From Lithium to Uranium: Elemental Tracers of Early Cosmic Evolution
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Early chemical evolution of the Milky Way

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Abstract. The earliest phases of the chemical evolution of our Galaxy are analysed in the light of the recent VLT results (concerning abundance patterns in the most metal-poor stars of the Galactic halo) and of stellar nucleosynthesis calculations. It is argued that, among the various suggestions made in order to explain the observed abundance patterns, nucleosynthesis in asymmetric supernova explosions appears most promising. The data suggest a correlation between asymmetry and metallicity, which is hard to justify theoretically. The data also confirm the absence of dispersion in abundance ratios, at least up to the Fe peak, in the early Galaxy; this may be related to the (presently poorly known) timescales of homogeneisation of the interstellar medium, but also on small yield variations among massive stars. Finally, the metallicity distribution of halo stars may provide important constraints on the formation of the Milky Way; at present, it is not clear whether observations support the hierarchical formation scenario.

Keywords. Galaxy: evolution – Galaxy: halo

1. Introduction

Despite the many uncertainties still affecting the ingredients of galactic chemical evolution (large scale gas movements, like inflows or outflows; interactions between stars and gas, like large scale star formation and supernova feedback; stellar yields, etc.) such studies provide a useful framework for the interpretation of the everincreasing wealth of observational data concerning abundances in stars of the Milky Way and other galaxies, as well as in the interstellar and even the intergalactic medium.

In particular, studies of abundance ratios in the oldest stars of the Milky Way allow one to put interesting constraints on the nature of the first stars that enriched the interstellar medium with metals. Ultimately, one may hope to find a distinctive imprint of the very first generation of massive stars (Population III), those that were born out of primordial material containing H and He only (as well as trace amounts of ^{7}Li, resulting from the Big Bang). The underlying assumption is that some property of those stars (characteristic mass, rotation, explosion energy etc.) was quite different from the corresponding one of their more metal rich counterparts and produced a different nucleosynthetic pattern in their ejecta. This pattern should then be visible on the surfaces of the next generation stars that were born from the enriched gas and are still around today (i.e. the oldest and most metal poor Pop. II stars).

The idea of a "peculiar" first stellar generation is mildly supported by theoretical and observational arguments. Indeed, star formation theory (and simulations) suggest that the first stars were very massive (Nakamura and Umemura 2002, Glover 2004 and references therein). On the other hand, WMAP data suggest that efficient ionizing agents existed early in the cosmic history (Kogut *et al.* 2003); very massive and low metallicity stars are quite hot and are thus "natural" candidates, although the idea encounters some problems (e.g. Ricotti and Ostriker 2004). In view of the many important implications

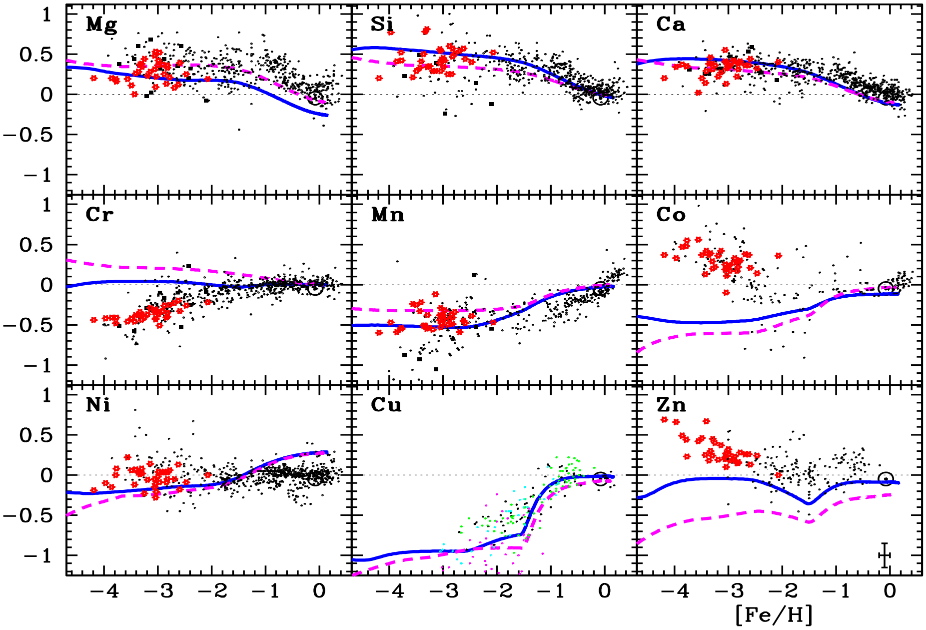

Figure 1. Abundance ratios [X/Fe] as a function of metallicity [Fe/H] in stars of the Milky Way; small data points are from various sources, while the large data points at low metallicity are from the recent VLT survey of Cayrel *et al.* (2004). Results of standard chemical evolution models, performed with two sets of metallicity dependent massive star yields (Woosley and Weaver 1995, *solid curves* ; Chieffi and Limongi 2004, *dashed curves*) are also displayed. Yields for SNIa are adopted from Iwamoto *et al.* (1999) and for intermediate mass stars from van den Hoek and Gronewegen (1997). While the behaviour of alpha elements and Mn is correctly reproduced (at least qualitatively), there are large discrepancies in the cases of Cr, Co and Zn.

of those ideas, it is interesting to investigate whether the observed abundance patterns of old stars reveal any trace of a Pop III stellar generation with peculiar properties.

2. Abundance patterns in the early Milky Way

In the framework of ESO's Large programme "First Stars", abundances for 17 elements, from C to Zn were obtained for about 30 giant stars with metallicities $-4.1 < [\mathrm{Fe/H}] < -2.7$, through high resolution and signal/noise ratio data of VLT/UVES (Cayrel *et al.* 2004, Spite *et al.* 2004).

The recent data on Extremely metal Poor (EMP) stars confirm some previously found tendencies (e.g. McWilliam *et al.* 1995).

– The constancy, down to the lowest observed metallicities, of the α/Fe ratio (where α stands for alpha elements like O, Mg, Si, Ca); the high value of that ratio ($\sim$3 times solar) is attributed to the late contribution of Fe by SNIa, with long lived progenitors.

– The constancy of the N/Fe ratio, which still lacks a satisfactory explanation (since N is produced as secondary in "standard" calculations of massive stars); mixing of protons in He zones of (rapidly) rotating stars appears a promising mechanism for the production of early primary N (Meynet, these proceedings).

– The decreasing values of Mn/Fe and Cu/Fe with decreasing metallicity, in qualititative agreement with theoretical expectations (e.g. Fig. 1).

However, more interesting are the cases where observations are at odds with theoretical expectations. These are the cases of Cr, Co and Zn, already suggested by older observations and confirmed by VLT data. The discrepancies are clearly seen in Fig. 1, where the results of a full-scale chemical evolution model of the Milky Way (originally presented in Goswami and Prantzos 2000) are displayed. The adopted stellar yields are from Core Collapse supernovae (CCSN) in the "normal" mass range of 12 to $\sim$40 $M_\odot$ and with progenitor metallicities from Z=0 to $Z=Z_\odot$ (Weaver and Woosley 1995, Chieffi and Limongi 2004).

The reasons for those discrepancies probably lie in our poor understanding of the explosion mechanism and of the nature of the early CCSN. Several attempts have been made in recent years to identify key ingredients of the stellar explosion/nucleosynthesis that would bring theory and observations into agreement; none of those produced convincing results up to now. In particular:

– *The position of the "mass-cut"*: a deeper "mass-cut" favors products of complete Si-burning, i.e. produces higher Co/Fe and Zn/Fe and lower Cr/Fe and Mn/Fe ratios; however, it also produces unacceptably large Ni/Fe ratios and should be ruled out (e.g. Nakamura *et al.* 1999)

– *Very massive stars exploding as PISN* (pair instability supernovae): they do not produce enough Zn (Heger and Woosley 2002, Umeda and Nomoto 2005), because they undergo very little complete explosive Si-burning, and should be ruled out.

– *High energy explosions* ("hypernovae", with kinetic energy values higher than the canonical one of $\sim10^{51}$ ergs): they produce large amounts of Zn, but also too much Ni, so that a combination of mixing and fallback has to be introduced to bring agreement with observations (Nakamura *et al.* 2001, Umeda and Nomoto 2005); however, Mn/Fe and Co/Fe are always undeproduced in that case (i.e. obtained values are much lower than observed ones in extremely metal poor or EMP stars), which should also be ruled out.

– The precise value of *the electron mole fraction* Y_e in the nucleosynthesis region of Fe-peak elements plays also an important role in shaping the final abundance ratios, like the ones of mono-isotopic and odd Co and Mn (Nakamura *et al.* 2001; Umeda and Nomoto 2005); although a careful treatment of all the weak interactions improves the situation with Zn (avoiding at the same time excessive Ni overproduction, Frohlich *et al.* 2004), it certainly cannot help with the other elements and is not the answer to the problem.

– *Asymmetric (bipolar) CCSN explosions of rotating stars* produce a more satisfactory picture (Maeda and Nomoto 2003): material ejected along the rotation (jet) axis has high entropy and is found to be enriched in products of a-rich freeze-out (Zn and Co), as well as Sc (which is generically undeproduced in spherical models), while Cr/Fe and Mn/Fe are found depleted. The energy of the explosion and the position of the mass-cut also play a role in determining the absolute yield of ^{56}Ni and the α-element/Fe ratio. This kind of models seems at present the most promising, but this is not quite unexpected (since they have at least one more degree of freedom w.r.t. spherical models).

Some of the results of the aforementioned models are displayed in Fig. 2 and are compared with the VLT data for EMP stars.

3. Are abundance patterns due to a metallicity dependent property?

Very massive stars (of a few hundred $M_\odot$, exploding as PISN) do not manage to reproduce the observed abundance patterns at low metallicity, at least at the present

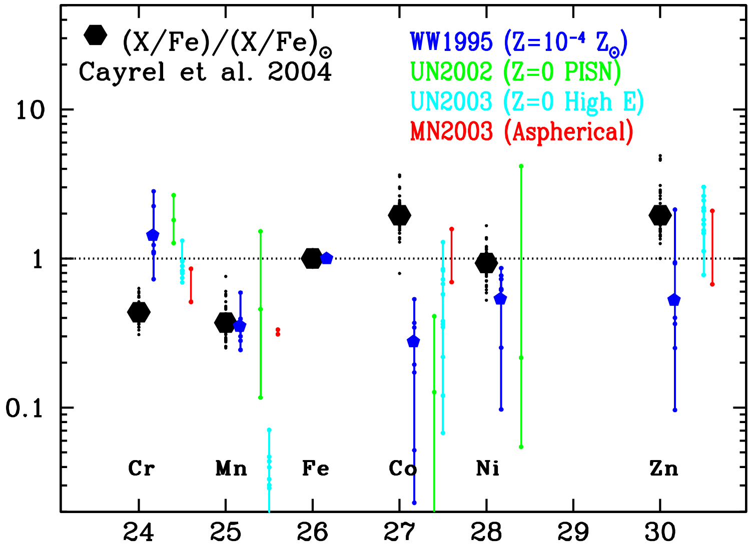

Figure 2. Abundance ratios X/Fe (in solar units) for Fe peak elements. Large hexagons correspond to the *average* values of the low metallicity stars of Cayrel *et al.* (2004); values for individual stars of that survey (giving an idea of the dispersion) are also shown as smaller symbols on the same vertical line. Adjacent lines connect results for stars of different masses calculated by various authors under different assumptions (see text); in the case of WW95 yields, the larger symbol indicates the average over an IMF.

stage of our understanding (as far as I know, no consistent models of *rotating PISN* have been explored up to now).

All the other potential answers (e.g. energy, mass-cut, rotation) concern *normal massive stars* of a few tens of M$_\odot$ and it is not at all clear how such stellar properties could be linked to metallicity. Indeed, the VLT data suggest a smooth variation of Cr/Fe and Co/Fe with Fe/H; taking into account the halo metallicity distribution function (see Fig. 3), one sees that a large fraction of the halo stars (up to ∼20%) may display such peculiar patterns. The conclusion is that the stellar property responsible for those peculiar patterns did not characterise only a single first generation of CCSN but *it varied smoothly with metallicity.*†

This picture is at odds with the idea (Ryan *et al.* 1996, Tsujimoto and Shigeyama 1998, Umeda and Nomoto 2005) that all the EMP stars were formed near a single (or very few) CCSN of the first generation and their metallicity was fixed by the amount of interstellar gas mixed with the SN ejecta; according to that idea, the more energetic CCSN would mix with more hydrogen and produce lower Fe/H ratios than the ones with smaller energy. However, it is hard to understand in that framework the observed constancy and low dispersion of α/Fe ratios at low metallicity: indeed, variations in the energy of the explosion should affect considerably that ratio (since the α elements are produced mostly hydrostatically and the Fe-peak elements explosively).

† In the case of rotation, one may understand such a variation (at least qualitatively) as resulting from loss of angular momentum due to mass loss (e.g. Meynet *et al.* 2004): mass loss becomes more important in more metallic stars and reduces their final rotation rate, making their nucleosynthesis less "exotic" than the one of zero metallicity stars.

4. The puzzling absence of dispersion in abundance ratios

Those questions are naturally related to the issue of dispersion in the abundance ratios of EMP stars. Simple-minded arguments suggest that dispersion should increase at low metallicities, under the explicit assumption that low metallicities correspond to such early times that complete mixing of SN ejecta with the interstellar medium is impossible (Argast *et al.* 2002, Karlsson and Gustafsson 2001). The VLT data reveal very small scatter in the abundance ratios of EMP stars, compatible with observational uncertainties and in full agreement with the results of a previous study (Carretta *et al.* 2002). This could mean that i) mixing timescales are (much) shorter than typical chemical evolution timescales at metallicities down to $[\mathrm{Fe/H}] \sim -4$, or ii) variations in abundance ratios of SN of different masses and energies are sufficiently small, or a combination of (i) and (ii).

Despite our current ignorance of the timescales of mixing and early chemical evolution, case (i) cannot be the whole truth, since large variations in abundance ratios are observed in the case of r-elements, also produced from (perhaps some class of) CCSN (see Ishimaru *et al.* these proceedings). Case (ii) obviously offers the opportunity to constrain variations in yield ratios of CCSN of different masses and metallicities (see Fig. 3 and Ishimaru *et al.* 2003). In that respect, it should be noted that the ad-hoc mechanism of mixture and fallback of the inner SN ejecta (adopted in Nakamura *et al.* 2001, Umeda and Nomoto 2005 etc.) may reduce considerably the scatter in hydrostatic/explosive or explosive/explosive element ratios and lead “naturally” to the absence of dispersion as a function of metallicity.

5. Metallicity distribution and halo formation

The metallicity distribution (MD) of long lived stars is one of the most powerful probes of galactic chemical evolution. The MD of the Galactic halo is poorly known below $[\mathrm{Fe/H}] = -3$, but ongoing surveys are expected to improve considerably the situation (Beers, these proceedings), bringing important information on the earliest stages of the halo formation (e.g. Prantzos 2003). In the metallicity range $-3 < [\mathrm{Fe/H}] < -1$ the halo MD is relatively well known: it is rather smooth and broad and peaks at $[\mathrm{Fe/H}] \sim -1.6$, which implies a reduced effective Fe yield of $\sim 1/40\ \mathrm{Z}_{\odot}$. This is most easily interpreted in the framework of simple chemical evolution models as the result of strong outflow, at a rate of ∼8 times the star formation rate (see Prantzos 2003 and references therein). But is it compatible with currently popular ideas of hierarchical galaxy formation?

The only quantitative study of the question, with numerical models of galaxy formation (Bekki and Chiba 2001) produces a halo MD which is considerably narrower than the observed one, but peaks (for reasons that are not obvious) at the correct [Fe/H] value, as seen in the histogram of Fig. 3. Moreover, the model MD is much less smooth than the observed one, the two displayed peaks reflecting probably the MDs of the last two big “chunks” that participated in the last major merger event.

It is not clear whether these features of the model MD of Bekki and Chiba 2001 (i.e. narrow and not smooth) characterise hierarchical scenarios generically; they could be simply due to poor numerical resolution or to poor modelisation of the complex physical processes in the early Galaxy. In any case, the issue of the halo MD is an important one (at least as important as the one of the abundance patterns of old stars) and requires further investigation, both observational and theoretical.

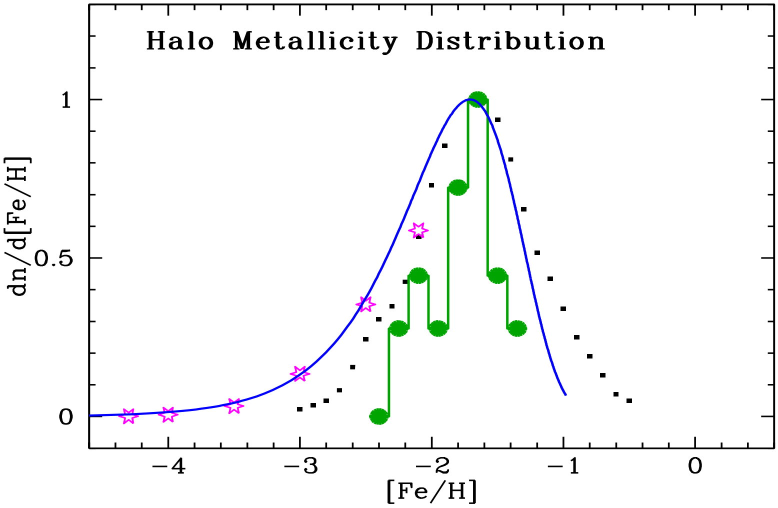

Figure 3. Halo metallicity distributions. Data are from Ryan and Norris (1991, *filled squares*) and the ongoing Beers survey (*asterisks*, incomplete above [Fe/H] = −2). A simple model with outflow rate = 8 times the Star formation rate (*solid curve*) and a numerical model in the framework of hierarchical galaxy formation (*histogram*, Bekki and Chiba 2001) are also displayed.

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