PROCEEDINGS OF SCIENCE

Silver and Palladium - tracers of the weak r-process

Camilla Juul Hansen[*]
ESO, ZAH, Landessternwarte, Heidelberg, Germany
E-mail: `cjhansen@eso.org, cjhansen@lsw.uni-heidelberg.de`

F. Primas
ESO, Germany
E-mail: `fprimas@eso.org`

K. -L. Kratz
Max-Planck-Institut für Chemie, Otto-Hahn-Institut, Mainz, Germany
E-mail: `k-l.Kratz@mpic.de`

N. Christlieb
ZAH, Landessternwarte, Heidelberg, Germany
E-mail: `N.Christlieb@lsw.uni-heidelberg.de`

What is the weak r-process and where does it occur? In order to answer these questions, we need to understand the underlying nuclear physics, derive accurate stellar abundances, and compare these to model yield predictions. We present a study of a large, unbiased sample of stars and the abundances of their heavy elements which provide key information on the various neutron-capture processes. We focus on two relatively unstudied elements, namely silver and palladium, in the range $40 < Z < 50$, because their abundances will allow us to elaborate on characteristics of their formation process – the "weak" r-process.

11th Symposium on Nuclei in the Cosmos
19-23 July 2010
Heidelberg, Germany.

---

[*] Speaker.

`http://pos.sissa.it/`

PoS(NIC XI)265

1. Introduction

Elements heavier than the iron-peak elements are mainly[1] created by neutron-captures. There are two main neutron-capture processes, which take place at different sites and neutron densities, namely the rapid neutron-capture process (r-process) and the slow neutron-capture process (s-process). The r-process is to date still not well understood, but we know that it takes place in very energetic environments offering high neutron densities, and that it is a primary process. Therefore several studies favour supernovae (SNe) as the preferred site. The s-process, on the other hand, takes place in less energetic environments with much lower neutron-densities. This process is a secondary process and is tied to AGB and RGB stars [12]. Since the s-process is connected to these rather evolved stellar stages, this process cannot take place in the first stars or at very low metallicity because the objects have simply not had enough time to develop. Hence, only primary processes such as the rapid neutron-capture process(es) can work at very low metallicities.

2. Sample and data reduction

The sample consists of 73 dwarf and giant stars spanning broad temperature (T: 4200 - 6500K), gravity (log g: 0.5 - 4.74 dex) and metallicity ([Fe/H]: -0.54 to -3.37) ranges. The sample consists of both r-process enhanced and chemically normal stars. All the dwarf spectra have been reduced using the UVES pipeline, whereas reduced spectra were obtained from UVES and HIRES archives for the giants. All the spectra were then shifted, added, and normalized using IRAF[2]. Only high signal-to-noise (S/N $>$ 100 at 340nm) spectra were used for this study.

3. Stellar parameters

Temperatures were primarily determined from T_{eff}-colour calibrations [1,2] and only in a few cases derived from excitation potentials. The surface gravities (log g) were derived from parallaxes where available, if not, we resorted to using ionisation equilibrium. Microturbulence velocities are based on Fe I lines and were derived by requiring that these give the same abundance regardless of line strength. Metallicities ([Fe/H]) were derived from Fe I lines (also due to the statistical low number of Fe II lines at low metallicity).

4. Abundances and line lists

To derive stellar abundances, we need the following input to our tools: stellar parameters, model atmospheres and atomic data. MARCS [7] stellar model atmospheres and MOOG [11] spectrum synthesis code were applied in order to derive the abundances.

---

[1] The p-process is responsible for creating a few of the heavy elements. This process is unimportant for this study and will not be mentioned further.

[2] IRAF is distributed by the National Optical Observatory, which is operated by the Association of Universities of Research in Astronomy, Inc., under contract with the National Science Foundation.

The atomic and molecular data are provided via line lists, which we compiled mainly from VALD[3] and Kurucz database[4]. Only for silver were new oscillator strengths with hyperfine structure components applied, recently measured by H. Hartmann (priv. comm.). We determined all the Ag and Pd abundances via spectrum synthesis. Figure 1 shows a clear correlation of these abundances. Both Ag and Pd were also compared to Fe and show flat trends with metallicity as found in [8]. We furthermore determined abundances of barium (Ba) and europium (Eu) via equivalent width measurements so that we could compare Ag and Pd to main s- and r-process elements, respectively (see Figure 2).

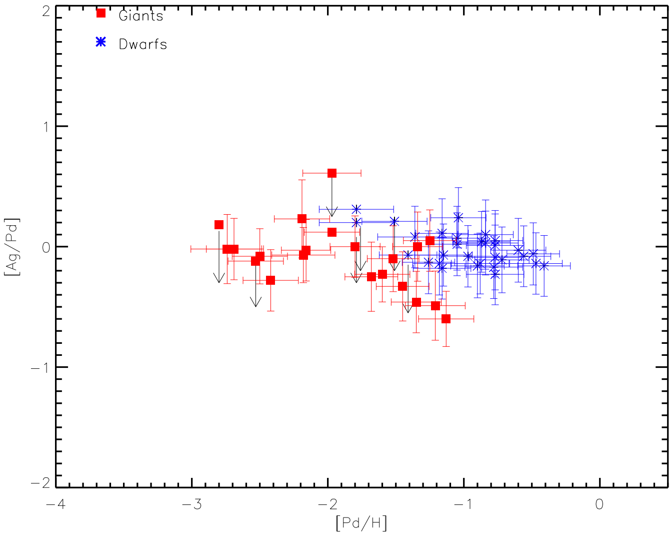

Figure 1: [Ag/Pd] as a function of [Pd/H] showing a flat trend, indicating that the two elements correlate. The dwarfs are shown as filled blue asterisks and the giants as filled red squares.

The fact that Ag and Pd correlate implies that the two elements are created by the same process. However we need more information to understand their formation process. By comparing Ag to Ba and especially to Eu and finding anti-correlations, we have added one extra piece of information, i.e. that silver and palladium are neither main s- nor main r-process elements.

5. Results - formation process and site

In order to further disentangle the origin of Ag and Pd we compare our derived abundances to recent High Entropy Wind (HEW) model predictions [5,6]. These models are improved follow-ups of the somewhat older site-independent main r-process yield calculations with neutron-captures on Fe-seed and waiting-point approaches [9]. The older models predicted the lighter elements such as Pd, Ag and generally elements within the range 40 < Z < 50 to be created in environments with neutron densities, $n_n = 10^{20} - 10^{23}$, while Ba would require densities around $10^{24} - 10^{26}$ and the third r-process peak elements would need even more neutron rich environments to form.

---

[3] http://vald.astro.univie.ac.at/ vald/php/vald.php

[4] http://kurucz.harvard.edu/linelists

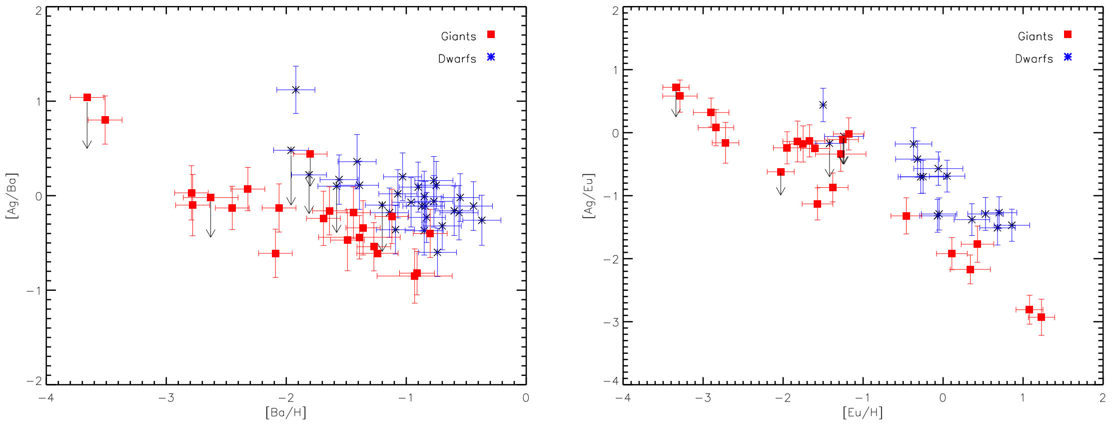

Figure 2: Ag compared to Ba (left) and Ag compared to Eu (right). Note the difference in y-scale. Ag shows a weak anti-correlation with Ba and a strong anti-correlation with Eu. Legend as in Figure 1.

The recent HEW winds [5,6] which we focus on here are linked to type II supernovae and are calculated based on a detailed network. These model predictions were computed with fixed wind expansion velocity and electron-to-nucleon fraction, Y_e, (7500 km/s and 0.45, respectively) but with varying entropy (S) and neutron-to-seed ratio (Y_n/Y_{seed}). This comparison helps us tie the formation process(es) of Ag and Pd to one or several specific sites. Silver is commonly thought to be a key tracer of the weak rapid neutron-capture process (r-process) [10]. In this sense, the HEW model with the above mentioned fixed parameters indicates that for these elements there is a transition from a minor component (a charged particle process existing at low entropies) to the central component responsible for creating Ag and Pd, namely the weak neutron-capture r-process ($110 < S < 150\ k_B$/baryon), which again transits to the main r-process with $S > 150\ k_B$/baryon. The main r-process is of minor importance for the production of Pd and Ag.

Since silver shows a good agreement with the HEW model predictions, this could indicate that the weak r-process is linked to SN II neurino-driven winds. As concluded in [8], we may need two r-process components either from one site or two different sites to explain the abundances of lighter elements, such as Ag and Pd, as well as heavier elements, such as Ba and Eu.

6. Conclusion

Neither Pd nor Ag show any trends with metallicity, confirming the findings of [4]. This could indicate either that the weak r-process works at all metallicities or that the s-process yields balance the large production of Fe from SN Ia at higher metallicities. On the other hand these elements show a clear correlation among each other, hence they are produced by the same process (Figure 1). We find that Ag is not an s-process element confirming the predictions of [3], and Ag is also not a main r-process element (Figure 2). From the HEW model predictions we obtain a best fit with an intermediate entropy ($S \sim 125$ k_B/baryon) and a neutron-to-seed ratio, $Y_n/Y_{seed} \sim 5$ (as in [8]). This means that we are in the light/weak r-process regime, and no longer have a charged particle process. This is in agreement with [5] who investigated which kind of process would be ongoing in four different entropy ranges. The values of S and Y_n/Y_{seed} we find are too low to involve a main r-process and thus suggest a need for two r-processes to explain the formation of both Ag and Eu. These model predictions confirm the trends seen in our abundances and again indicate a second r-process.

The results of this investigation into the tracers of the weak r-process show that Ag and Pd are produced by the same process at all metallicities, and, keeping in mind that the r-process is working at low metallicities, we conclude that the formation could be driven by a second rapid neutron-capture process. Furthermore, this "weak" r-process might be linked to a SN wind, but more investigations/comparisons are required to firmly draw this conclusion. Such investigations should include comparisons to other s- and r-process elements as well as to model predictions connected to differing sites.

References

[1] A. Alonso et al., *The empirical scale of temperatures of the low main sequence (F0V-K5V).*, *A&A* **1996** 313 873

[2] A. Alonso et al., *The effective temperature scale of giant stars (F0-K5). II. Empirical calibration of* T_{eff} *versus colours and [Fe/H], A&A* **1999** 140 261

[3] C. Arlandini et al., *Neutron Capture in Low-Mass Asymptotic Giant Branch Stars: Cross Sections and Abundance Signatures, AJ* **1999** 525 886

[4] J. L. Crawford et al., *Detection of Silver in Metal-Poor Stars, AJ* **1998** 116 2489

[5] K. Farouqi et al., *Nucleosynthesis Modes in The High-Entropy Wind of Type II Supernovae: Comparison of Calculations With Halo-Star Observations, ApJ letters* **2009** 694 L49

[6] K. Farouqi et al., *Charged-particle and Neutron-capture Processes in the High-entropy Wind of Core-collapse Supernovae*, *AJ* **2010** 712 1359

[7] B. Gustafsson et al., *A grid of MARCS model atmospheres for late-type stars. I. Methods and general properties*, *A&A* **2008** 486 951

[8] C. Juul Hansen et al., *The origin of Palladium and Silver*, *A&A letters* **2011** 525 L5

[9] K. L. Kratz et al., *Explorations of the r-Processes: Comparisons between Calculations and Observations of Low-Metallicity Stars*, *AJ* **2007** 662 39

[10] F. Montes et al., *Nucleosynthesis in the Early Galaxy*, *AJ* **2007** 671 1685

[11] C. Sneden et al., *Carbon and Nitrogen Abundances in Metal-Poor Stars*, *The University of Texas at Austin* **1973**

[12] C. Sneden et al., *Neutron-Capture Elements in the Early Galaxy*, *ARA&A* **2008** 46 241