. Instead, it is replaced by a clumping of the points at the maximum value of [Ti/Fe] and [Eu/Fe].

4. Tentative scenario

According to the results presented above, we can distinguish between two separate stellar populations. Roughly 50% of the stars in our sample show a range of moderate overabundances of the α-elements and a slowly varying abundance of the s-process elements relative to the iron peak. The other 50% of the stars in the sample show a constant (and maximum) overabundance of the α-elements relative to the iron-peak elements, and varying s-process abundances. This behaviour must be related to nucleosynthesis processes.

The first interpretation which comes to mind is to relate one of these populations to the most metal-rich part of the halo and the other to the most metal-poor part of the disk. This interpretation is somewhat similar to what has been recently proposed by Nissen and Schuster (1997). However, upon examination of the kinematical data for our sample, there is no clear distinction between these populations on this basis alone, both populations containing high velocity stars typical of halo kinematics.

We therefore propose an alternative interpretation in which the halo stars can be divided into two sub-classes of Pop II stars, namely Pop IIa and Pop IIb, forming the two branches in Fig. 3. The stars belonging to the disk do not exhibit such correlations in their element abundances, unless they are very metal-poor. We will discuss these points in more details in a subsequent paper. In the following, we propose a scenario explaining the origin of the two sub-classes of halo stars.

4.1. General picture

First we assume a burst of star formation with at least some massive stars. As these massive stars evolve and end their lives in supernova (SN) explosions, α-elements and r-process elements are ejected in the surrounding interstellar matter (ISM). A second generation of stars will form out of this continuously enriched ISM. These stars will form the Pop IIa stars, with values of [α/Fe] and [r/Fe] increasing with time. The slope in [Y/Fe] versus [Ti/Fe] for Pop IIa stars indicates an overproduction of Y relative to Fe in massive stars. Our results show the same tendency for Sr and Zr.

Assume now that after this burst phase no more massive stars are formed. The lower mass stars are either still reaching the main sequence or in a more evolved phase, maybe already processing s-elements. These elements will be ejected through stellar wind or superwind events and will contaminate the surrounding ISM. After the SN phase, the ISM was already enriched in α and r-process elements, showing a unique [α/Fe] and [r/Fe]. The interstellar matter will continue to condense in new stars, now with a constant value of [α/Fe] and increasing values of [s/Fe]. These stars will form the Pop IIb stars.

Note that [Eu/Fe] shows a perfect correlation with [α/Fe] in Pop IIa stars, as expected. The points representative of Pop IIb stars are clumped at the maximum value of [α/Fe] and [r/Fe], i.e. at the values reached at the end of the massive stars outburst. This shows that, if produced by lower mass stars, it must be in the same proportions as Fe.

4.2. Globular clusters and EASE scenario

We now suggest that the formation of the field halo stars takes place in the globular clusters (GCs). This requires two reasonable assumptions. The first one is that the evaporation of low mass stars from GCs happens since the early phases of the evolution of the cluster and accounts for the field Pop II stars. The second one is that the matter ejected by SNe and stellar winds, although generally assumed to be mostly expelled from the cluster, nevertheless contributes to the enrichment of the lower mass stars, first by mixing with the ISM and then by accretion at the surface of already formed stars. The possibility of self-enrichment by SNe has been discussed by Smith (1986, 1987) and Morgan and Lake (1989).

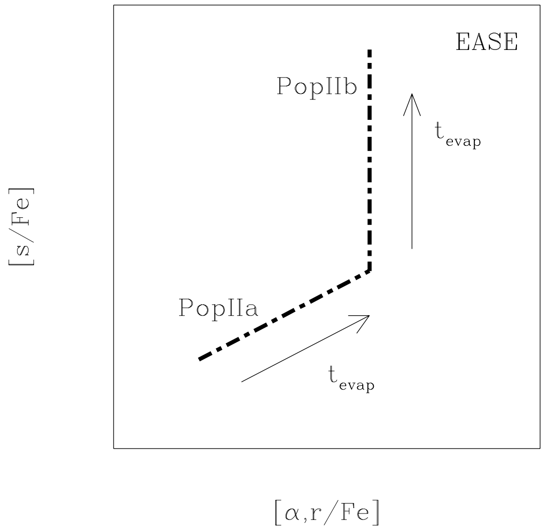

Fig. 5. EASE scenario. Here, t_{evap} is the time elapsed between the cluster formation and the evaporation of the star from the cluster

In the early phase of the GC evolution, massive stars will form SNe until all stars more massive than about $8M_{\odot}$ have completed their evolution. This fixes the end of the α and r elements synthesis and the maximum value of [α/Fe] observed in Fig. 3. The second phase will lead to a relative enrichment of s elements only.

Our two phases scenario nicely explains the features observed in Fig. 3. Pop IIa stars are evaporated during the massive stars outburst, [α/Fe] increasing with time, and the Pop IIb stars escape later in the evolution of the cluster, after the end of the SN phase. The stars located at the top of the vertical branch are those which have escaped the cluster in the most advanced phases of its evolution. A schematical illustration is given in Fig. 5.

The range of metallicity at a given location in Fig. 3 corresponds to stars evaporated from clusters of various global enrichments (due to different initial mass functions) and, thus, different present day metallicity. As the evolution time for a star of a given mass is about the same in all GCs, it is no surprise that the abundance ratios, contrary to the metallicity, do not depend on the cluster from which the halo stars have evaporated.

The similar numbers of Pop IIa and Pop IIb stars suggest that either the evaporation was much more efficient in the early phases of the GC evolution or that a large fraction of Pop IIa stars originate from GCs which have been disrupted during the massive stars outburst. This is in agreement with the view that GCs with a flat mass function are weakly bound (Meylan and Heggie, 1997). This is also in agreement with the recent work of Brown et al. (1995), where they develop a model for the early dynamical evolution and self-enrichment of GCs.

The EASE (Evaporation/Accretion/Self-Enrichment) scenario also nicely explains the larger metallicity range covered by the field halo stars, extending to much lower metallicities than the GCs. The very metal-poor stars would be evaporated from the GCs at a very early stage of the outburst phase, when the self-enrichment of the cluster was still very low.

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