STUDY OF THE DISTRIBUTION OF THE HEAVIEST ELEMENTS IN THE GALACTIC HALO

Author: Gerard Navó Perez
Advisor: Jose Maria Solanes Majua
Facultat de Física, Universitat de Barcelona, Diagonal 645, 08028 Barcelona, Spain.

Abstract: We study the concentration of an r-process element such as europium in the north galactic halo, by examining the optical spectra of a sample of about 500 K1 stars distributed among 30 different plates from the SEGUE-2 at high galactic latitude. We have developed an automated method that ranks the stars by their likelihood of having an enhanced abundance of this element and identifies the plates that contain one or more of the stars which fall in the upper decile. For the present investigation, we specifically focus on the 4129.70 Å and 4205.05 Å absorption lines of Eu, finding several plates that contain a relatively high fraction of stars (> 5%) with show significant absorption around both wavelengths. The most promising plate is SEGUE-2's number 3166, where we have measured fractions of stars potentially rich in Eu of 12% from each of the two lines, which are also the largest values reached in the present work.

I. INTRODUCTION

Understanding the origin of the elements heavier than iron remains one of the major challenges in modern astrophysics. The metals in a star today are a snapshot of the metals in the interstellar medium (ISM) at the time and place where that star was born. Ancient halo stars offer the opportunity to make a reasonable connection between individual stellar nucleosynthesis events and the metal distributions found in the oldest stars. As it is shown in Fig.(1), binding energy per nucleus increases only until ^{56}Fe, so heavier elements, which have been detected in the ancient stars of the Galactic halo, in the ISM, dust grains, meteorites, and on Earth, are formed by endothermic neutron-capture reactions Eq.(1). The two predominant mechanism of n-capture are s-process and r-process, from slow and rapid n-capture respectively [1].

In s-process, the time related to β-decay, Eq.(2), τ_β is short compared to the neutron capture time τ_n: $\tau_\beta \ll \tau_n$, creating elements close to valley of β-stability, which is formed by the stable elements (Fig.(2)).

$$n + (Z, A) \rightarrow (Z, A+1) + \gamma \qquad (1)$$

$$(Z, A) \rightarrow (Z+1, A) + e^- + \overline{\nu_e} \qquad (2)$$

Instead, in r-process the time related to β-decay is larger compared to neutron capture time: $\tau_\beta \gg \tau_n$, allowing to form elements beyond the valley of β-stability [1] [2]. While τ_β only depends on nuclear species, τ_n hinges on the neutron flux involved.

S-process take place in the He shell burning phase in AGB stars [4], where neutrons produced inside of it are captured by heavy-element seed nuclei. Due to the relatively low neutron densities (~10^8 cm^{-3}), timescales of n-capture and most of β-decay satisfies the s-process condition mentioned above: $\tau_\beta \ll \tau_n$. AGB stars observations show overabundances of elements beyond ^{56}Fe [5], evidencing s-

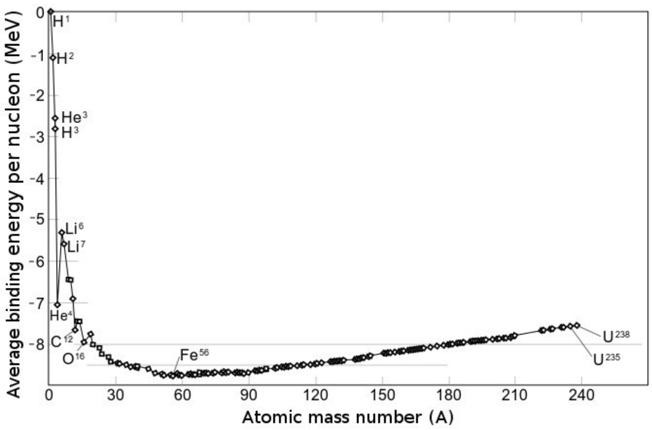

FIG. 1: Binding energy per nuclear particle in front of atomic mass number. We see ^{56}Fe is the lowest point of valley of β-stability, being the most stable nuclide [3].

process may take place in asymptotic giant branch phase in the evolution on stars from 0.8 $M_\odot$ to 8 $M_\odot$.

Although it is still unclear where r-process take place, it is well known that the neutron densities involved have to be greater than ~10^{20} cm^{-3} [6], implying, contrarily to the s-process, that it cannot be produced inside stars. Therefore, is thought that the neutrino-driven wind of Type II supernovae [7] [8] and neutron star mergers are the two events which are able to gather the condition of those neutron fluxes and thus $\tau_\beta \gg \tau_n$.

Recently, with the detection of gravitational waves coming from a "kilonova" by LIGO, and the spectrum observed of the light it emitted, astronomers have been able to determine it was a very energetic event which ejected about 1-5 earth masses of europium and 3-13 earth masses of gold. This discovery could prove that neutron star mergers would be the dominant mode of r-process production in the Universe, according with the current chemical evolution models [9] [10].

The aim of this work is to localize regions of our Galaxy which show signs of potential enrichment in r-process

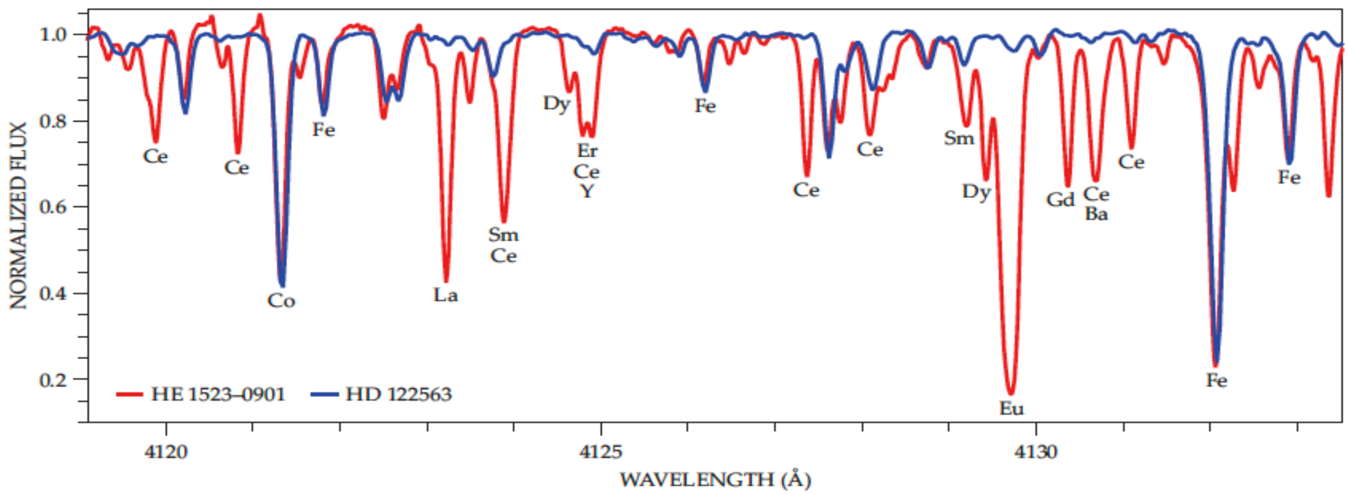

FIG. 2: High resolution spectra of two different stars: HD 122563 and HE 1523-0901. While HD 122563 has low abundances of r-process elements, HE 1523-0901 is the richest ever found in Galactic halo. On its spectrum we observe several strong absorption lines of lanthanides. (Obtained from [6]).

elements. For this purpose, we use the complete spectral sample from the second Sloan Extension for Galactic Understanding and Exploration (SEGUE-2) survey included in the SDSS-III Collaboration [11]. SEGUE-2 has obtained spectra for around 119,000 unique stars, focusing on the stellar halo of the Galaxy, from distances of 10 to 60 kpc, where it specifically targets blue horizontal branch stars, K-giants and M-giants. Given that we are trying to detect a very weak effect that demands a large sample size, the latter two spectral types are best suited for this task as they are more numerous. Our goal is to look for the presence of Eu in the spectrum of these stars, since it is an element formed practically on its totality in r-process (94% according to Arlandini et al. 1999 [12]) and it has several strong spectral lines in the visible part of the spectrum, the strongest ones at 4129.70 Å and 4205.05 Å [13]. It is interesting to look at Fig.(2), where is clearly shown the spectral differences between an abounding r-process element star and another one which not and we can see the strong peak of Eu in 4129.70 Å. Therefore, if a star presents the characteristic spectral lines of this lanthanide, it means its environment has been at some point enriched by some r-process [10].

Regarding the spatial distribution, is thought that supernova explosions contaminate the medium with r-process formed matter in a roughly isotropic way and reaching large radial distances, while a collision of two neutron stars ejects most of the matter in the equatorial plane of the merger, adulterating the environment probably in an aspherical, and likely more localized, way [14]. It is therefore a question of designing a test that not just is capable of finding evidence of anomalous Eu enrichment, but also pays attention to the spatial distribution of the contaminated stars, so it can help us discern the type of event which causes it.

II. METHOD

A. COLLECTING THE DATA

The spectra in the SEGUE-2 catalogue range from 385-920 nm with a spectral resolution ($R \equiv \lambda/\Delta\lambda$) ~ 2,000 (4 km s^{-1}) which, we believe, is the minimum acceptable resolution that makes our statistical procedure feasible, although it is insufficient to resolve the individual lines. The catalogue is divided in 202 plates (7 deg^2), each one containing 640 fibers, mostly focused on the northern galactic halo (see Fig.(3)). The total area covered is 1,317 deg^2, and the total number of observed stars 118,151 up to magnitude g=19.

To test our procedure 30 plates at high galactic latitude have chosen arbitrarily taking into account that they should not be too close to each other and that they must contain a number of stars with good spectra large enough to perform a reasonable statistical analysis.

Sloan divides the spectra in the following subclass for K type stars: K1, K3, K5 and K7. Regarding to M type, the corresponding subclasses are M0, M1, M2, M3 and M4.

Finally, as Sloan's online manual advises in order to obtain spectra with a reasonable quality, it has been chosen spectrums with a signal-to-noise ratio SNR ≥ 10 and a radial velocity v ≤ 600 km/s.

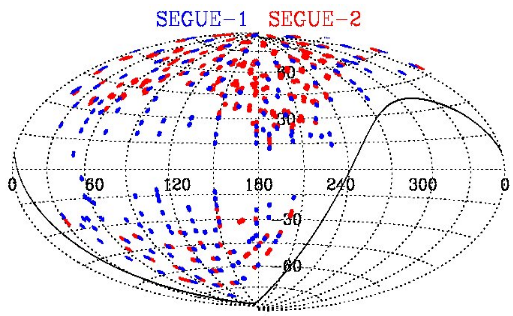

FIG. 3: Scheme of mapping performed by SEGUE, in galactic coordinates [11].

B. SPECTRAL ANALYSIS

Our methodology consists essentially first on averaging the spectra of stars with the same spectral type and then comparing each individual spectrum with the inferred mean trying to identify the most discordant ones in the narrow windows where we expect to find the absorption lines of Eu II.

For this we have a Python tool developed by José Luis Tous, a master student of the research group of my advisor, which does the rebinning and the stacking of any dataset of spectra, giving as output the averaged spectrum and its associated error. The main inputs of the program are the spectral signal-to-noise (SNR) and the range of wavelengths required for the continuum normalization. In this latter case, it is very important that we choose intervals that are close to the range of wavelengths that we want to study in order to ensure a continuum as flat as possible. For this reason, we decided to make the stacking differentiating between each subclass and each Eu II line. This tool has been included into an automated, unsupervised procedure (also written in Python) that we have developed with the intention of finding which stars in a given sample have the largest concentration of r-process material.

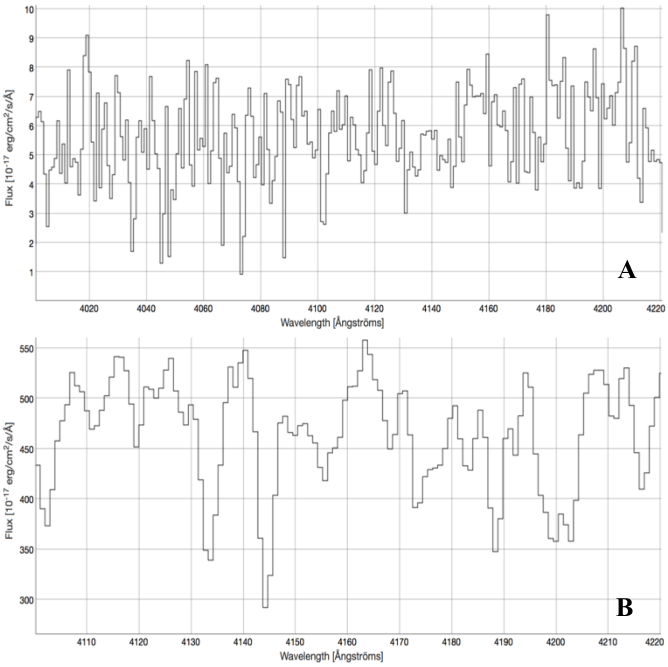

FIG. 4: This figure shows spectrum templates proportioned by SSDS in the range comprised between 4100 and 4220 Å [15]. **(A)** This spectrum belongs to an M class template. **(B)** This template corresponds to K1 subclass.

Regrettably, we soon realized that it was impossible to work with most of the M-star spectra because they both are frequently heavily incomplete and have plenty of strong molecular absorption lines in the range of wavelengths around 4100 Å chosen for the present study (see Fig.(4A)), which makes the continuum normalization impossible. In addition, the SDSS does not provide spectral templates for the K3, K5 and K7 subclasses, so we decided to focus on the K1 subclass, which is the only one with a decent spectrum template[1] available a priori [15] (see Fig.(4B)).

We have also taken into account that in the SEGUE-2 spectra the individual narrow lines of heavy metals, such as the strong absorption line of Eu expected around 4129 Å shown in Fig.(2), do not show up clearly due to the limited effective spectral resolution (a few angstroms) of the instrument. Because of this the flux corresponding to a given line is spread into the adjacent pixels (pixel size at ~ 4000 Å is a bit less that one Å), making the line lower and wider, as well as increasing the likelihood that it overlaps with other nearby lines. This means that the strongest absorption lines of Eu should appear in the SEGUE-2 spectra as moderately deep depressions of the continuum of a few angstroms of width. Therefore, to detect one of these lines, we have devised a technique that consists simply in calculating the differences, within a narrow range of wavelengths centered on the line, of the integrated fluxes of each of the K1 stars in the plate and the average spectrum of the plate, then ranking all the integrated flux differences in in order of increasing size and finally identifying the 10% of stars that show the most extreme values. Two lines of Eu II have been selected to carry out this exercise which are among the strongest in the optical window: the line at 4129.70 Å, which we expect will show up between 4127 and 4131 Å, and the line at 4205.05 Å, which should produce a detectable depression between 4203 and 4207 Å.

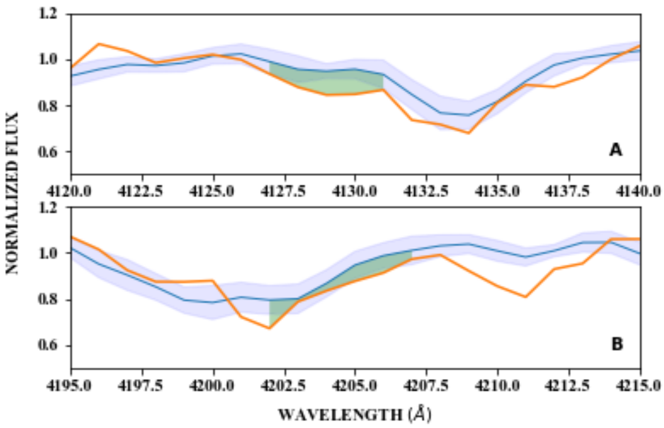

FIG. 5: Each plot shows the comparison between spectrum of a star (orange line) and the average of the sample (blue line) in a determined wavelength range. The surrounding lighter blue of averaged spectrum corresponds to its error associated, and green coloured area appertains to difference we have integrated. **(A)** Spectrum of star that presents more difference regarding to the average along 4127-4131 Å interval, which SDSS identifier is specobj_id= 3616517026002083840. **(B)** In this case, we see the spectrum with largest difference with respect to the average between 4203 and 4207 Å, corresponding to SDSS identifier specobj_id= 3590512751069470720.

Fig.(5), provides a graphical example of the sort of calculations involved in our methodology. On it we have represented two of the individual stellar spectra which differ more with respect to the average in the entire sample. The flux difference within the desired range comprised between the

[1] We could have attempted to derive ourselves the missing templates with our tool for stacking spectra, but we were discouraged by the limited time available for the present study.

star spectrum and averaged one is coloured in solid green area. In the upper plot, we can see that there is an extra depression between 4127 and 4131 Å, which could be an absorption line of Eu II. In Fig.(5B) the depression is not so clear. Yet, the star spectrum remains below the template along the whole interval comprised between 4203 and 4207 Å. To be fair, we notice that the second region investigated partially overlaps with a strong adjacent peak; therefore, in this case we cannot exclude that part of the measured depressions between ~ 4203 and 4207 Å are produced by a strong peak of Fe I (see next Section).

III. RESULTS

Next, we comment on the results we have inferred looking at the fluxes around 4129.7 Å and 4205.05 Å in a sample of more than 500 K1 stars distributed along 30 different SEGUE-2 plates.

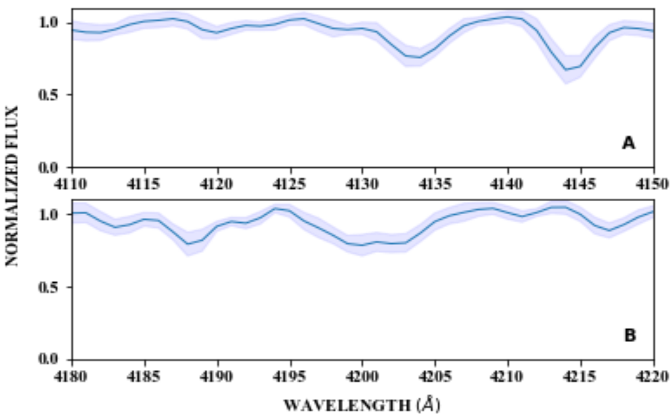

FIG. 6: Average spectrum of the whole sample of K1 stars with its associated error in a lighter blue. **(A)** Shows the average in the interval comprised between 4110 and 4150 Å and **(B)** Is represented the averaged spectrum along 4180 and 4220 Å.

Fig.(6A) shows the template corresponding to the 4129.7 Å line in the interval comprised between 4110 and 4150 Å. It shows a relatively flat spectrum up ~4130 Å followed by two broad absorption features around 4133 Å and 4145 Å. By looking at NIST Atomic Spectra Database Lines Data [13], we are able to confirm these depressions are lines from Fe I. As explained in the previous section, strong (narrow) metal lines show up in the SEGUE-2 spectra with relatively large widths because of the limited spectral resolution. In Fig.(6B), we show the template corresponding to the 4205.05 Å line in the interval comprised between 4180 and 4220 Å. The normalization is not as good as in the former case and we can observe several depressions suggestive of the presence of strong metal lines. The peak about 4188 Å is related to Fe I [13]. The second depression centered near 4200 Å is made by several lines so close to each other that slightly overlap, producing the impression of a single but very wide line. Because of the limited resolution, we are not able to determine exactly how many lines are in the range between ~ 4199 and ~ 4203 Å and what are their parent elements. Nevertheless, according to the NIST tables, we know that there should be several lines of Fe I and V I comprised in this interval. Similarly, the peak around 4218 Å would correspond to Fe I and VI.

Plate ID	l (º)	b (º)	f1	f2
3166	190.88	25.48	0.12	0.12
3206	187.00	15.70	0.12	0.06
3216	159.89	63.85	0.06	0.02
3160	187.00	17.85	0.06	0.00
3178	217.50	53.13	0.06	0.04
3170	229.70	69.00	0.06	0.10
3171	105.00	80.93	0.06	0.02
3188	191.81	31.23	0.06	0.04
3167	162.02	38.46	0.06	0.02
3208	150.00	32.15	0.04	0.12

TABLE I: This table shows the plates with major frequency (>0.06) of likely enhanced r-process stars inside and their corresponding galactic coordinates. F1 is the frequency related with 4129.7 Å line, while f2 is the fraction related with 4205 Å.

In Table 1 we list the (IDs) numbers and mean galactic coordinates of the plates with the highest fraction (>0.05 for at least one of the two lines) of Eu-enriched stellar candidates. Interestingly, in plate number 3166 we have detected a 12% fraction of K1 stars with an excess of Eu as measured from both lines, which ultimately makes the halo region sampled by this plate an interesting site where to start to look for stars rich in r-process elements.

IV. CONCLUSIONS AND FUTURE WORK

In this work we have developed an automated statistical algorithm to identify candidate stars that are richer than average in r-process elements from measuring the strength of two absorption lines of Europium, and tested in a sample of about 500 K1 stars of the Galactic halo observed with the SEGUE-2 optical spectrograph. Despite the simplicity of our approach, the results obtained are positive enough to encourage us to continue on this pathway to try to improve its performance.

Particularly encouraging has been the fact that the most significant results for the two absorption lines investigated have been obtained for the same plate, which might indicate that we have discovered a region of the MW halo with an abnormally high abundance in r-process heavy-elements. Admittedly, this finding is still plagued by large uncertainties, so much more work is needed before we can be sure that we are doing things right.

In the first place, we do not know, for instance, if our positive detections are caused by a real local presence of Eu in these regions, or in fact, by a gradient of metallicity in the galactic halo. To resolve this disjunctive, we need to increase the sample size by taking all plates provided by SEGUE-2, so we have a higher statistic to work with.

Another obvious extension of the work is to include other spectral types and subtypes of stars, specially M dwarfs which are very abundant, as well as finding (or building ourselves) spectral templates which help us to improve the continuum normalization, even in the presence of a forest of molecular absorption bands.

It is also essential that we work with a catalogue of spectra with high resolution (ideally a factor ten), since the typical widths of metal lines in stars are of the order of 0.1 Å. At the same time, we could try to extend our search beyond the optical window. For instance, it is well known that the spectral region between 1900 and 3050 Å (near UV) contains dozens of neutron-capture absorption lines (many from Selenium) that have been demonstrated to be good abundances indicators.

Finally, we could use other catalogues such as GAIA to carry out a long-term monitoring of the radial velocities of our best stellar candidates. This would help us to determine if the extra r-process elements were formed by a companion star— for example, in a supernova— and then transferred to the presently observed star.

Acknowledgments

I would like to thank Jose Maria Solanes for his implication and all help he gave me. Special mention to José Luis Tous for lending me the stacking tool.

[1] Burbidge E. M., Burbidge G.R., Fowler W. A., & Hoyle F., 1957, Reviews of Modern Physics 29, 547.

[2] René Reifarth, 2010, J.Phys: Conf. Ser. 202 012022.

[3] Wikimedia Commons contributors, 'File:Binding energy curve - common isotopes2.jpg', 2017, https://commons.wikimedia.org/w/index.php?title=File:Binding_energy_curve_-_common_isotopes2.jpg&oldid=261080038

[4] Lugaro M., Herwig F., Lattanzio J. C., Gallino R. & Straniero O., 2003, Ap. J. 586, 1305.

[5] Smith V. & Lambert D., 1990, Ap. J. Suppl.72, 387.

[6] Frebel A. & Beers T.C., 2018, Physics Today 71, 1, 30.

[7] Woosley S.E. & Hoffman R.D., 1992, Astrophys. J. 395, 202.

[8] Woosley S. E., Wilson J. R., Mathews G. J., Hoffman R. D. & Meyer B. S., 1994, Ap. J. 433, 229.

[9] Côté B., Fryer C. L., Belczynski K., Korobkin O., Chruslinska M., Vassh N., Mumpower M. R., Lippuner J., Sprouse T. M., Surman R. & Wollaeger R., 2018, Ap. J. 855, 2.

[10] Argast D., Samland M., Thielemann F.K. & Qian Y. Z., 2004, A&A 416, 3.

[11] SEGUE-2, Sloan Digital Sky Survey: http://www.sdss.org/surveys/segue/

[12] Arlandini C., Käppeler F., Wisshak K., et al. 1999, Ap. J. 525, 886.

[13] National Institute of Standards and Tecnology. NIST Atomic Spectra Database Lines Form: https://physics.nist.gov/PhysRefData/ASD/lines_form.html

[14] Kasen D., Metzger B., Barnes J., Quataert E. & Ramirez-Ruiz E., 2017, Nature 551, 80.

[15] SDSS. Spectral cross-correlation templates: http://classic.sdss.org/dr5/algorithms/spectemplates/index.html