Abundance Correlations in Thick Disk and Halo Stars*

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Abstract: We have analysed high resolution and high signal-to-noise spectra of 21 mildly metal-poor stars ([Fe/H] ~ -1). 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 metal-poor stars which differ by the behaviour of the s-process elements versus the α and r-process elements.
We suggest a scenario for the formation of metal-poor stars, which closely relates the origin of these stars to the evolution of globular clusters. According to this scenario, thick disk and field halo stars were born in proto-globular clusters from which they escaped, either during an early disruption of the cluster or through a later disruption or an evaporation process.

1 Introduction

Traditional abundance analyses of metal-poor stars aim at determining abundance ratios of some chemical elements as a function of the overall metallicity, usually measured by the iron abundance [Fe/H] [1]. These trends are then compared to predictions from models of nucleosynthesis and chemical evolution of the Galaxy, in order to provide constraints on the sites and mechanisms for element synthesis.
However, many of these abundance ratios show rather considerable star-to-star scatter, so that they provide 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. In a first step, this allows to decrease the scatter in the abundance ratios, but only down to a certain point, since there is a genuine cosmic scatter which can now be measured and analysed, provided the data are of sufficient quality.
With such high quality data, we can therefore investigate the cosmic scatter in the relative

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[1] We adopt the usual spectroscopic notation: $[A/B] \equiv \log_{10}(N_A/N_B)_* - \log_{10}(N_A/N_B)_\odot$ for elements A and B.

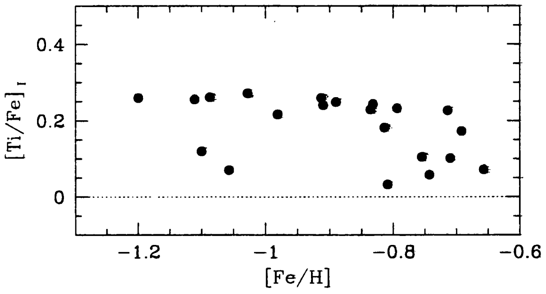

Figure 1: Traditional plot: the abundance of Ti relative to Fe versus [Fe/H].

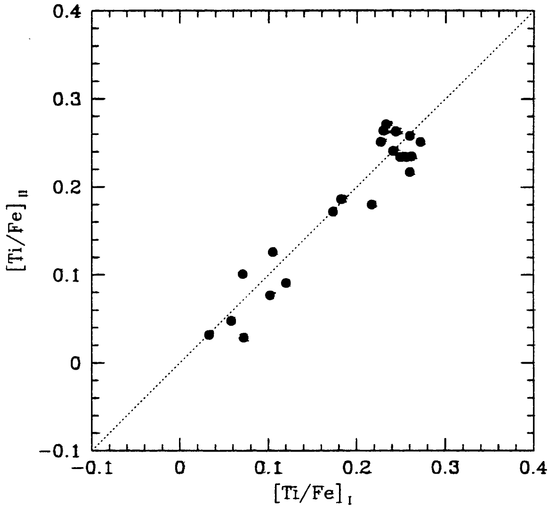

Figure 2: Comparison of the values of [Ti/Fe] determined from ionic and from neutral lines.

abundances at a given metallicity, and look for correlations between different elements. These correlations should give better constraints on the sites of formation of these elements, and on the nucleosynthetic mechanisms responsible for their formation.

Here, we present the results of such an analysis (Jehin et al. 1999) for a sample of moderately metal-poor stars and we suggest a scenario explaining the observed trends.

2 Observational data and abundance analysis

We have selected a sample of 21 unevolved metal-poor stars with roughly solar temperatures and one tenth of the solar metallicity. This metallicity range is very interesting because it corresponds more or less to the transition between the halo and the disk.
The observations were carried out with the Coudé Echelle Spectrometer (CES) fed by the 1.4 m Coudé Auxilliary Telescope (CAT) at the European Southern Observatory (La Silla, Chile). The spectral resolution is of the order of 65 000 and the signal-to-noise ratio in the continuum of the reduced and coadded spectrum is at least 200 in the 4 spectral regions chosen for each star. About 100 lines belonging to 16 elements have been measured and a comparison of our EW's with those of Zhao and Magain (1991) indicates that our precision is better than 1 mÅ.

2.1 Atmospheric parameters

The effective temperatures $T_{\rm eff}$ were determined from the Strömgren b−y and Johnson V−K colour indices, using the calibration of Magain (1987) which is based on the infrared flux method (Blackwell and Shallis, 1977). The agreement between the temperatures deduced from the two colour indices is very good ($\Delta T_{\rm eff} = 45\,K \pm 40\,K$) and indicates that the internal precision is around 20 K. The model metallicities were taken from previously published analyses. For the surface gravities we have used the Strömgren c_1 index, with the calibrations of VandenBerg and Bell (1985) for the adopted temperatures and metallicities. A comparison of this method

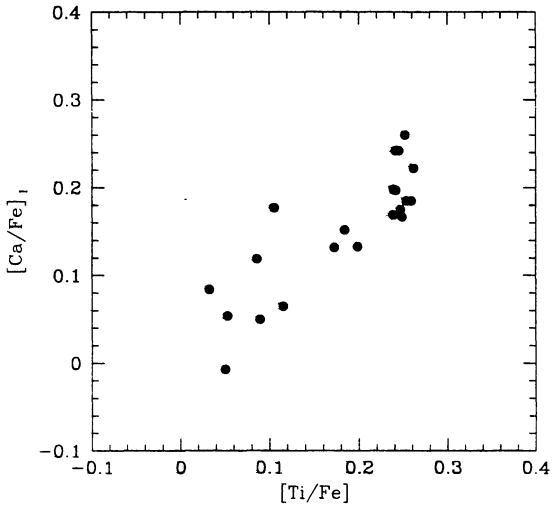

Figure 3: [Ca/Fe] versus [Ti/Fe]

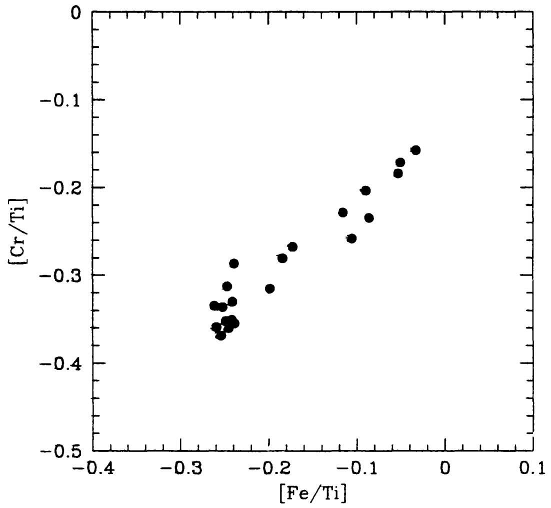

Figure 4: [Cr/Ti] versus [Fe/Ti].

for stars having Hipparcos parallaxes based gravities (Nissen et al. 1997) indicates that these photometric gravities are excellent ($\Delta\, log\, g = -0.07 \pm 0.11$). Microturbulence velocities ξ were obtained by forcing the FeI lines with different EW's to indicate the same abundance. The precision is around 0.1 km s^{-1}. The adopted model parameters for the 21 stars are listed in Table 2 of Jehin et al. (1999).

2.2 A strictly differential analysis

In order to reduce the analysis uncertainties, the lines were chosen, whenever possible, to have similar dependences on the stellar atmospheric parameters. Moreover, as the stars have similar atmospheric parameters, the analysis was carried out differentially inside the sample (each star was compared to all other stars in the sample). The zero point was then fixed by analyzing one of the stars using oscillator strengths available in the literature (the precise value of this zero point is relatively unimportant as it does not affect the abundance correlations).

2.3 A genuine cosmic scatter

Following the typical abundance analysis, we show in Fig. 1, the abundance of Ti relative to that of Fe, [Ti/Fe], plotted as a function of [Fe/H]. In the following figures, the subscripts I and II stand for neutral and ionized species and no specifications means that we have used a mean of the two species. We note a roughly constant overabundance of Ti relative to iron, with a 1σ scatter amounting to 0.080 dex (20%).

Now we address the following point: is this scatter real or is it due to observational and/or analysis uncertainties ? To answer this crucial question, we compare the values of [Ti/Fe] deduced from neutral lines with those deduced from lines of singly ionized species, as shown in Fig. 2. We can see a very nice correlation, with a scatter of 0.026 dex (6%) only. As the neutral and ionized lines have different dependences on the stellar atmospheric parameters, the analysis and observational uncertainties should not exceed 6%, and most of the scatter in the abundance of Ti relative to Fe represents therefore real cosmic scatter.

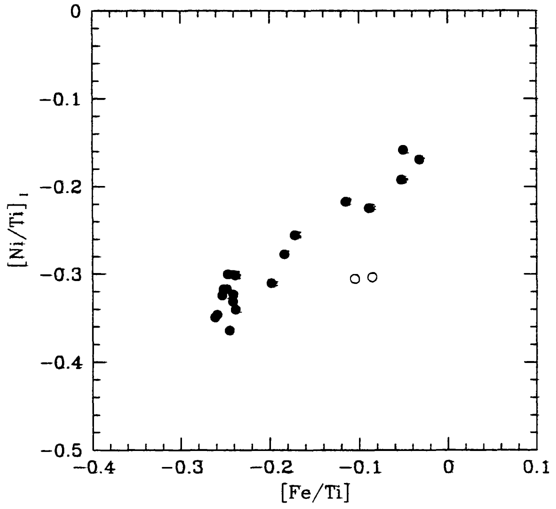

Figure 5: [Ni/Ti] versus [Fe/Ti].

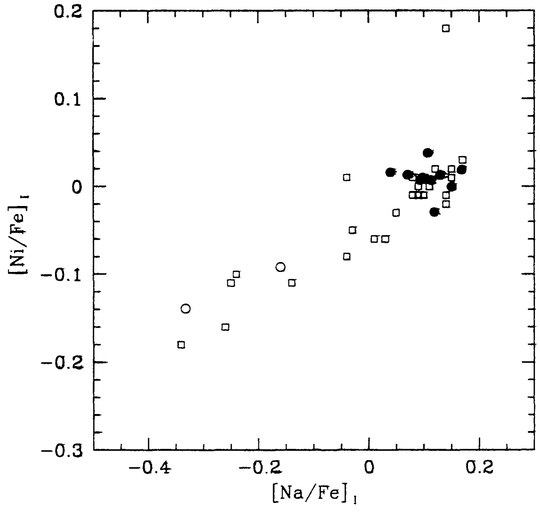

Figure 6: [Na/Fe] versus [Ni/Fe]

We can thus conclude that our data are of sufficient quality to investigate the cosmic scatter in the relative abundances of the chemical elements, and proceed in the analysis of these correlations.

3 Abundance correlations

In Fig. 3 we show the abundance of Ca relative to Fe, as a function of [Ti/Fe]. We see immediately that the two elements Ca and Ti are closely correlated. The same is true for Mg. We conclude, and this is certainly no surprise, that the so-called α-elements were synthesized by the same process in the same objects. This is in agreement with the accepted view that the α-elements are mainly produced during supernova explosions of massive stars.
The abundance of Cr and Fe relative to Ti also show a remarkable correlation (Fig. 4), indicating a common origin for these two iron-peak elements. The same holds true for Ni (Fig. 5), with two exceptions: the stars HD193901 and HD194598 appear to be somewhat depleted in Ni. These two stars, which present other abundance pecularities, will be identified by open symbols in all subsequent figures.

Recently we have also determined Na abundances for some of our stars and we confirm (circles in Fig. 6) the clear correlation between Ni and Na, already pointed out by Nissen and Schuster (1997) (open squares in Fig. 6). Moreover these abundances seem to be also correlated with the kinematics (Jehin and Bancken, these proceedings).

The main purpose of this work was to study the behaviour of the neutron-capture elements, in order to identify the sites and mechanisms for the synthesis of these elements, in a relatively early phase of the galactic evolution.
In Fig. 7 the abundance of the prototypical r-process element Eu is compared to the Ti abundance. The correlation is almost perfect, except for the same two stars which show a Ni depletion. Now, they stand up as relatively enriched in Eu. The nice correlation allows us to

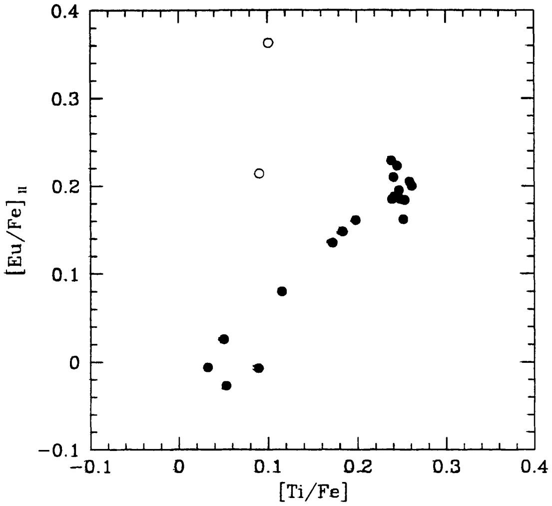

Figure 7: [Eu/Fe] versus [Ti/Fe].

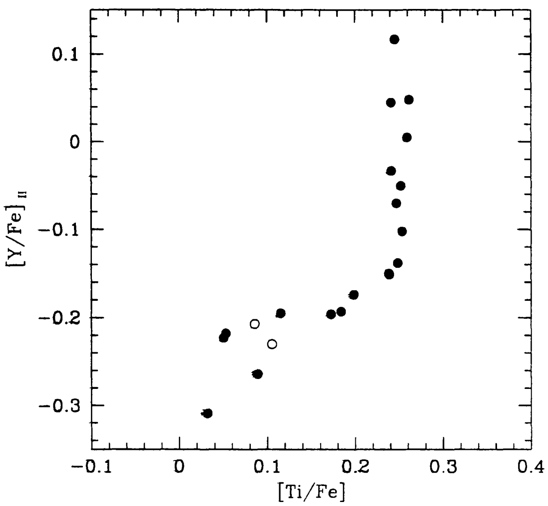

Figure 8: [Y/Fe] versus [Ti/Fe].

conclude that, in general, the r-process elements are synthesized in the same objects as the α-elements, i.e. most probably in the supernova explosion of massive stars, which confirms the generally accepted scenario.

A more complex situation appears when one examines the s-process elements (Fig. 8). In a first group of stars (Pop IIa) the relative abundance of Y increases slightly with the α-elements abundance, until a maximum value for the α-elements abundance is reached. In the second group of stars (Pop IIb), the α-elements to iron ratio is constant and maximum while the [Y/Fe] shows a large range of enhancement. We find similar results when any of the light s-elements, Sr, Y and Zr is compared to any of the α-elements. We called this behaviour the "two-branches diagram".

4 The two-branches diagram and the EASE scenario

This peculiar and well defined behaviour, which should be related to nucleosynthesis processes, has led us to distinguish between two sub-populations of metal-poor stars, namely Pop IIa and Pop IIb. The first interpretation which comes to mind is to relate one of these populations to the most metal-rich stars of the halo and the other to the most metal-poor stars of the disk.

In Fig. 9 we have added to our data (black squares), and after zero-point corrections, the stars from Zhao and Magain (1991) (full pentagons), Nissen and Schuster (1997) (full triangles), and Edvardsson et al. (1993) (full circles for stars with [Fe/H] < -0.6 and open circles for the more metal rich ones). All the stars with [Fe/H] < -0.6 fall on the two-branches diagram, but it is not true for the more metal rich stars, which have disk kinematics. On the other hand, no obvious distinction in term of metallicity or kinematics was found between the two branches.

This leads us to propose an alternative interpretation linking field metal-poor stars to globular clusters (GCs). We propose that thick disk and halo stars were born in GCs or proto-GCs, from which they escaped, either during an early disruption of the cluster (Pop IIa) or later through an evaporation process (Pop IIb). We distinguish between two distinct phases of chemical enrichment in GCs : a first one consisting in supernovae explosions of massive stars which could disrupt the cluster and account for the Pop IIa (G. Parmentier et al., these proceedings)

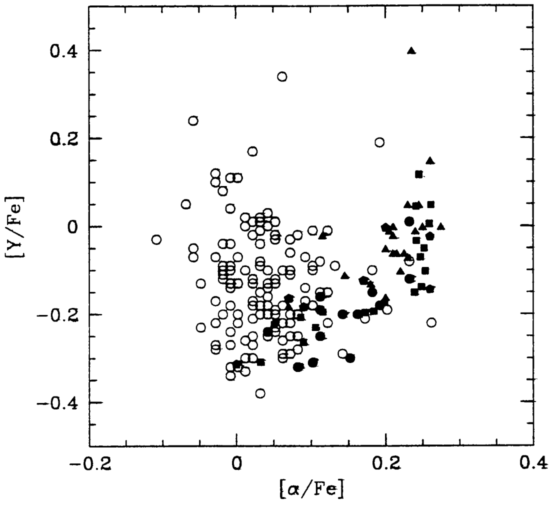

Figure 9: A universal two-branches diagram for metal-poor stars ? For symbols, see text.

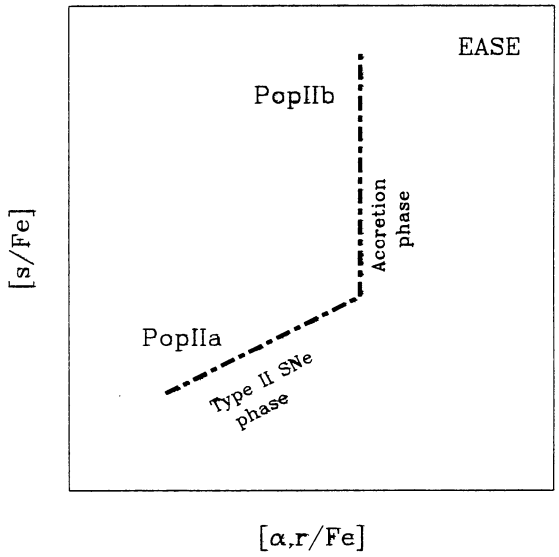

Figure 10: The EASE scenario for : Evaporation Accretion and Self Enrichment.

and, later, a second phase, to account for Pop IIb, where the stars atmospheres are enriched in *s*-process elements by the accretion of the products expelled by AGB stars onto the intra-cluster medium (A. Thoul et al., these proceedings).

Acknowledgements

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DISCUSSION

P.E. Nissen: Why do you disregard the contribution of elements from SNIa in your EASE scenario ?

R. Gratton: Winds from type Ia SNe are too fast to significantly pollute other cluster members. You need a slower wind.

P. Magain: As soon as a Type Ia SN explodes in a (proto-) GC, its strong wind is likely to sweep all the remaining gas out and to stop the chemical evolution.

G. Gilmore [Comment]: One source of abundance "anomalies"particularly relevant to globular cluster models of galactic chemical evolution is mass transfer in close binaries, and possibly even stellar mergers, leading perhaps to blue stragglers. In a dense cluster, of the type which will disrupt through internal dynamical evolution, binaries are repeatedly formed, destroyed and reformed. These binaries preferentially provide the high velocity escapers from the cluster, through 3-body interactions. Many of these must have undergone mass transfer – in the early stages, when many massive stars and large AGB stars, were common, this must have been common. Perhaps the surprise is that so few field stars show evidence for this history.

F. D'antona: In answer to the previous comment, mass exchange in today's binaries in GC stars regards quite low mass (uninteresting ?) stars, while the scenario here regards accretion from gas in early stages, when the more massive (3-5 $M_\odot$) heavily s-process enriched AGB stars were evolving. Pollution from their envelopes is then more effective in altering surface stellar composition.

B. Carney: I like your idea of searching for abundance anomalies in globular clusters. Variations from AGB evolution might affect cluster stars generally, but you should be careful to understand if the program stars are binaries, in which case the accretion could be "local" to the star rather then "global" and involving the entire cluster.

A. Helmi: If you would attribute all halo field stars to disruped globular cluster, this would mean that the initial population of GCs would have been at least ten times the present one. Evidence coming from studies of RR Lyraes in the bulge show that, if you would attribute all these stars to disrupted GCs, the initial popul ation could not have been more twice the current one.
However, the type of constraints or modelling may be applied to satellite galaxies, rather than GCs, which are better motivated in current cosmological models. Have you thought about applying what you find to such systems ?

E. Jehin: Nobody really knows what was the population of GCs and proto-GCs in the past. According to some recent studies, the processes of disruption and evaporation of GCs could have been and still is quite efficient. There is however no clear consensus about this subject in the litterature. I have the feeling that the count of RR Lyraes can

only provide a lower limit.
GCs (or proto-GCs) are good progenitor candidates for field metal-poor stars (FMPS) since the metallicity distribution function and the kinematics of the GCs population and the FMPS are very similar. GCs also provide the right physical conditions for accretion of material (a crucial point in our scenario) to be effective (Thoul A. et al., this meeting). However Nissen and Schuster (1997) suggested that the stars with low α and Na to iron ratios (the stars corresponding to our PopIIa branch) are coming from disrupted dwarf galaxies, the low values being due to the production of iron by type Ia SNe. However these stars seem to have rather eccentric orbits, a characteristic which exclude the possibility that the progenitors could be lightly bound systems such as dwarf galaxies (Jehin and Bancken, this meeting). In our scenario, we propose that these stars are coming from disrupted proto-GCs and thus the chemical composition of their atmospheres would be typical of yields of massive stars only.

C. Travaglio: You showed the correlation between Eu and Y with alpha-elements. Did you try to do the same with Ba and alpha-elements ?

E. Jehin: We have obtained data for the heavy s-process elements Ba and La. These two elements correlate very well with each other. The comparison with the alpha-elements is somewhat different from that of the light s-process elements Sr, Y and Zr. Once again, we can distinguish two groups of stars, the first one with variable [Ti/Fe] and a second vertical one at the maximum value of this abundance ratio. But the slope of the first group of stars is not as well defined as in the case of the lighter s elements. This may be due to the lower quality of the data, but might also reflect a different nucleosynthetic history. The latter hypothesis is supported by the fact that at least one of the anomalous stars, which perfectly fits in the light s diagrams, now shows up again as overenriched in heavier s elements.