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SPECIFIC FEATURES OF THE ENRICHMENT OF METAL-POOR STARS WITH NEUTRON-CAPTURE (R-PROCESS) ELEMENTS

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ABSTRACT. In contrast to stars with near-solar metallicity (Galactic disk stars), metal-deficient stars show an abundance scatter of up to 3 dex in the enrichment with neutron-capture elements, in particular the r-process elements. The reasons of such a large variation in the in the r-process nucleosynthesis is currently matter of debate. Possible scenarios could be the presence of various r-process stellar and mechanisms in the early unevenly mixed Galaxy, as well as different stellar origin, either galactic or extragalactic, that reflect entering the Galaxy after the capture or coalescence of both individual stars and more complex stellar associations and star formations. In order to study differences in the enrichment with the r-process elements, we selected 20 metal-deficient stars, the spectra of which were collected in the UVES/VLT archive. We employed earlier determined atmospheric parameters to calculate the abundances of about 20 neutron-capture elements via the synthetic spectrum method, taking into account the hyperfine structure for a number of elements. We performed an analysis of the enrichment with the r-process elements grounded on multiple levels of enrichment intensity – namely, limited r-process, r-I and r-II – and the arrangement of stars by their belonging to different populations of the Galaxy, based on the stars' spatial velocity components.

Keywords: stars: abundances – stars: atmospheres – stars: stellar evolution.

АНОТАЦІЯ. На відміну від зір із близькосонячною металічністю (зорі диска Галактики), зорі з дефіцитом металів демонструють розкид вмістів до 3 dex у збагаченні елементами, що захоплюють нейтрони, зокрема елементами r-процесу. Причини такої великої варіації в нуклеосинтезі r-процесу наразі є предметом дискусій. Можливі сценарії полягають в наявності різноманітних зір і механізмів r-процесу в ранній нерівномірно змішаній Галактиці, а також різного походження зірок, галактичного чи позагалактичного, що відображає входження в Галактику після захоплення або злиття як окремих зірок, так і більш складних. зоряних асоціацій та зоряних утворень. Що б вивчити відмінності у збагаченні елементами r-процесу, було відібрано 20 зір з дефіцитом металів, спектри яких ми отримали з архіву UVES/VLT. Ми використовували раніше визначені параметри атмосфери для розрахунку поширеності близько 20 елементів, які утворені в процех захоплення нейтронів, за допомогою методу синтетичного спектра, враховуючи надтонку структуру ряду елементів. Ми провели аналіз збагачення елементами r-процесу на основі кількох рівнів інтенсивності збагачення, а саме обмеженого r-процесу, limited-r, та надлишкового збагачення r-I та r-II типів. Для зір категорії limited-r існує ймовірність збагачення елементами з атомним номером більше 70. Авторами запропоновано різні механізми та процеси збагачення у випадку зір, класифікованих як різні типи r-збагачення, це Наднові, колапсуючі в ядрі, швидко обертові магніто-гідродинамічні наднові, колапсари, та злипання нейтронних зір та чорних дір в різних варіантах. Показано, спираючись на компоненти просторової швидкості, що зорі досліджуваної вибірки належать до різних популяцій Галактики, як до товстого диска, так і до внутрішнього та акреційного гало.

Ключові слова: зорі: вміст – зорі: атмосфера – зорі: еволюція зір.

1. Introduction

The study of neutron capture elements in metal-deficient stars is important to understand the evolution of the early Galaxy, the Galaxy as whole, and to search for souses and mechanisms of their production.

Metal-poor stars in our Galaxy show marked enrichment in r-process elements, up to 3 dex (e.g. Roederer et al., 2014), compared to enrichment in the Galactic disk stars. The degree of enrichment in neutron capture elements was reviewed by Beers & Christlieb (2005), and the following classification was proposed dividing the stars into two main categories (Beers & Christlieb, 2005): the r-I stars have 0.3 ≤ [Eu/Fe] ≤ +1.0, while r-II stars have [Eu/Fe] > +1.0; both require [Ba/Eu] < 0 to avoid contamination from the s-process. Currently, based on the work of Holmbeck et al. (2020); Cowan et al. (2021); Farouqi et al. (2022), we can talk about three different categories of r-process: (1) limited-r stars which have elements as heavy as Eu but no third r-process peak elements and essentially no elements with Z > 70. Its value for [Eu/Fe] < 0.3, but it could be reduced to [Eu/Fe] < 0 (Farouqi et al. 2022). Additional conditions for Sr and Ba are following: [Sr/Ba] > 0.5, [Sr/Eu] > 0. (2) r-I stars are clearly r-process enriched and show a close to solar r-process pattern with 0(0.3) < [Eu/Fe] < 1 and [Ba/Eu] < 0, i.e. the Ba/Eu ratio being smaller than a solar-like s-process-dominated composition. (3) r-II stars are highly r-process enriched with [Eu/Fe] > 1 and follow a [Ba/Eu] constraint as in (2).

Sources (sites) of production of r-process elements are: a weak r-process, which is associated with supernovae, where the innermost ejecta close to the central neutron star were supposed to be neutron-rich (e.g. Wanajo, Janka & Kubono, 2011), a strong r-process, for which quite different scenarios are possible, such as neutron-star mergers (e.g. Freiburghaus, Rosswog & Thielemann, 1999), ejecta from binary neutron-star mergers (e.g. Eichler et al., 1989; Goriely et al., 2015; Thielemann et al., 2017; etc.), neutron star-black hole mergers (e.g. Lattimer & Schramm, 1974; Surman et al., 2008; etc.), certain rare classes of fast-rotating supernovae with powerful magnetic fields (e.g. Symbalisty, Schramm & Wilson, 1985; Nishimura et al., 2006; Winteler et al., 2012; etc.), as well as hypernovae or collapsars (e.g. Thielemann, Wehmeyer & Wu 2020; etc.), and perhaps to a lesser extent the innermost ejecta of regular core-collapse supernovae (CCSNe) (e.g. Woosley et al., 1994; Farouqi et al., 2010; Arcones & Thielemann, 2013; etc.).

The aim of this work is to determine uniformly and highly precisely the abundances of neutron-capture elements in a number of metal-deficient stars differing in the degree and pattern of the enrichment, as well as to analyse plausible causes of such differences.

2. Observations, spectrum processing, spatial velocity components

To study differences in the enrichment of r-process elements, we selected 20 metal-deficient stars, and we used spectra from the UVES/VLT archive, based on the data obtained from the ESO Science Archive Facility (DOI(s): https://doi.org/10.18727/archive/50): the resolution R = 41000-60000, the range of wavelengths λλ 3200-6500 ÅÅ, the signal-to-noise ratio S/N > 100. The spectral processing, including individual spectrum normalization to the local continuum, identification of spectral lines of different chemical elements, measurements of the line depth and equivalent width (EW), was performed for each star using the DECH30 software package developed by Galazutdinov (http://gazinur.com/DECH-software.html).

Spatial velocity components (U, V, W) with respect to the Local Standard of Rest (LSR) were computed based on the coordinates, proper motions and radial velocities from Gaia DR3 (Vallenari et al. 2023). We used the solar motion with respect to the LSR by Robin et al. (2022) from Gaia DR3: (U, V, W) sun =10.79±0.56, 11.06±0.94, 7.66±0.43 km·s^{-1}. The Toomre diagram for the stars under study is shown in Fig. 1.

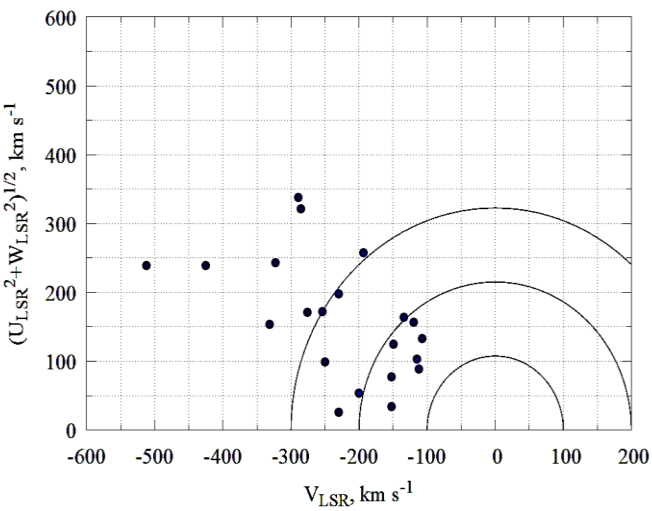
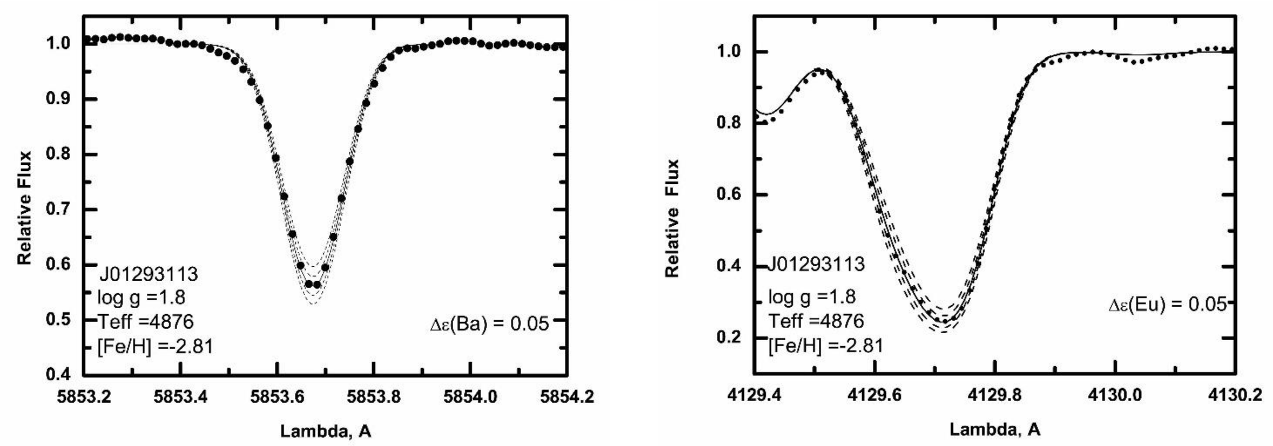


Figure 1: Toomre diagram for studied stars

3. Atmospheric parameters and abundance determinations

We used the atmospheric parameters determined earlier (Table 1).

To calculate the abundance of about 25 neutron capture elements (Sr, Y, Zr, Nb, Mo, Ru, Rh, Pd, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Hf, Os, Ir, Pb, Th) we used the LTE approach and the atmospheric models by Castelli & Kurucz (2004). The choice of model for each star was made by means of standard interpolation for Teff and log g. The abundances were employed the synthetic spectrum method by a new version of the STARSP software (Tsymbal, 1996) and new version of the VALD2018 line list (Kupka et al., 1999). Hyperfine structure for a number of elements (Ba, La, Eu) was take into account the, and solar isotope composition was used in the case of Ba. The spectrum synthesis fitting of the Ba and Eu lines to the observed profiles for star J01293113 is shown in Figs. 2, 3 with the values of [Ba/Fe] = 0.76 and [Eu/Fe] = 1.66.



Figures 2, 3: Spectrum synthesis fitting of the Ba and Eu lines to the observed profiles.

Table 1: Lists the name of stars, the parameters (effective temperature T_{eff}, gravity logg, microturbulent velocity V_t, metallicity [Fe/H]) and the references of relevant papers.

Name	T_{eff}	log g	v_t	[Fe/H]	Ref
BD+17 4708	6000	4	0.7	-1.56	Mish03
BD+23 3130	5100	2.25	1	-2.62	Mish01
BD+23 3912	5750	3.7	1.3	-1.39	Mish00
BD+26 4251	5860	3.5	1.7	-1.42	Mish00
BD+29 2091	5850	4.2	1.6	-1.93	Mish03
BD-18 5550	4600	0.5	1.2	-3.01	Mish01
HD 002796	4900	1.6	1.5	-2.21	Mish01
HD 008724	4600	1.5	1.5	-1.65	Mish01
HD 019445	5830	4.00	1.10	-2.16	Mish17
HD 025329	4850	4.25	1.5	-1.73	Mish01
HD 026297	4300	0.5	1.7	-1.91	Mish01
HD 084937	6325	3.95	1.4	-2.24	Mish17
HD 108317	5250	2.4	1.7	-2.17	Mish01
HD 122563	4570	1.1	1.2	-2.42	Mish01
HD 216143	4455	1.05	1.90	-2.26	Mish17
HD 221170	4415	1.05	1.9	-2.26	Mish17
J20554594-3155159	4581	0.94	2.26	-2.67	Holm20
J03142084-1035112	4769	1.15	2.11	-3.75	Holm20
J12044314-2911051	4465	0.92	2.49	-2.35	Holm20
J01293113-1600454	4876	1.80	-2.81	-2.13	Hans18
J22021636-0536483	4668	0.93	-2.75	-2.57	Hans18

4. Results and discussions

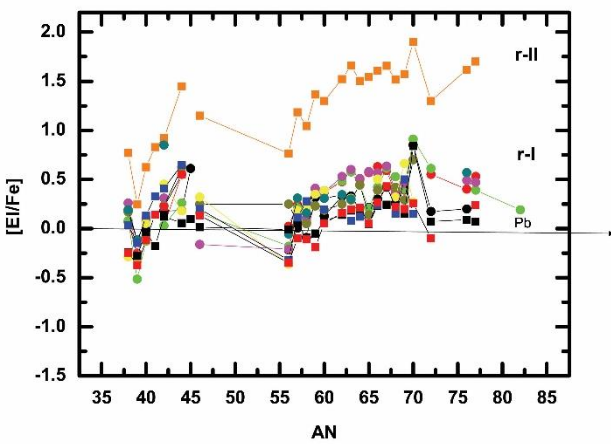
4.1. Analysis of the behavior of the r-process elements in the studied stars

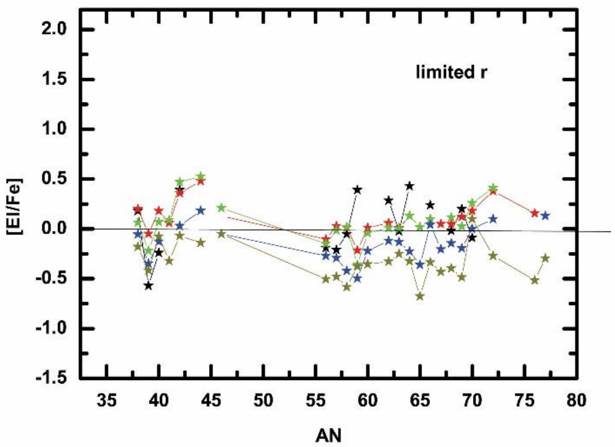
To consider the different various features of the r-process of enrichment of metal-deficient stars we compare the obtained Sr, Ba, Eu abundances for our studied stars to find (define) indicators (types) of the r-process or, in other words, to determine the degree of r-process enrichment based on the Sr, Ba, Eu abundance criteria.

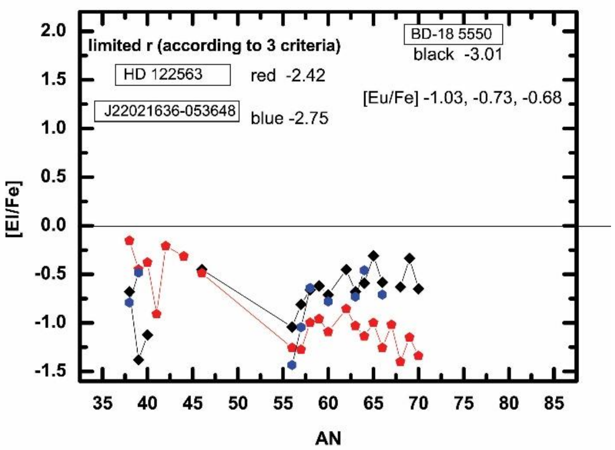
As we noted in the introduction, three classes (types) of enrichment in r-capture elements are currently considered. The first criterion is the abundance of europium, often using [Eu/Fe], an element predominantly formed by the r-process. Among our stars, only one is of the r-II type, 11 stars are of the r-I type, and 8 stars are of the limited r type. Also for classification additional criteria are used for classes (types) r-I and r-II, this is the ratio of [Ba/Eu], this value confirmed the classification by [Eu/Fe]. And for stars of the limited-r type two additional criteria are introduced [Sr/Ba] and [Sr/Eu]. For two stars with very low europium abundance these criteria are met unconditionally, and for 6 stars, taking into account the errors of determinations for [Sr/Ba].

Let us consider the behavior of the element abundances depending on the Atomic Number for the groups (Fig. 4 upper. r-I and r-II stars, Figs. 5, 6 middle, bottom limited-r stars). For all groups we see different behavior of the r-process elements, increased for r-II, lower, but quite compact for r-I stars (spread about 0.5 dex), and with a large spread for limited-r stars (from -0.5 dex to -1.5 dex). Two figures for limited-r stars differ in the europium abundance, if in the first case (Fig. 5) these are small negative values of [Eu/Fe], then in the second (Fig. 6) these are stars with a fairly low value of [Eu/Fe], less than -0.6. As mentioned above, for limited-r stars there are essentially no elements with AN > 70, which is what we observe in the bottom (Fig. 6), and in the middle (Fig. 5) such elements are present. We believe that one reason for the presence of elements with AN > 70 may be a "shift" of the upper limit for r-I from 0 to -0.2 dex due to errors in the Eu abundance determination (~0.2 dex), and this may change the classification and transfer limited-r stars to the r-I category. However, this may also indicate that some limited-r stars have the elements with atomic numbers greater than 70, in other words, it may indicate contributions of two or more events to their enrichment.

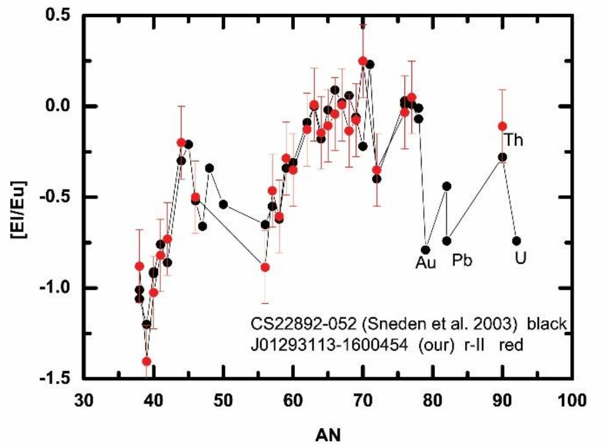
At the moment, it is difficult to say whether this reflects the enrichment features of limited-r stars in general, or only in our particular set of stars.

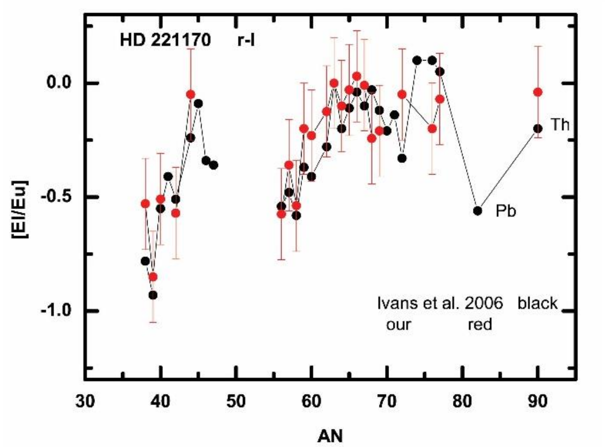


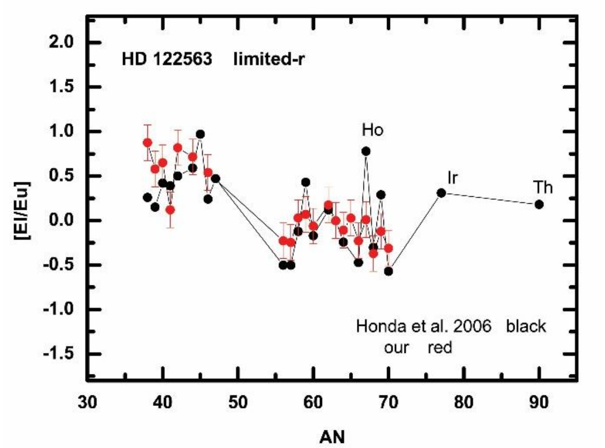




Figures 4, 5, 6: Distribution of the element abundances from the Atomic Number for these three groups (Fig. 4 upper. r-I and r-II stars, Figures 5, 6 middle, bottom limited-r stars).







Figures 7, 8, 9: Comparison our results for one typical star of each group with those of other authors.

We then compared our results for one typical star of each group with those of other authors, namely, J01293113-1600454 (r-II) with the classical r-process star CS22892-052 (Sneden et al., 2003) (Fig. 7), HD 221170 (r-I) with the work of Ivans et al. (2006) on this star (Fig. 8), and HD 122563 (limited-r) with the data of Honda et al., 2006 (Fig. 9), that show typical weak- r-process.

We see good agreement between the data (Fig. 7, r-II), confirming a noticeable enrichment in the r-process, as well as good agreement for HD 221170 (r-I), which is moderately enriched in the r -process (Fig. 8). As for HD 122563 (limited-r), this is a star with a noticeable europium deficiency, Honda et al. (2006) have found abundance of elements with AN > 70, the upper limit of iridium and thorium (Fig. 9). Is it caused by the errors in determination or there is a possibility of the enrichment in elements with AN > 70? Besides, it may also indicate that several (some) limited-r stars have the r-enrichment, i.e. two or more sources were involved in their enrichment. Note, there are also other possible interpretations, as e.g. Montes et al., 2007 (LEPP source).

4.2. Plausible sources of r-enrichment

In analysis of r-process nucleosynthesis and chemical evolution of Galaxy, two types of r-process sources with different delay times are considered, a quick source (e.g. CCSNe) and a delayed one (CBM – compact binary mergers, common name). As shown in a number of works (e.g., Wehmeyer, Pignatari & Thielemann, 2015; Farouqi et al., 2022; Mishenina et al., 2024; etc.) both a quick source (e.g. CCSN) and a delayed one (CBM) produce r-process material. We suggest that high values of the abundance of r-process elements in class (r-II) stars can be provided by CBM as the main astrophysical site of the r-process, as a result of the merger of neutron stars or black holes. A moderate enrichment of (r-I) also can be provided by CBM: it is still debated whether two types (r-I and r-II) are produced in different sites or result from variations within the same site (e.g. neutron star mergers) (Farouqi et al., 2022). Limited-r stars may be enriched predominantly from different types SNe (e.g. magneto-rotational SNe), but the presence of elements with AN > 70 substantiates the hypothesis of possible contributions from other sources with different delay times. Different mechanisms and sources of the r-process are responsible for the enrichment of stars of different r-types, but the exact yields of elements resulting from the r-processes in the indicated stars are still highly debatable, thus requiring additional research.

4.3. Kinematics

If we look at the space velocities and the Toomre diagram, using the criteria of Marsakov & Borkova (2006) to separate of different structures of the Galaxy, we can say that our stars belong to the thick disk, as well as to the proper and accreted halo (i.e. captured by the Galaxy). The velocity separating the thick disk and the halo is 180 km/s. We have about 8 such stars (3 r-I, 5 limited-r). Stars with residual velocities of 175–240 km/s belong to the proper halo of the Galaxy, 4 stars (3 r-I, 1 limited-r). Stars with velocities higher than 250 km/s belong to the outer accreted halo, taking into account retrograde velocities, there are 9 of them (1 r-II, 6 r-I, 2 limited-r). The star with the highest V velocity is BD+23 3130, limited-r, the second is J01293113-1600454 (r-II). Stars with different levels of r-process enrichment belong to different galactic populations.

5. Results and conclusions

1) The abundance of 25 r-process elements in 20 metal-poor stars was determined.

2) The r-enrichment type was determined for all stars and it was shown that, in general, the criteria under consideration are quite reliable.

3) For stars of the category, type limited-r, there is a probability of enrichment with elements with an atomic number greater than 70.

4) The authors suggest different mechanisms and processes of enrichment in the case of stars classified as different r-types.

5) The stars of the studied sample belong to different galactic structures, both to the thick disk of the Galaxy and to the inner and accreted halo.

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