ABUNDANCE PATTERNS AMONG VERY METAL-POOR STARS IN THE HALO OF THE GALAXY: A STATISTICAL APPROACH

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Abstract

The main goal of this work is to explore the abundance patterns of the very metal-poor stars ([Fe/H]<-2.0) observed by the HERES (Hamburg ESO R-process Enhanced Star - Christlieb et al. 2004) survey. This type of study allows the analysis of the correlations among chemical elements and place some constraints on the operation of the neutron-capture (r and s) processes in the early Galaxy. This approach made use of statistical tools, such as agglomerative nesting, which can identify the formation of natural groups based on relations among elemental abundances (e.g. [C/Fe], [Sr/Fe], [Ba/Fe] and [Eu/Fe]), and can also be used in a series of "large-sample like" studies.

In this context, this study provides a comprehensive analysis of a 326 metal-poor stars sample and introduces two new subclasses (r-0 and s-I) for metal-poor stars with determined abundances of neutron-capture elements, aiming to standardize the nomenclature for those objects and, by reproducing early results, confirms the validity of the statistical method used.

1 Background

- Chemical Evolution of the Galaxy based on stellar abundances;
- Metal-poor stars – related with early stages of Galactic evolution, unmixed environments;
- Clues on the onset of the s-process;
- Beers & Christlieb 2005 classification;
- Standard diagram for n-capture enhancements using Ba (85% s-process) and Eu (94% r-process).

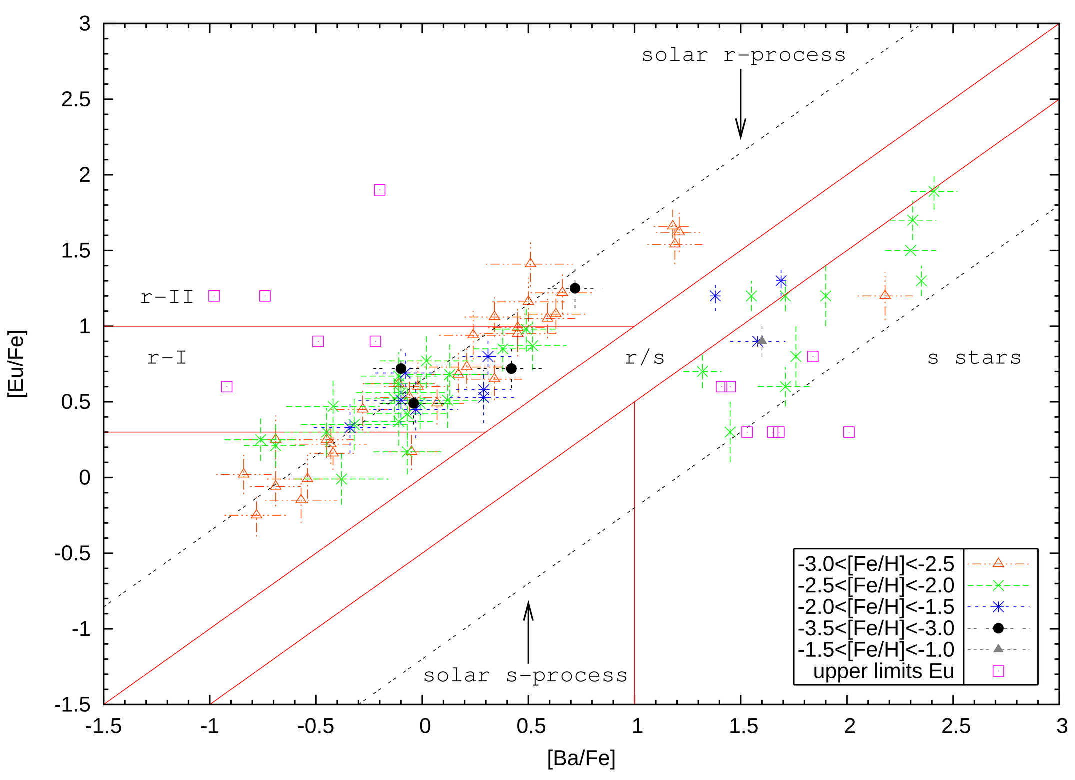

Figure 1: Diagram for identification of Ba/Eu rich metal-poor stars. The solid lines (red) represent the constraints proposed by Beers & Christlieb (2005). The dashed lines are the solar r and s process values for the [Ba/Eu] ratio, based on Grevesse & Sauval (1998) solar abundances and Arlandini et al. (1999) r and s fractions.

2 Database

- HERES (r-process enhanced stars from HES);
- Snapshot spectroscopy - $R \sim 20000$;
- 326 stars - Barklem et al. 2005, T. C. Beers and S. Lucatello;
- [Fe/H] and [X/Fe] for carbon, α and neutron-capture elements.

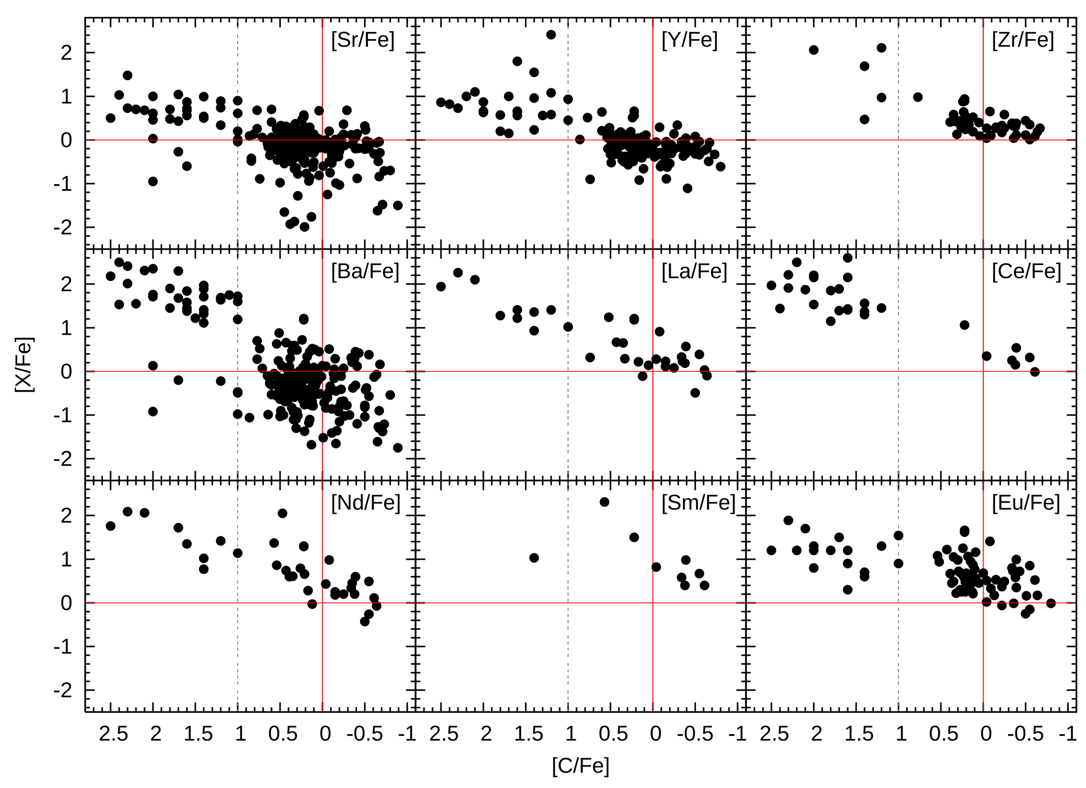

Figure 2: Abundances for the nine neutron-capture elements measured as a function of [C/Fe]. The solid (red) lines represent the solar values and the vertical dashed line is the definition for carbon enhanced stars ([C/Fe]$>+1.0$).

3 Method: Agglomerative Nesting

- Identification of natural groups based on known parameters (no upper-lower limits allowed);
- **[Eu/Fe]** (r-process), **[Ba/Fe]** (s-process 2^{nd} peak), **[Sr/Fe]** (s-process 1^{st} peak) and **[C/Fe]** as input parameters;
- Measurements and comparison of euclidean distances in the 4-abundance space;
- Separation criteria based on the stability of the groups formed.

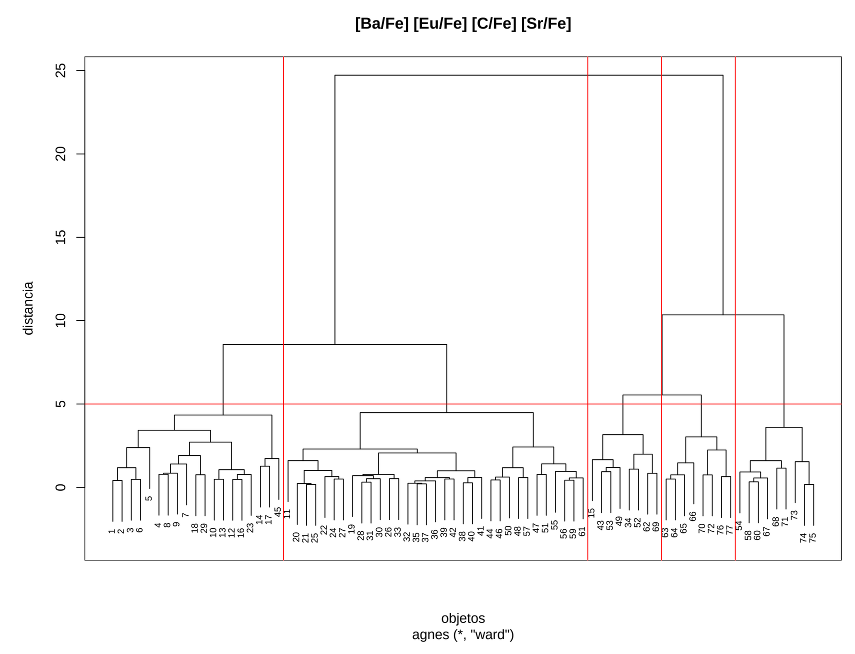

Figure 3: Dendrogram generated for the 77 object clustering. The vertical solid lines represent the boundaries of each group and the horizontal line shows the cut that determine the number of clusters formed.

- Five natural groups found. The method could not separate r/s objects, due to lack of abundance measurements;
- Use of [C/Fe] and [Sr/Fe] as inputs helps in assigning classes for stars with overlapping abundances of Ba and Eu;
- Strong correlation between Ba and Sr;
- r-0 and s-II: lowest and highest values for elemental abundances.

4 Abundance distributions

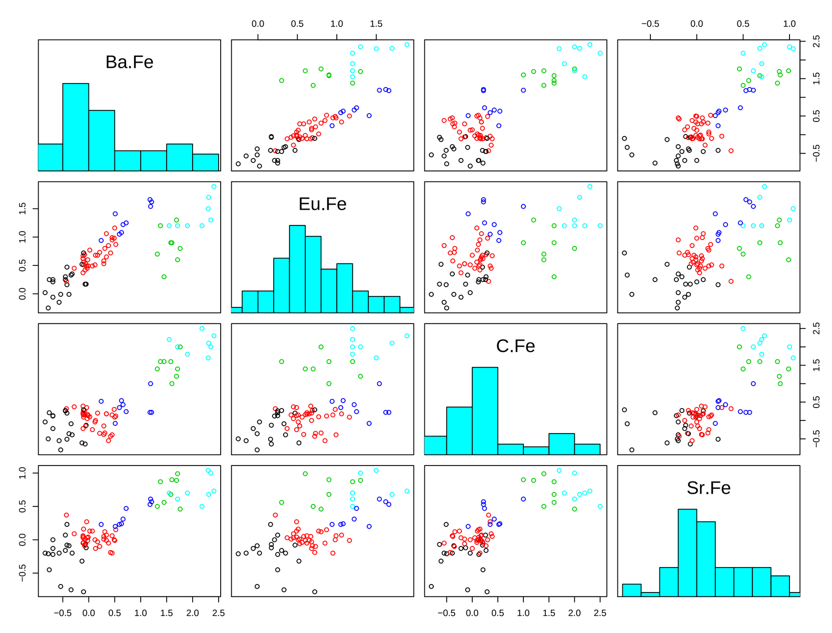

Figure 4: Abundance distributions for the elements used in the clustering analisys. All the panels off the main diagonal shows the scatter between combinations of variables and are color-coded by the groups found in this analysis.

5 New proposed classification scheme

Table 1: Subclasses proposed by this work for metal-poor stars with neutron-capture elements enhancement. Adapted from Beers & Christlieb (2005).

Class	Criteria		
r-0	[Eu/Fe] $<+0.3$	and	[Ba/Eu] <0.0
r-I	$0.3 \leq$ [Eu/Fe] $\leq +1.0$	and	[Ba/Eu] <0.0
r-II	[Eu/Fe] $>+1.0$	and	[Ba/Eu] <0.0
s-I	[Ba/Fe] $>+1.0$ [Eu/Fe] $<+1.0$	and	[Ba/Eu] $>+0.5$
s-II	[Ba/Fe] $\geq +1.0$ [Eu/Fe] $\geq +1.0$	and	[Ba/Eu] $>+0.5$
r/s	$0.0 \leq$ [Ba/Eu] $\leq +0.5$		

- Improved classification for n-capture enhancements;
- Introduces **r-0** class and divides class **s** in **s-I** and **s-II**;
- **r/s** class not identified due to the lack measurements;
- 2-D classification scheme based on the abundances of 4 elements. Reproduces early classification and extends to low n-capture enhancements.

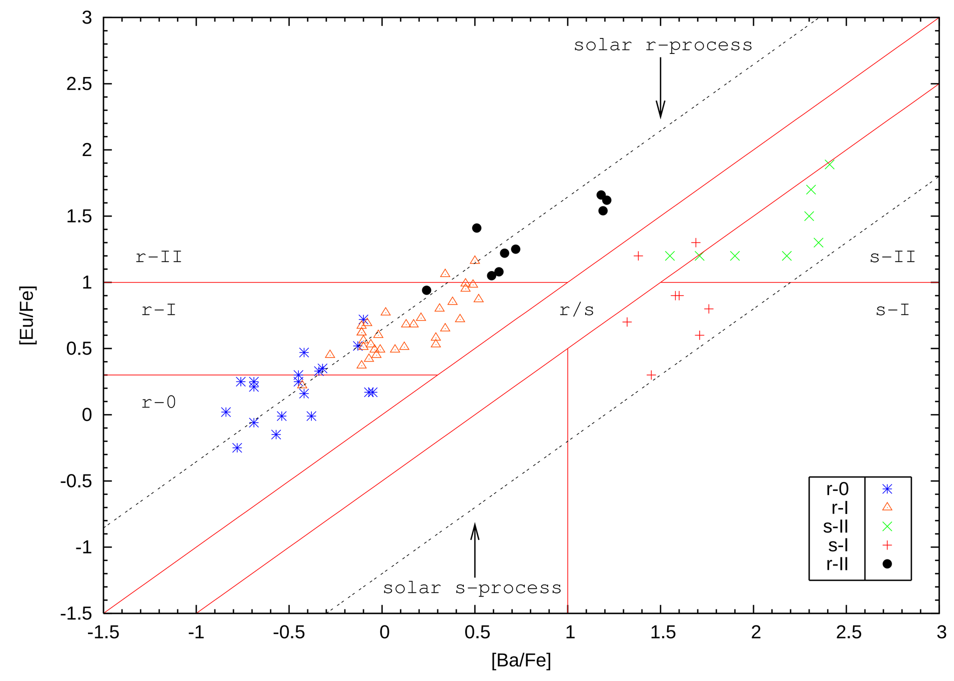

Figure 5: Same as Figure 1, but showing the groups formed in the cluster analisys (without the upper limits for Eu). Some overlaps are expected and the r/s subclass could not be separated due to the lack of objects and abundance determinations.

6 Abundance patterns

- (s-II) For the s-II objects, Sr, Y and Zr reproduce the solar-system r-process and Ba, La, Ce and Nd reproduce the solar-system s-process;
- (s-I) Sr, Y and Zr do not reproduce the solar-system r-process neither the s-process, but they still have the same behavior among each other;
- (r-II) All the elements (in a 3σ level) reproduce the solar-system r-process;
- (r-I) Sr, Y and Zr are closer to the solar-system r-process than for the r-0 stars;
- (r-I) La, Ce, Nd, Sm $\rightarrow$ solar-system r-process scaled to Eu;
- (r-0) Sr, Y and Zr abundances are above the solar-system r-process;
- (r-0) Ba is close to the scaled r-process;
- (r-0) La and Nd follows the r-process pattern, just like Ba.

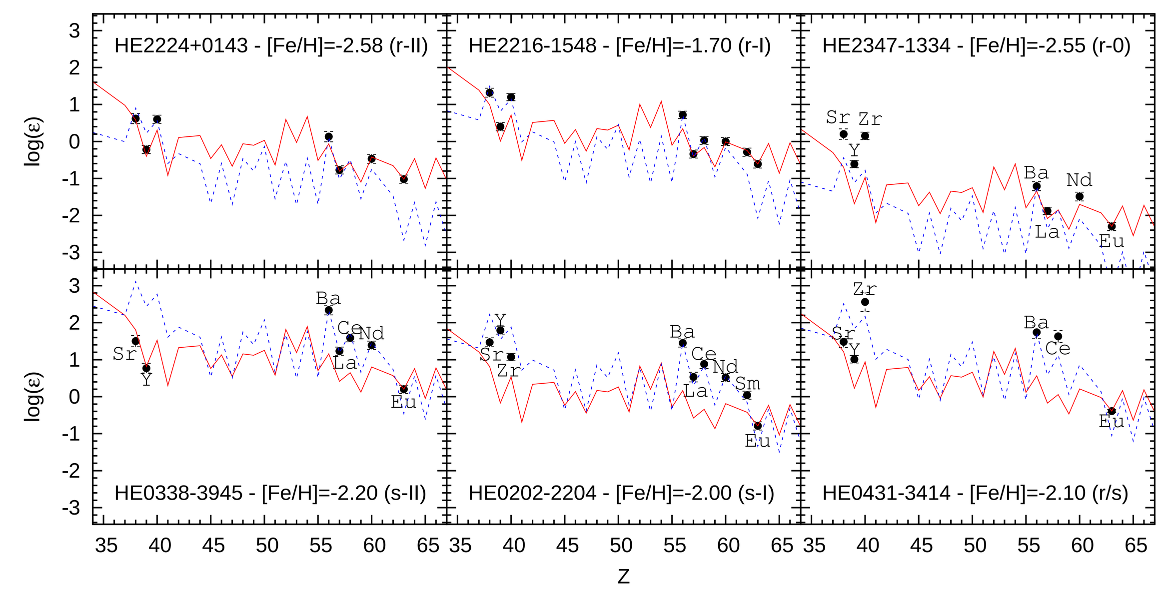

Figure 6: Abundance pattern for the different types of HERES stars. The full line (red) shows the scaled solar-system r-process abundances, scaled to match the Eu. The dashed line (blue) shows the scaled solar-system s-process abundances, scaled to match the Ba. Fractions used are from Arlandini et al. (1999).

7 Summary and discussion

- Metallicity distribution for Ba and Eu enhancements;
- Different behaviors for s-I and r-0 subclasses;
- Narrow [Fe/H] range for r-II stars may suggest a narrow range of stellar masses ($\sim$10-15M$_\odot$) that would form r-process elements in the early Galaxy ([Fe/H]~ -3.0);
- Onset of the s-process (based on HERES data): [Fe/H]≈ -2.5.

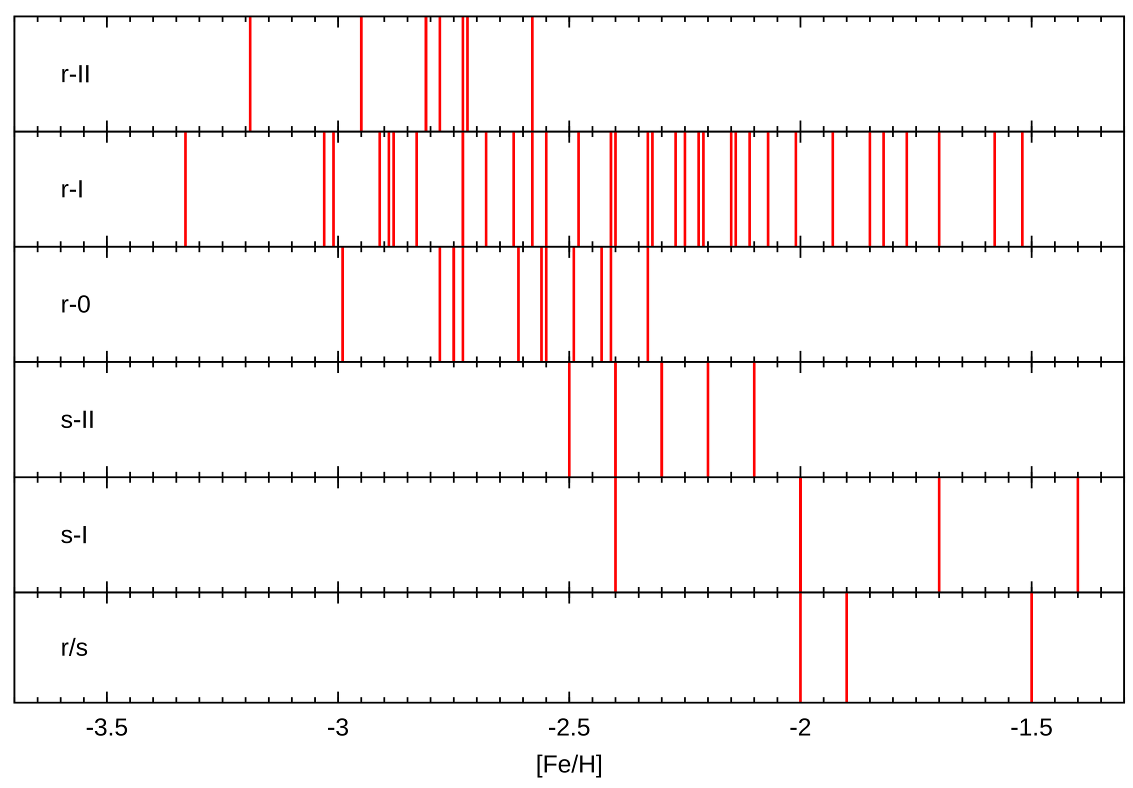

Figure 7: The distribution of [Fe/H] for neutron-capture enhanced stars identified in HERES, divided using the criteria of Beers & Christlieb (2005) and this work.

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