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Using stellar observations to trace the formation processes of Mo, Ru, Pd, and Ag

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Abstract. The exact formation mechanism of many heavy elements remains unknown. Models of the formation site and environment have greatly improved over the past decades, and experiments have provided new data for many of the heavy isotopes. However, much information is still missing to fully describe the neutron-capture formation processes and their sites. Stellar observations combined with mass spectroscopy of meteorites can help to place some of the needed constraints. This, in turn, will help to improve the models and our knowledge on the formation channels creating these heavy elements. Recent studies of Mo, Ru, Pd, and Ag showed that different processes or environments other than the main r-process (forming, e.g., Eu) are needed to explain the production (and observations) of elements with $40 < Z < 50$. An observational study of Mo–Ag is presented, where stellar abundances are compared to meteoritic isotopic abundances (at metallicities [Fe/H] > -1.5) to extract information on differences or similarities in their production. Finally, the number of formation processes needed to describe the chemical composition in low metallicity stars ([Fe/H] < -2.5) is discussed.

1. Introduction and Motivation

To understand the heavy element production in the early (high z) universe old, unevolved, unmixed stars are crucial study cases. These have preserved the chemical signatures of the processes and sites that created the stellar abundances. At these early times only primary formation channels will have had time to operate, most likely in the form of a main rapid neutron-capture (r-)process.

Observations and theoretical predictions indicate that the r-process has two components and/or take place in different astrophysical environments giving rise to a main and a weak formation channel. The slow n-capture (s-)process also has a weak component associated with massive stars which creates the lighter elements with $Z > 30$ [1, 2] and a main component that takes place in asymptotic giant branch (AGB) stars of typically less than $4M_\odot$ and forms more massive elements like Ba [3, 4].

The presence of more than one r-process was observationally deduced by, e.g., a large observational star-to-star abundance scatter seen among n-capture elements in stars with $-4 \lesssim$[Fe/H]< -2.5 but not in $\alpha-$elements ([5] and see Figure 1) which are mainly formed in type II supernovae (SNe II). A long standing quest is therefore to unveil how many n-capture formation processes exist at low metallicity and understand the nature of these processes.

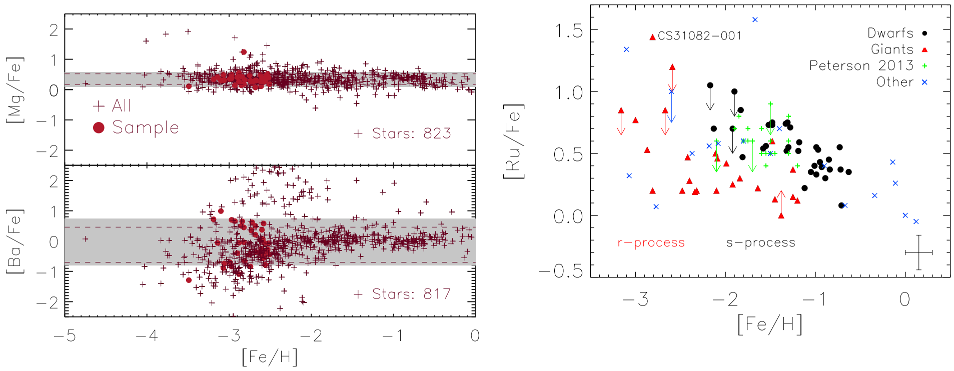

Figure 1. A large star-to-star scatter in n-capture elements but not in α-elements [5].

2. Observational indications of a second, weak r-process

The integrated area of the absorption lines (equivalent width, W) relate to the stellar abundances in the following way,

$$\log \mathrm{W} = \log(const) + \log(A) + \log(gf\lambda) - \theta\chi - \log(\kappa) \tag{1}$$

where A is the abundance, $gf\lambda$ is the product of the statistical weight, oscillator strength, and wavelength, $\theta = 5040\mathrm{K/Temperature}$, χ the excitation potential, and κ the absorption coefficient. When two elements X and Y are formed by the same process their [X/Y][1] ratio will grow at the same rate and we find a flat trend. However, if we consider the absolute logarithmic abundances of two elements co-produced by the same process a linear (1:1) trend is expected. Comparing a well known main r-process element like Eu to Ag shows a clear 'anti-correlation'. This indicates that Eu and Ag are not produced by the same process, while Ru and Ag clearly correlate which indicates co-production by a weak r-process (Figure 2).

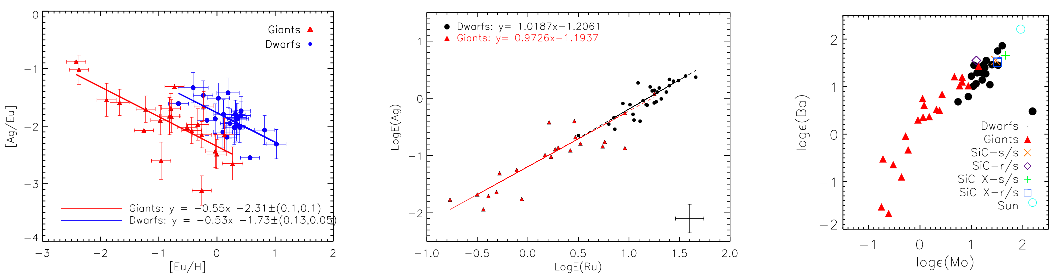

Figure 2. Left: Ag vs. Eu (from [7]) and middle: Ag vs. Ru ([6]). Giant stars are shown as red triangles, and dwarf stars as blue or black circles. Right: Comparing isotopic r/s and s/s fractions in two different SiC grains to elemental stellar abundances [6].

[1] where X and Y are the abundances of two elements scaled to the solar ($\odot$) abundances. The metallicity is typically based on the stellar (*) Fe abundances, in which case we have:

$$[\mathrm{Fe/H}] \equiv \log(N_{\mathrm{Fe}}/N_{\mathrm{H}})_{*} - \log(N_{\mathrm{Fe}}/N_{\mathrm{H}})_{\odot} \tag{2}$$

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By intercomparing Sr, Y, Zr, Mo, Ru, Pd, Ag, Ba, and Eu we find a number of correlations and anti-correlations. At solar metallicity, the elements are produced by the following processes:

- Weak s-process: $Z \lesssim 40$ (or 42)
- Main s-process: a broad atomic range - typically Ba ($Z = 56$) and heavier
- Weak r-process: $40 < Z < 50$ - in particular Ru, Pd, and Ag
- Main r-process: possibly the full range - or $Z > 50$

Isotopic abundances can be measured in presolar grains. These provide more information on the underlying nuclear formation processes than elemental abundances. By comparing the isotope fractions of r-/s-process and s-/s-process in Silicon Carbide (SiC) grains to the elemental stellar abundances we can extract more direct information on the nuclear formation process than from the elemental abundances ([6]). From this comparison we find that the r/s ratio of SiC X grains (formed in SNe [8]) are larger than the same ratio in mainstream SiC grains. One explanation is that mainstream grains are enriched by AGB stars where the s-isotopes are created at the expense of the r-isotopes. Moreover, the r/s fraction is both types of grains agree with the elemental Zr, Mo, and Ba abundances in stars with a metallicity of $-1.1 <$[Fe/H]< -1.5 confirming the formation processes extracted from elemental stellar abundances. The SiC grains contain more s-process material than stars, which could indicate that the gases stars form from are more diluted or differently mixed than the gases in presolar grains. Below log(Mo) $=$ log(Ba) $= 0$ the tight correlation breaks down and more scatter is found. This point coincides with [Fe/H]~ -2.5 (see Figure 1).

3. Discussion: The neutron-capture processes at low metallicity

Many recent observations indicate that some of the most Fe-poor stars are strongly enhanced in carbon ([C/Fe]> 0.7). These stars might be amongst the first stars that ever formed [9, 10] and are generally referred to as carbon enhanced metal-poor (CEMP) stars. They are subclassified by their heavy element content, namely CEMP-s, CEMP-r, CEMP-r/s and CEMP-no (with little or no heavy elements; see [11]). The CEMP-s stars are thought to reside in binary systems, where an AGB star enriches the low-mass, less evolved companion in C and s-process elements, while CEMP-no stars can possibly be explained by fall-back SNe [12]. However, the origin of CEMP-r and -r/s stars is less straightforward to disentangle. Figure 3 shows that enrichment

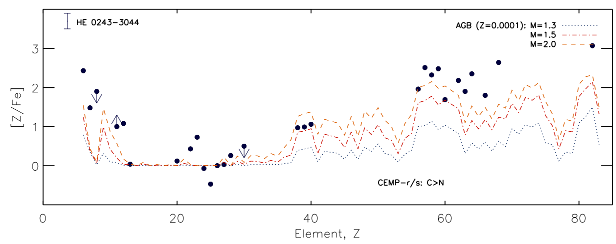

Figure 3. A CEMP-r/s star compared to AGB yields (from [10]).

by a low-mass AGB star cannot account for the full stellar abundance pattern in a CEMP-r/s star. Instead an intermediate process (between r and s) is required – the so-called $i-$process [13], while the CEMP-r stars are thought to form from a medium that was pre-enriched in C and r-process elements.

Numerous nuclear processes have been suggested as early chemical enrichment channels. Hence we explore if a linear superposition of only two primary processes is sufficient to describe

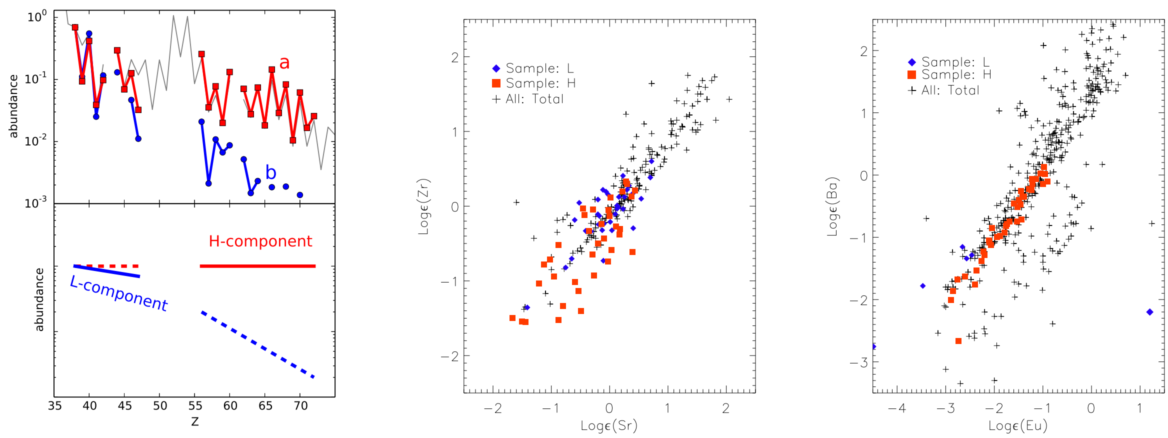

Figure 4. Left: Illustation of the H and L components. Mid and right panel: Scatter in total observed abundances (+) vs. calculated L (blue circles) and H (red squares) abundances [5].

the composition in most metal-poor stars. This test is site independent and follows [14] in using two components: H and L (Figure 4) which are characterised by the two well-studied stars, CS22892-052 and HD122563. Moreover we assume that:

1) All metal-poor stars ([Fe/H< -2.5) are enriched by only two primary processes (H and L);
2) Each of these processes produce a robust abundance pattern in every event.

This leaves us with a calculated abundance pattern that for every element, Z, can be accounted for by a weight (C) and a component abundance (Y) for each of the H and L components:

$$Y_{calc}(Z) = (C_H Y_H(Z) + C_L Y_L(Z)) * 10^{[Fe/H]} \tag{3}$$

By separating every elemental abundance into its L and H fraction we find that the H component is robust and can explain the primary production of the heavy elements very well (this agrees with the main r-process pattern), while L may be less robust or only explain the formation of elements lighter than $Z \sim 50$ (Figure 4).

We used the calculated L component to show the potential of using observations to constrain the extreme astrophysical conditions (e.g., $\nu-$driven winds) where heavy elements are produced.

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