THE FIRST STARS: WHAT WE KNOW AND DO NOT KNOW

THE H&K SURVEY OF BEERS, PRESTON & SHECTMAN HAS BEEN THE MINE OF EXTREMELY METAL-POOR STARS DURING THE LAST DECADE OF THE XXTH CENTURY. THE VLT-UVES COMBINATION HAS ALLOWED US TO STUDY THE CHEMICAL COMPOSITION OF THE BRIGHTEST MEMBERS OF THIS POPULATION, FOSSIL COMPONENT OF EVENTS WHICH HAVE OCCURED EITHER DURING THE FORMATION OF THE GALAXY, OR EARLIER IN SMALLER SYSTEMS HAVING EVENTUALLY MERGED INTO OUR BEAUTIFUL MILKY WAY. WE REPORT HERE WHAT HAS BEEN DERIVED FROM A VLT LARGE PROGRAMME DEVOTED TO THESE OBJECTS, AS WELL AS ON OTHER QUESTIONS RELEVANT TO THE FIRST STARS.

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THERE IS AN INFALLIBLE WAY for recognizing a first star: it is born with the primordial composition left a few minutes after the big bang. The primordial big bang nucleosynthesis (BBN) is one of the safest part of nuclear astrophysics. The medium is very uniform, temperatures and densities are in a range where the reaction rates are known or inferred from experimental nuclear physics. There is a single free parameter, the density at a given temperature, or, in other words, the baryon-to-photon ratio η. The expansion, at its relativistic rate, sets the future of the medium, once the baryon-to-photon ratio is known. Figure 1 gives the result of such computations (Coc et al. 2004), adapted by the authors for the exact values of the observational results, and their uncertainties.

Qualitatively, the chemical composition is mostly hydrogen and ^{4}He, with traces of rare elements such as deuterium, ^{3}He and ^{7}Li. Quantitatively, it is necessary to know the value of η. Thanks to the results of the Wilkinson Microwave Anisotropy Probe (Spergel et al. 2003) this value is now firmly braketted $(6.2 \pm 0.2) \cdot 10^{-10}$, as shown in Fig. 1. It is remarkable that the predictions of the BBN are so close to the observations. Note that ^{7}Li is the only stellar abundance among the three. ^{4}He is observed in metal-poor blue-compact galaxies, and D in Lyman-α damped systems at high redshifts, because it has been destroyed in stars.
What do we see in extremely metal poor (XMP in short) stars? We see hydrogen, the main constituent. We do not see ^{4}He, because of its lack of lines in the observed spectral range, but indirect inference from the position of the main sequence indicates an abundance of helium in agreement with BBN. We also see the primordial element ^{7}Li, with about the expected BBN abundance (actually a little below), but we see also carbon, oxygen, magnesium, silicium, iron, etc..., admittedly in tiny proportions with respect to what we see in the sun (10^{-3} to 10^{-4} less), but still not zero, as it should be in a true first star. Sorry for that. We cannot offer a first star to you.

What does this mean? It means that the low mass stars still around, have been polluted by the ejecta of supernovae explosions, which have occured before their birth, or during their birth. The consolation is that analysing the abundances of these elements imprinted in an originally primordial matter gives an idea of the composition of the ejecta of primordial supernovae, which is interesting too.

THE ESO LARGE PROGRAMME 165.N-0276

In April 2000 an ESO Large Programme began: "*Galaxy Formation, Early Nucleosynthesis, and the First Stars*". Thirty eight nights were granted to this programme which spanned four ESO periods, 65 to 68. The aim of this programme was to observe, with VLT-UVES, all known stars of extremely low metallicity, bright enough to be observed with spectral resolution of 40,000, and S/N ratio of 200 per resolved spectral element.

The members of this LP were J. Andersen (DK), B. Barbuy (Brazil), T.C. Beers (US), P. Bonifacio (I), R. Cayrel (PI, F), E. Depagne (F), P. François (F), V. Hill (F), P. Molaro (I), B. Plez (F), F. Primas (ESO), B. Nordström (DK), F. and M. Spite (F). The programme has observed about 70 objects, 35 giants, 23 Turn-off (TO) stars and several other stars, practically all coming from the H&K survey of Beers, Preston and Shectman (1985). A significant part of them were classified as XMP, after medium resolution observations led at ESO, with slit

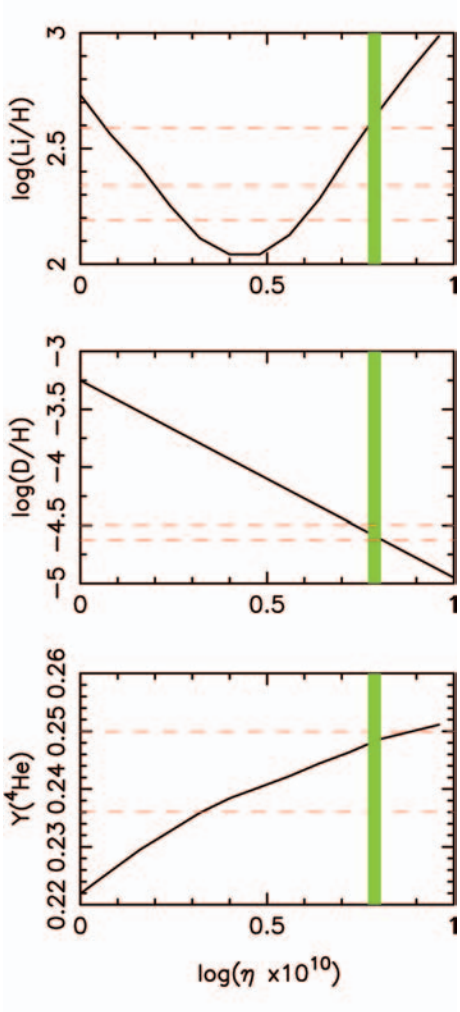


Figure 1: The primordial nucleosynthesis. η is the baryon/photon ratio. The ordinate are the logarithmic abundances per 10^{12} hydrogen atoms, except for helium, where the usual mass fraction Y is given. The curves are the theoretical predictions. The green lane is the WMAP determination of η. The horizontal red lines are the observed values, with their error bars. The error bar of Li is asymetrical because it includes the possibility that Li be depleted by gravitational settling or nuclear burning.

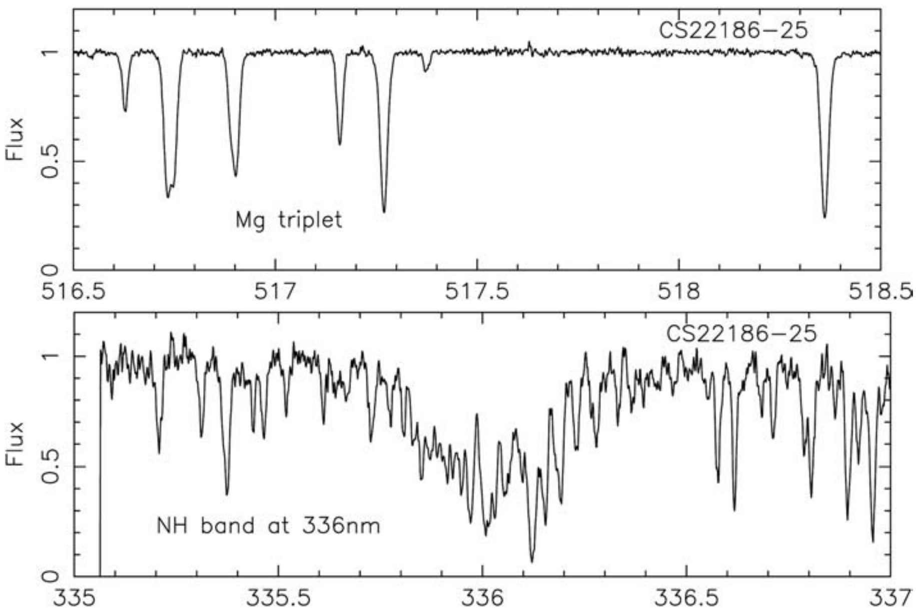


Figure 2: Sample spectrum of the Large Programme. The upper panel is the region of the Mg I *b* lines. The S/N ratio is about 200 per pixel. The lower panel shows the NH band at 336 nm. The S/N ratio has dropped to 30.

spectroscopy at 0.1 nm resolution, with the 1.5-m spectroscopic telescope. Figure 2 gives a sample spectrum of the observations with the spectrograph UVES. Note the weakness of the magnesium *b*-lines near 510 nm, very strong lines in pop. I, and the band of NH in the UV, but with an important loss in S/N ratio, due to the low flux in the UV of cool giants.

We summarize in the following sections a few findings of this programme, mostly in the 35 giants of the sample. The next section is devoted to three outstanding objects which have brought new insights into physical processes occuring in the early Galaxy. The following section summarizes what we have learned on the yields of the first supernovae, for the elements from C to Zn. A paper is near completion on the neutron-capture elements in the same sample of stars. Let us just say that the scatter is much larger for these elements than for those up to Zn. The last section comes back to the question of the absence of true population III objects in the observations.

CS 31082-001:
THE URANIUM STAR

When we started our programme, only upper limits had been obtained on the amount of uranium in halo stars. One of them, CS 22892-052 (Sneden 2003), though, was highly enriched in all *r*-process elements (by 1.5 dex), including thorium, but was also C and N rich, with the best line of U II at 385.97 nm obliterated by a CN line. One of our program stars CS 31082-001, a giant of metallicity [Fe/H]= –2.9 (Hill et al. 2002), is also enriched in *r*-process elements by a similar factor, but with two favorable features: CN lines are much weaker and U and Th are even more enriched than the other *r*-process elements, by a factor of about two. This has allowed a good measurement of both U (see Fig. 3) and Th in the star, making available for the first time the cosmochronometer U/Th. The difficulty is of course to know the production ratio of U and Th, but the availability of this uranium abundance has immediately triggered work in this field. From available pubished data in 2001, we derived an age of 14.0±2.4 Gyr for the formation of the *r*-process elements present in the atmosphere of CS 31082-001, completely independent of the cosmological estimate of the first star formation age by WMAP (13.5±0.4 Gyr). We do not hope to reduce our uncertainty to 0.4 Gyr, but only to reduce it to 1.5 Gyr in the near future. This value is also to be compared with the age of 13.2±1.5 Gyr obtained by Chaboyer for the galactic globular clusters, by a method independent of the other two. This convergence is very impressive.

Curiously, what has caused the greatest impact in the astronomical community was not the new availability of the U/Th chronometer, but the fact that the use of the older Th/Eu cosmochronometer was giving a negative age for CS 31082-001, under the assumption that the production ratio of Th/Eu was universal. If instead the age derived from U/Th is believed, one must conclude that U and Th have been overproduced with respect to the “universal ratio” by more than a factor of two, clearly not good for the universality hypothesis. More stars have now been found with Th/Eu values incompatible with the “universal” production ratio , such as CS 30306-132 and HD 221170.

CS 31082-001 has a gorgeous spectrum of the neutron capture elements. For example, thorium has ten measurable lines, when only two or three are such in the other XMP stars. Our abundances of U and Th would have been very uncertain without the crucial work of physicists in Lund (Sweden), who redetermined the absolute oscillator strengths of the lines of uranium and thorium. Unfortunately a large number of atomic data are still missing for heavy nuclei, hampering a non-LTE analysis of their stellar spectra.

The abundance of lead was also recently obtained in CS 31082-001 (Fig. 4). As lead is produced in the radioactive decay of Th

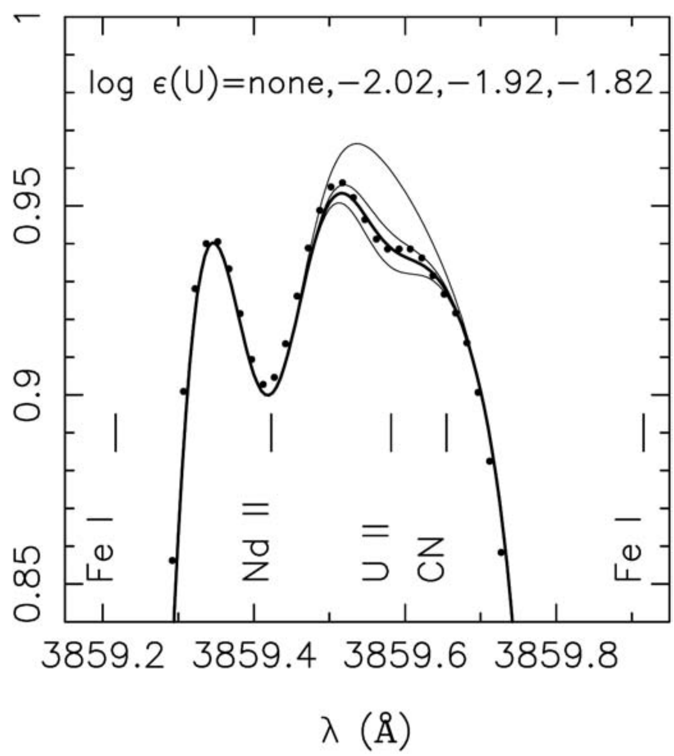
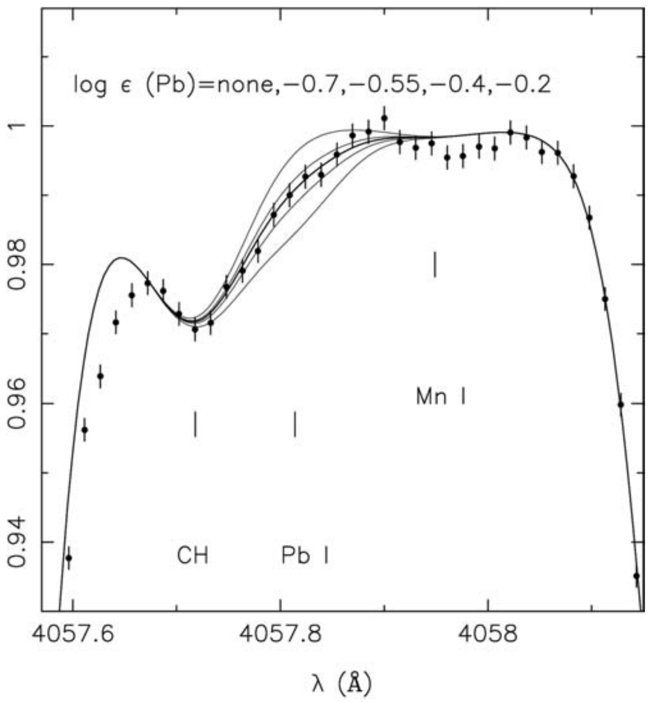


Figure 3: The spectrum of CS 31082-001 near the 3859.7 U II line.

Figure 4: The Pb I 4057.81 line in CS31082-001. It has been necessary to expose 17 hours to get this tiny feature out of the noise (S/N=600 for the cumulated exposures). The feature missing on the left is an unidentified molecular line containing carbon, because it becomes stronger in carbon-rich objects.



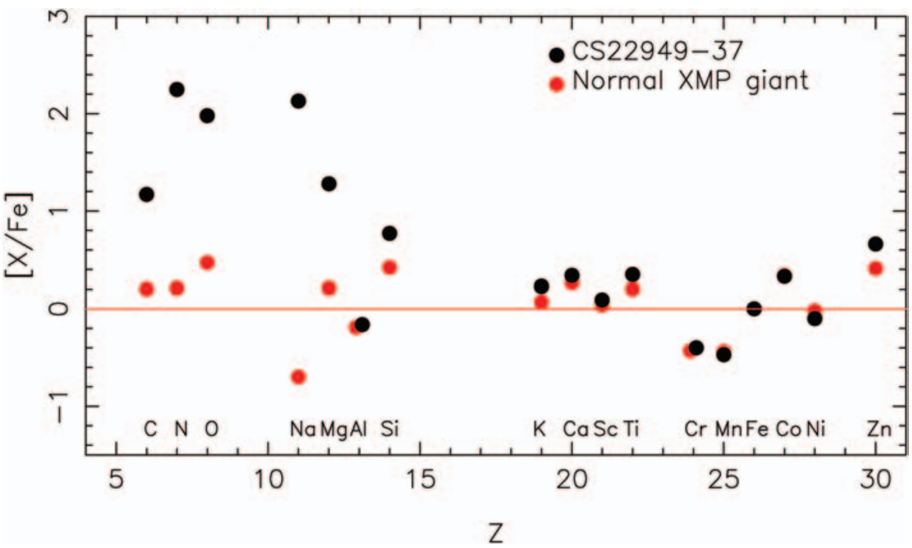


Figure 5: Abundance ratios in CS 22949-037 ([Fe/H]=–4), and in a normal mean XMP giant with [Fe/H] < –3. The abundance ratios are similar in both stars for elements heavier than Si. For the lighter elements there is a trend of decrease with increasing atomic number at variance with the normal XMP giants. This is very like what was predicted by Woosley and Weaver in 1995 as fall back in a supernova explosion.

(producing the isotope ^{238}Pb) and U (producing the isotopes ^{206}Pb and ^{207}Pb), it is interesting to know what fraction of lead is produced by this channel. The result of our LTE analysis is that 90 to 100 % of lead is produced by the decay of U and Th. A non-LTE analysis may lead to a smaller fraction, but it is unlikely that it can drop below 50 %. A non-LTE analysis is presently hampered by the lack of knowledge of the photoionization cross-sections of the ion Pb I.

Over 40 orbits of the HST have been obtained to extend our analysis of the neutron-capture elements to the spectral range 270 to 300 nm. The analysis is underway.

CS 22949-037: The evidence for fall-back in SN II explosions

We have not discovered CS 22949-037, which is a XMP giant with [Fe/H] = –4.0, and which was already studied by Norris, Ryan, Beers et al. (2002). But we have found, against expectation for such low metallicity, that the forbidden line of [O I] at 630 nm was measurable, and determined the abundance of oxygen in the star. It was found that [O/Fe] = 2.0 ± 0.15, i.e. that oxygen is less deficient than iron by a factor of 100. This value is similar to what is found for nitrogen, [N/Fe]=2.2, and carbon, [C/Fe] = 1.2. Morover, we found evidence in this star, as well as in all XMP giants which have lost their lithium, that dredge up bringing to the surface carbon processed into nitrogen has occured , suggesting that most of the N in CS 22949-037 was initially carbon, with [(C+N)/Fe] =1.7. If we plot the abundances as a function of [Fe/H] (Fig. 5), it is clear that the deficiency levels off at Si to a constant level.

In 1995 Woosley and Weaver had found, in a milestone theoretical paper, that if a supernova of 40 solar masses explodes with an energy of $1.9 \cdot 10^{51}$ erg, it expels only the upper shells containing C, O, and Ne (N if it has produced it), but that the lower layers fall back onto the core, feeding the remnant and not the interstellar medium. At an energy of $3 \cdot 10^{51}$ erg, on the contrary, the synthesized elements are all expelled.

The abundances in CS 22949-037 (Depagne et al. 2002) strongly suggest that we are witnessing a fallback event, as the deficiency gradient exactly follows the onionskin structure of the hydrostatic formation of the elements, those formed near the surface being much less depleted than those formed deeper. Usually, the computations with fallback expells a completely negligible amount of the most internal shells. The fact that CS 22949-037 shows a plateau for the elements produced in the most internal shells (K, Ca, Ti, Cr,Fe, Ni, ...) suggests that the fallback event occurred in a SN II born from a medium already slightly enriched, at the level [Fe/H] ≈ –4. Alternatively, some mixing may have occurred between the onion skins before or during the explosion.

CS 29497-030: A lead-star at very low metallicity

Another remarkable object emerged from our programme. A theoretical prediction by Goriely and Siess in 2001 led to the expectation that *s*-process elements could be synthesized not by neutron-capture by Fe nuclei, but by neutron-capture of abundant species as C or Ne in zero-metal (primordial) AGB stars. Quickly after, Van Eck et al. discovered 3 stars, HD 187861, HD 196944, HD 224959, showing the predicted pattern of this theoretical work. The signature is a very high abundance of Pb, with a Pb/Ba ratio much greater than one. Because the mass of AGB stars is less than the mass of SN II, the yields of AGBs are expected to pollute a matter already enriched in iron by SN II, *even if these AGBs are initially of primordial chemical composition.* Indeed the three quoted stars have metallicities [Fe/H] in the range –1.7 to –2.5. This last metallicity was considered by former studies a little bit like the onset of the appearance of the *s*-process, only the *r*-process ocurring at lower metallicities. We were then very surprised (Sivarani et al. 2004) to find in our programme, devoted to stars of metallicity below –2.7, a lead-star, and not only a lead-

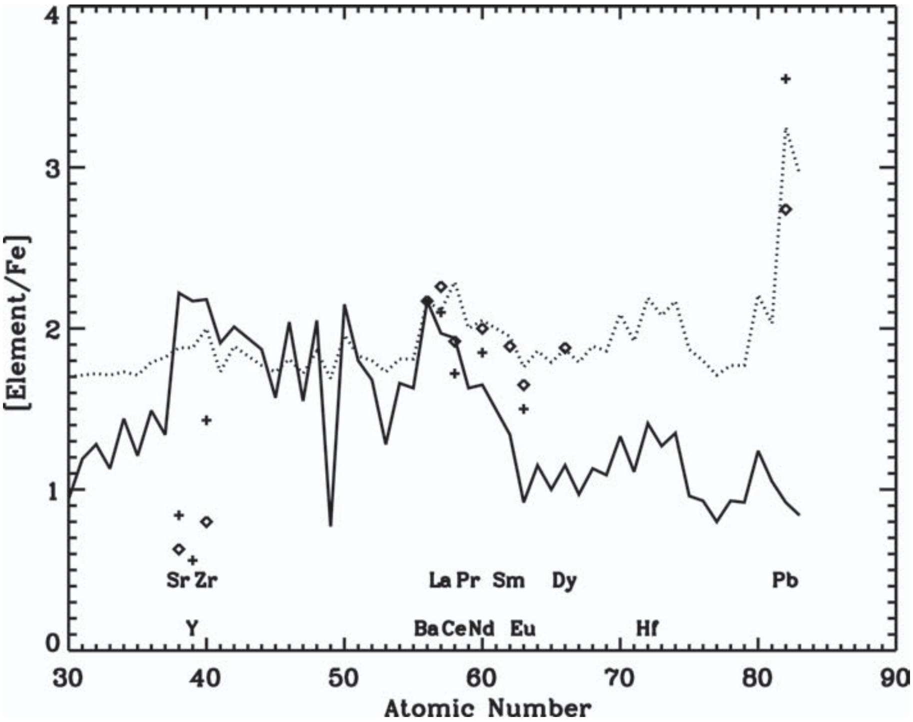


Figure 6: This figure represents the abundances of the neutron-capture elements in the star CS 29497-030 (+signs). The full line represents the s-fraction of the rescaled solar abundances. The dotted line shows results of computations by Goriely and Mowlavi (2000) for a metal-poor AGB stars after 50 thermal pulses. The lozenges are for a prototype lead-star CS31062-050. It is clear that CS 29497-030 is an extreme lead-star.

star, but the most extreme case of a lead-star, with [Pb/Fe] = 3.55 and [Pb/Ba] = 1.38 (Fig. 6).

The yields of SNe in the primeval Galaxy

The first elements in the Universe, aside from those synthesized in the primordial nucleosynthesis, were produced by massive supernovae of type II. This is simply a question of time scale. There are, though, two difficult questions with no certain answers. Did these first SNe pollute only the mini-halo (mostly composed of dark matter) in which they originated, or the whole intergalactic medium (IGM)? What delay has occured between the pollution of the surrouding matter by the ejecta of a SN and the moment in which this polluted matter has formed the small mass stars that we have observed with the VLT? These questions are part of the what we "do not (yet) know" of the title.

The first new element synthesized by massive SNe is carbon, formed by triple α-particle encounters. Our statistics on carbon are strongly biased by the fact that we have purposedly avoided carbon-enriched stars in our observing programme, because of the nuisance caused by CH and CN lines in the study of the rare elements, whose lines are frequently blended by the lines of these molecules, of course enhanced in C-rich objects. Even so, our diagramme [C/Fe] versus [Fe/H], Fig. 7, clearly shows an intrinsic dispersion of the abundance of carbon in our sample.

This is a first feature of the yields of the primeval SNe. A fraction of 15 to 25% of XMP stars are carbon rich, for their metallicity in iron-peak elements. The most extreme case is the star HE0107-5240, which has [Fe/H] = –5.3, the record for low metallicity, but [C/H]=–1.3. Note that, like CS 22949-037, the deficiency in O and N is also much less than for iron, with [O/H]=–3.3 and [N/H]=–3.0 (Christlieb et al. 2003, Bessell et al. 2004).

The intrinsic scatter, conspicious for carbon, is also significant for sodium, but the great surprise in our LP was that the scatter is surprisingly small from the majority of the other elements. The case of the diagram [Cr/Fe] versus [Fe/H] (Fig. 8) is especially puzzling. The scatter is entirely explained by observational errors! So, there is no room for intrinsic scatter. If there was no slope, we would concude that Cr and Fe are produced in a constant ratio by the SNe, and that we observe objects born from a primordial matter polluted by the ejectas, at various levels. No problem. But if the slope is interpreted as a variable production ratio of Cr and Fe in SNe as a function of the metallicity, we then have the problem, with no intrinsic dispersion, that a SN II has to mix its ejecta with a prescribed amount of interstellar matter. We do not accept this interpretation for two reasons. The first is that we believe that the mixing process is unavoidably of stochastic nature, and that the scatter in this process cannot be below 0.05 dex. The second reason is that, as we shall see later, there is a high probability

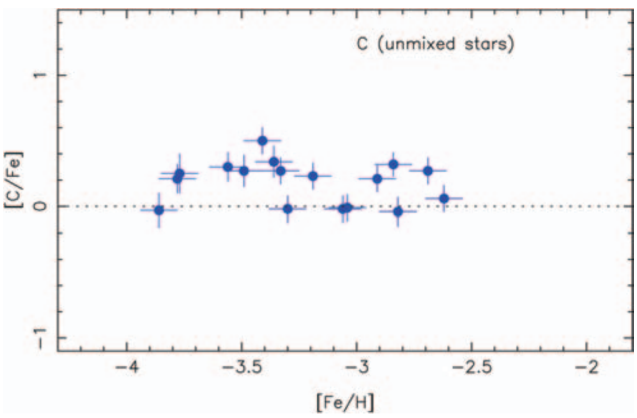


Figure 7: The abundance of carbon is affected by internal mixing in the giants brighter than the « bump ». This figure show the scatter in the original carbon abundance, after elimination from the sample of the giants affected by internal mixing, recognizable by the fact that they have lost their lithium and that they are nitrogen rich.

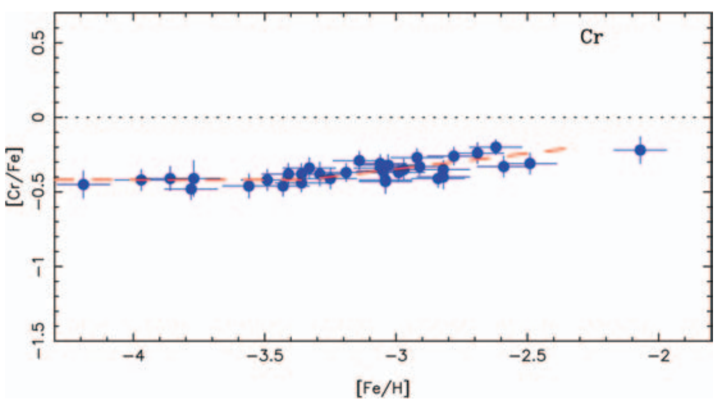


Figure 8: This plot was the one which puzzled us the most, from our Large Programme. The scatter is so small that it is entirely explained by the observational errors, about 0.05 dex. See the text for a discussion of this diagram. The slope disappears below [Fe/H] =-3.3.

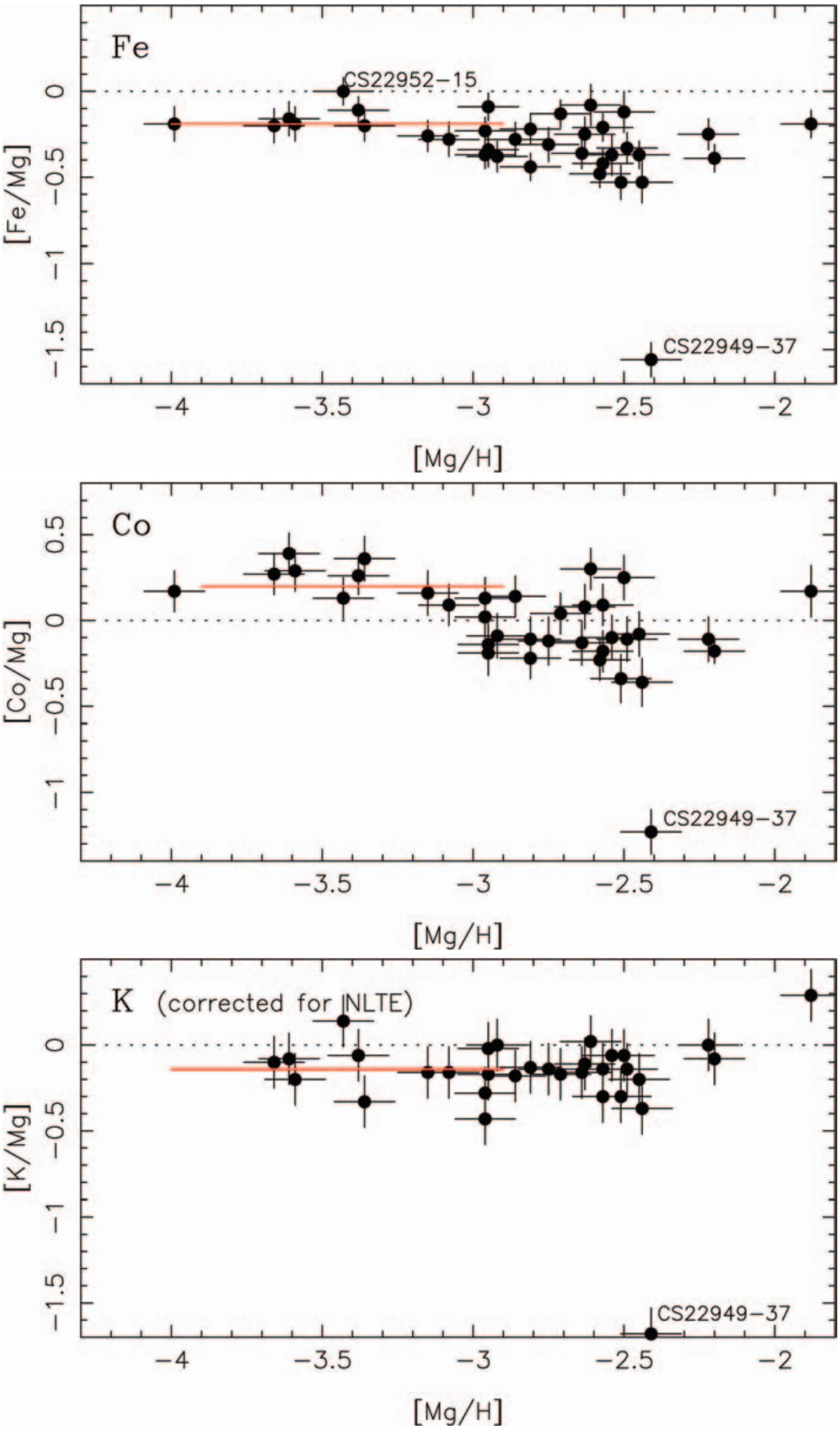


Figure 9: Three plots representing, from bottom to top, [Fe/Mg], [Co/Mg] and [K/Mg] versus [Mg/H]. Note that the production ratios are not solar, but that no slope is apparent for [Mg/H] less than –3.0.

that, at the level of metallicity of our sample, we oberve ejectas of primordial SNe, in which there is no dependence of production ratios with metallicity, as the metallicity is zero. Then, how do we explain the slope? Theoretical computations of departure to LTE for iron in dwarfs and sub-giants, have found a metallicity dependance, with corrections to LTE, about zero at solar metallicity; increasing to 0.3 dex at metalliciy –2.5. Virtually nothing is known for what is occurring between –2.5 and –3.5, still less in giants of log(*g*)=1.5, and still less for chromium. Note also that no significant slope is visible between [Fe/H] ≈ –3.5 and –4.2.

All of that leaves the impression that the slope may be spurious, generated by over-simplifications in the abundance determinations, and have nothing to do with nuclear physics.

The choice of iron as tracing the so-called metallicity in the sample is made for practical reasons, essentially the very large number of available lines. But iron may be a poor choice from a nucleosynthesis point of view. It is formed very close to the frontier between the ejected layers and the remnant core. The famous cut. It is safer to take an α-element as oxygen, magnesium or silicon. Oxygen is very difficult from a practical point of view. So we have tried magnesium, which has the advantage of being more easily ejected than silicon. A sample of plots of ejecta production ratios with [Mg/H] are given in Fig. 9a,b,c. Indeed there is very little metallicity effect visible in these diagrams.Table 1 summarizes the values of the abundances found in such diagrams,i.e. the flat abundance ratios when [Mg/H] is below –3.0. The last column is the number of stars in the mean. For the elements C, N,Na and Al, only the stars with no dredge up have been included.

We then conclude that we have reached the primordial yields of the early Galaxy, and we compare them to several theoretical yields in Fig. 10a,b,c. Obviously the yields to be rejected are the yields of the pair-instability SNe (Heger & Woosley 2002). The yields of the 15 to 50 solar mass SNe by Woosley and Weaver (1995), or Chieffi and Limongi (2003) are clearly closer to our observational results.

Return to population III stars

The details of the formation of massive stars are poorly known even in population I. Actually, the September 2004 issue (No. 117) of the *Messenger* contains the most up to date information on this subject (*The Birth of a Massive Star*, R. Chini et al.) for the stars in formation in our Galaxy. In a zero-metal environment, things are different, and what we know relies almost exclusively on theoretical work. The major physical change from star formation in the today Galaxy is that the cold gas from which stars form cools only by the unefficient H_2 quadrupole radiation, and has great difficulty to radiate. This may prevent fragmentation of the collapsing cloud below a certain limit, which may be higher than a few solar masses.

The exact value of this limit is one more thing we do not really know. But if this limit is 0.9 solar mass or larger, even the less massive primordial stars are now fully evolved as white dwarfs or neutron stars, not visible in our observing programmes. This is probably the simplest explanation for the lack of observed population III stars. Let us note,

Table 1: This table gives the production ratios of the elements for [Mg/H] less than –3.0, believed to represent the yields of primordial supernovae, imprinted in the chemical composition of the most metal-poor stars

Elem	dex	rms	N
[C/Mg]	–0.01	0.10	9
[N/Mg]	0.00	0.11	9
[O/Mg]	+0.32	0.21	13
[Na/Mg]	–0.91	0.16	9
[Al/Mg]	–0.39	0.05	9
[Si/Mg]	+0.21	0.14	14
[K/Mg]	–0.14	0.14	13
[Ca/Mg]	+0.06	0.09	14
[Sc/Mg]	–0.17	0.14	14
[Ti/Mg]	–0.01	0.09	14
[Cr/Mg]	–0.63	0.09	14
[Mn/Mg]	–0.65	0.20	14
[Fe/Mg]	–0.21	0.10	14
[Co/Mg]	+0.13	0.17	14
[Ni/Mg]	–0.23	0.13	14
[Zn/Mg]	+0.21	0.19	14

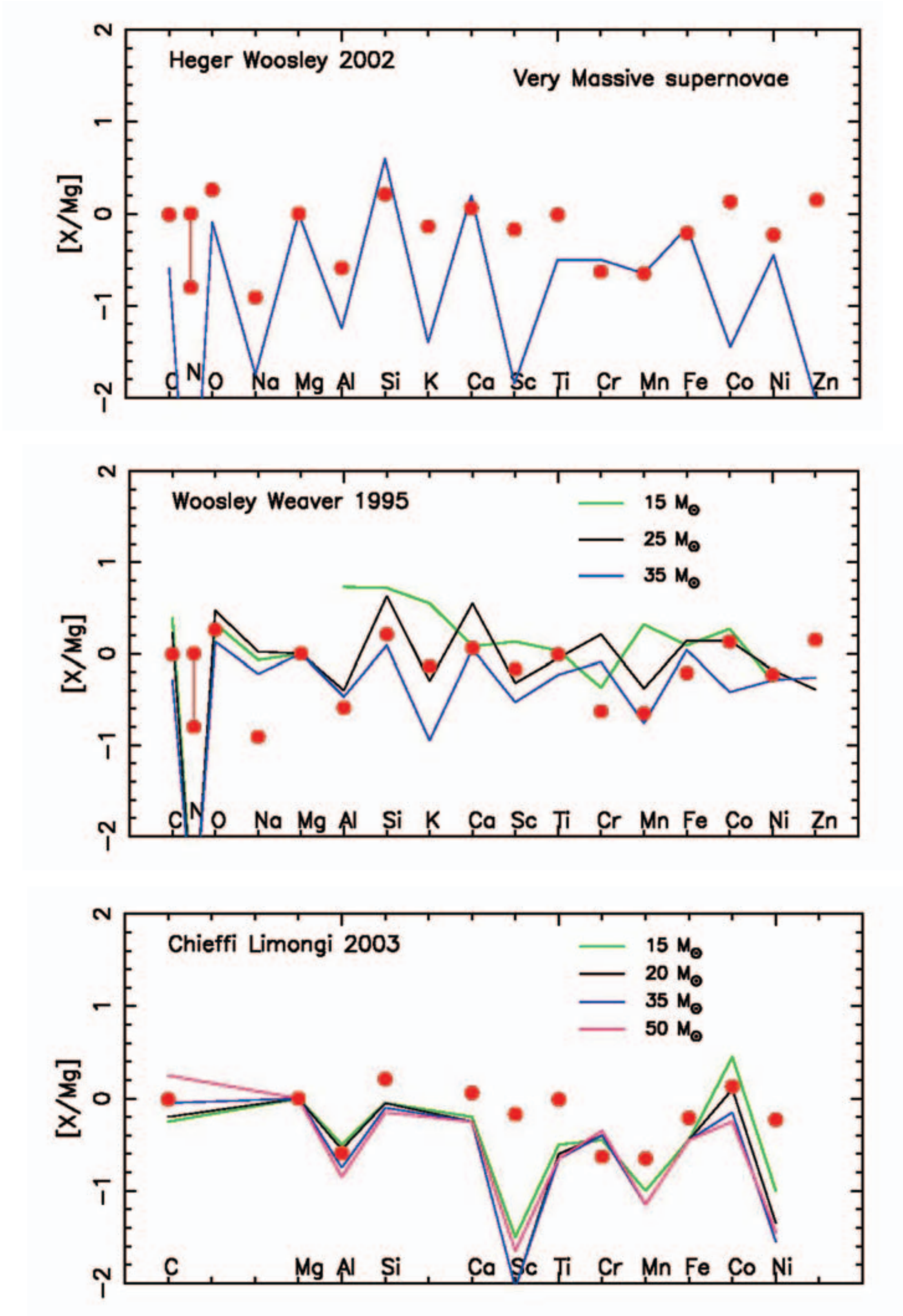


Figure 10: Three plots comparing our yields with theoretical yields (bottom to top) of pair-instability hypernovae, with masses from 140 to 260 solar masses (Heger & Woosley 2002), SN II of masses between 15 and 35 solar masses (Woosley & Weaver 1995) and SN II of masse 15 to 50 solar masses (Chieffi & Limongi 2003). The pair-instability hypernovae have the larger misfit with our observations, in particular for odd elements and zinc.

however, that even if protostellar cores of small mass have developped in the vicinity of young massive stars, they have not had enough time to complete their formation before strong winds and supernovae explosions of the most massive stars have polluted their infalling matter, or brought their formation to abortion.

An excellent review paper on the theoretical work on the formation of population III has just been published (Bromm & Larson, 2004). It contains a wealth of information.

One of the most fascinating hopes for the future is the direct observation of the SNe having produced the yields that we have described here. In 1997, Miralda-Escudé & Rees established that these supernovae should be the brightest objects of the Universe at the epoch z = 5 to 10. They should be bright enough to be observed with the James Web Space Telescope in the K-band (2.2 μm). An interesting firework.

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