Proceedings Title IAU Symposium
Proceedings IAU Symposium No. IAU228, 2005

doi:10.1017/S1743921305006289

Very Metal Poor Stars in the Milky Way: Constraints on Stellar Nucleosynthesis

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Abstract. The living record of early Galactic nucleosynthesis is written in the chemical compositions of metal-poor stars. For stars with metallicities $-1.0 \geqslant$ [Fe/H] $\geqslant -2.5$, several decades of spectroscopic studies have delineated the abundance trends of elements that are synthesized by major nuclear fusion reaction chains. There is very strong observational evidence that the r-process isotopes identified in metal-poor stars and the solar system matter are in fact the product of two distinct types of r-process events. The observed pattern beyond Z $\geqslant$ 40 up to Th-U should most likely be produced by only one (or a few) r-process event(s) in a unique stellar site. This "main" r-process then produces the "low-Z" elements (40 $\leqslant$ Z $\leqslant$ 48) under-abundant compared to solar, and reaches the full solar values presumably around Te.

Keywords. nuclear reactions, nucleosynthesis, abundances, stars: population II

1. Two r-processes in the early Galaxy

Taking the waiting-point approach (Kratz *et al.* 1998) to fit the ($N_{r,\odot}$) pattern, it could be investigated under which stellar conditions the possible two r-processes have to run. For CS 22892-052 both, the general trend as well as the detailed structure of the "low-Z" abundance are nicely reproduced in our fit. At the same time, the good overall reproduction of the "high-Z" elements (beyond Ba) is maintained. It should be mentioned in this context, that our approach would imply a roughly constant abundance ratio between the "low-Z" and "high-Z" elements. This has been confirmed in the case of HD 115444, where our prediction for Ag agrees with the observation (Westin *et al.* 2000). Consequently, the abundance "residuals" ($N_{r,\odot} - N_{r,main} = N_{r,weak}$) at low Z will require a separate "weak" r-process of secondary, yet unknown stellar origin. When assuming seed compositions from Si to Cr or Ni in solar-system fractions, our calculations can reproduce the $N_{r,weak}$ pattern in CS 22892-052 with neutron densities of $n_n = 10^{20}$ cm^{-3} and process durations $\tau = 0.5$–1.0 s. An outcome of these calculations is that the "weak" component does not make a significant contribution to the A $\approx$ 130 abundance peak. We have, at least, one r-process-poor star (HD 122563), where the abundance data seem to depend on, and fall with, increasing Z. This might suggest an incomplete r-process in the halo progenitors, or may imply that stars like HD 122563 formed so early in the Galaxy that the main sites for r-process (e.g. SNe from a certain progenitor mass range) had not yet formed. We also do not know a great deal about the earliest Galactic stellar progenitors; these stars have long since disappeared.

2. R-process sites in the Galaxy

R-process synthesis of A $\approx$ 130–140 isotopes happens early in Galactic history, prior to input from AGB stars to abundances of heavy s-process isotopes. The r-process mechanism for A $\approx$ 130–140 isotopes ("main" component) is extremely robust. This is reflected in the fact that the abundance patterns in most metal deficient (oldest) stars, which have received contributions from only one or a few r-process events, are nevertheless entirely consistent with the solar r-abundance pattern. There are three mechanisms considered as synthesis sites: (i) neutrino-driven winds from forming neutron stars, (ii) magnetic jets from collapsing stellar cores, (iii) neutron star mergers. The "weak" r-process for A $<$ 130 does not exhibit the consistency of the main component. It requires a different timescale for production and seems to occur in He/C shells in Type II supernovae.

An alternative possible site for r-process synthesis is that associated with the He and C shells of massive stars undergoing supernovae (Truran *et al.* 2002). Shock processing of these regions can give rise to significant neutron production via reactions as $^{13}C(\alpha,n)^{16}O$, $^{18}O(\alpha,n)^{21}Ne$, and $^{22}Ne(\alpha,n)^{25}Mg$, involving residues of hydrostatic burning phases. Studies have shown that those reactions can not contribute to the main r-process, because heavier elements up to Th and U could be produced only with the use of excessive and quite unrealistic concentrations of e.g. ^{13}C. But using $^{13}C(\alpha,n)^{16}O$ – or other above mentioned reactions - as an active neutron source acting on a preexisting solar abundance pattern as seed nuclei, and calculated nucleosynthesis occurring on an expansion time scale, one can get significant contributions to the lighter elements A = 130, which represents the weak r-process. The great sensitivity to conditions of temperature, density, and initial composition suggests that this r-process mechanism is less robust in its ability to reproduce the observed r-process pattern in the mass range A $<$ 130.

3. Time Scales

Earlier studies of the canonical r-process have commonly assumed an Fe seed. Starting with Fe, the three neutron-magic (N = 50, 82 and 126) "bottle-neck" in the r-matter flow had to be overcome, resulting in a total duration to produce r-isotopes in the Th-U region of about 3.5s. Realistic r-process scenarios, i.e. the high-entropy wind in SN II and neutron-star mergers, however, suggest that the seed composition may lie beyond the N = 50 shell in the A $>$ 90 Sr - Zr region (Hannawald *et al.* 2001). This seems to be confirmed by the observation of less-than-solar elemental abundances below A $>$ 130 in metal-poor halo stars. Therefore, with updated nuclear-physics input, we have performed theoretical computations starting with an A $>$ 90 seed to reproduce both the solar-system isotopic r-abundances beyond A $>$ 120 and the elemental abundances beyond Zr in the halo-star CS 22892-052. With this approach, avoiding the N = 50 "bottle-neck" and speeding-up the r-matter flow in the N = 82 (A $>$ 130) peak region, it is now possible to synthesize all heavy elements beyond A $\geqslant$ 120 in solar proportions within 0.9 to 1.0 s. This time-scale for the "main" r-process component would solve one of the current problems with the SN II scenario.

References

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