Tracing the First Supernovae in Halo Dwarf Stars

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Abstract: Interesting correlations and clustering phenomena are expected to be found in diagrams relating different elemental abundance ratios of extremely metal-deficient stars (A/A-diagrams). Assuming that the interstellar medium of the Galactic Halo suffered from incomplete mixing during its star formation epoch and that the majority of the most metal-poor Halo dwarf stars are formed of material mainly polluted by the first generations of supernovae, the abundance correlations and sub-structures in the diagrams emerge from the effect of mass dependent SN type II yields. These structures seem to be fairly independent of the initial mass function, even though the density of stars in a particular structure may vary. This means that the abundance relations for the population of the extremely metal-poor stars can be used for the determination of SN type II yields and, in addition, for putting constraints on star formation conditions and mixing scenarios in the early Galaxy.

1 The Method

The model used to simulate the A/A-diagrams is based on the assumption of incomplete mixing, i.e. the time-scale of chemical mixing in the system as a whole is longer than the time-scale of star formation. This can easily be achieved if star formation is confined to certain regions and interactions between different regions are weak even though mixing within a particular region, or cloud, is efficient.

Initially, within each model cloud a limited number of first generation high-mass stars are randomly generated (weighted with the IMF) over the mass interval 10–100 $M_\odot$. They are allowed to explode as SNe type II and the ejecta are instantaneously mixed with the hydrogen gas which has a mass of approximately one Jeans mass, $M_H = 5 \times 10^5 M_\odot$. The elemental abundance ratios are then read off and taken as surface abundance ratios of Halo dwarf stars.

One way is to read off the abundances after the lightest high-mass stars have exploded as SNe. A more realistic alternative is to read off the abundances at a random time (i.e. continuous low-mass star formation in the model cloud) which gives qualitatively similar results. Preliminary results using a continuous SFR including high-mass star formation show no drastic differences from the burst-model where the massive stars are all formed in the initial phase. Since continuous star formation only modifies the mass-generating weighting function, equal to the IMF in the burst-model and a time-varying mass distribution function (MDF) in the continuous case, it does not have a large impact on the formation of structures in A/A-diagrams.
Figure 1: Simulated A/A-diagram for [Ca/Fe]–[Fe/H] using in total 400 H clouds wherein 1–40 SNe type II were allowed to explode. Crosses (+) denote simulated stars while filled circles (●) are observations by McWilliam et al. (1995). The Ca yield (Woosley & Weaver 1995) is scaled a factor of 3 to match the position of the observations

The procedure described above is valid as long as the ejecta expelled by each successive generation of SNe remain similar. This is true for a metal-poor system since the ejecta is completely dominated by the yield, leading to the same mass-dependence, and yields are not much metal-dependent at these metallicities (Portinari et al. 1998).

2 Results

Examples of A/A-diagrams are shown in Fig. 1–3. A randomly generated read-off time for each cloud is used. The stellar yield data is taken from Woosley & Weaver (1995) using their zero-metallicity (Z) models. The IMF is of Salpeter form (\(\propto m^{-2.35}\)) if nothing else is stated. Generally, varying the IMF does not change the qualitative results. As seen in Fig. 2 and 3 discrete band-like structures appear in the diagrams. The number density of stars in the A/A-diagrams may vary but the structures do not disappear. They are formed by features in the dependence of the yields on stellar mass and are not much influenced by variations in SNe number densities.

Since low-mass stars are allowed to form continuously over the star formation epoch of the cloud the scatter in the A/A-diagrams will not decrease below a certain value as the number of high-mass stars increases with star formation rate (SFR) in the most active clouds. This is since a low-mass star formed when only the most massive stars have enriched the cloud will have different relative abundance ratios than a star formed when also less massive stars have begun to enrich the cloud. This effect is independent of SFR and will be present as long as the clouds do not mix. When large-scale cloud-mixing becomes efficient the scatter decreases rapidly and the abundance ratios evolve towards mean ratios.

In Fig. 1 the evolution of [Ca/Fe] can be studied in the [Ca/Fe]–[Fe/H] plane. The crosses
Figure 2: a Simulated A/A-diagram for [C/Mg]–[Mg/H] using in total 300 H clouds wherein 1–30 SNe type II were allowed to explode. Crosses (+) denote stars formed by gas which has been polluted by a single SN, circles (○) are stars polluted by two SNe, squares (□) by three, diamonds (◇) by four and dots (·) are stars polluted by five or more SNe. b Same as Fig. 2a but with different coding of the stars. Here, crosses (+) denote stars which have not been polluted by any SN above 27 $M_\odot$, circles (○) denote stars polluted by one SN above 27 $M_\odot$, squares (□) are polluted by two such SNe, diamonds (◇) by three and dots (·) are stars polluted by four or more SNe above 27 $M_\odot$. c Stellar yields from Woosley & Weaver (1995). The carbon yield (+), magnesium yield (○) and the ratio C/Mg (□) are plotted. The structures in Fig. 2b arise from the increase in the magnesium yield between 25 and 30 $M_\odot$. 

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Figure 3:  a Simulated A/A-diagram for [N/O]–[O/H] using in total 300 H clouds wherein 1–30 SNe type II were allowed to explode. Crosses (+) denote stars enriched in metals by SNe of any progenitor mass excluding the interval $25 M_\odot \leq M \leq 35 M_\odot$, circles (o) are stars polluted by one SN with a mass in this interval, squares (□) are polluted by two such SNe, diamonds (◇) by three and dots (·) are stars polluted by four or more SNe in the interval $25 M_\odot \leq M \leq 35 M_\odot$.  b Same as Fig. 3a but the progenitor masses of the SNe are randomly generated using a shallower IMF $\propto m^{-1.35}$.  c Same as Fig. 3a but with a steeper IMF $\propto m^{-4.35}$.  Fig. 3a–c are obviously similar in spite of the large variations of the slope of the IMF.  The relative stellar number densities change and the absolute final oxygen (and nitrogen) abundance(s) differ from the different simulations but the structures persist.  d Stellar yields from Woosley & Weaver (1995). The nitrogen yield (+), oxygen yield (o) and the ratio N/O (□) are plotted. The pronounced peak in the nitrogen yield produces the structures seen in Fig. 3a–c
are simulated Halo stars while the filled circles denote measured abundance ratios in stars observed by McWilliam et al. (1995). The stellar calcium yield is multiplied with a factor of 3 to match the position of the observations. A symmetric, decreasing scatter with increasing iron abundance is seen. No structures or large-scale features are present.

Fig. 2a–b display [C/Mg] as a function of [Mg/H]. Note, that incomplete mixing does not automatically lead to increasing scatter with decreasing metallicity. Here, another effect is observed. The [C/Mg] ratio increases towards lower magnesium abundances. This effect originates from a decreasing C/Mg-yield ratio with increasing progenitor mass, i.e. decreasing stellar life-time (Fig. 2c). At the same time the Mg yield increases, which causes the negative slope. These stars, with the lowest [Mg/H], represent a time-sequence. At somewhat higher metallicity the [C/Mg] ratio flattens out and the scatter decreases towards the finite value described above. Also, note the bands perpendicular to the time-sequence, easiest observed in Fig. 2b, which arise from an increase in the Mg yield between 25 and 30 \( M_\odot \) (Fig. 2c). Unfortunately, the location of these structures is sensitive to the total mass of the hydrogen cloud.

As seen in Fig. 3 another type of structure is formed due to the pronounced maximum around 30 \( M_\odot \) in the nitrogen yield. These structures are even more insensitive to changes in the IMF. Moreover, due to the horizontal alignment and the gap between the band with the lowest [N/O] ratio and the higher bands, the appearance of the structures is not as easily erased by variations in the hydrogen cloud mass as for the structures in Fig. 2.

3 Conclusions

The A/A-diagrams for metal-deficient systems are found to show significant scatter and interesting structures, dependent on supernova yields and mixing conditions in the star-forming regions. Similar results for the scatter have been found by several authors (Travaglio et al. 1999; Tsujimoto et al. 1999; but see also Ikuta & Arimoto 1999). We do not claim that the structures in Fig. 2–3 should necessarily be present for the specific elemental ratios discussed. The A/A-diagrams are computed using theoretical yields, known to be uncertain. The point we want to make is that specific features in the yields, such as sudden changes or pronounced extrema as in the Mg- and N yields above, will have a large impact, producing structures for metal-poor systems. The structures are also less sensitive to other parameters than the yields.

The possibilities seem promising to use forthcoming chemical analyses of statistically well-defined samples of Halo stars for exploring star formation, SN properties and nucleosynthesis in the early Galaxy. It is then, however, necessary to acquire a high internal consistency in the abundance analyses.

References

Ikuta C., Arimoto N., 1999, PASJ 51, 459