A statistical method for the identification of stars enriched in neutron-capture elements from medium-resolution spectra

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We present an automated statistical method that uses medium-resolution spectroscopic observations of a set of stars to select those that show evidence of possessing significant amounts of neutron-capture elements. Our tool was tested against a sample of ~70 000 F- and G-type stars distributed among 215 plates from the Galactic Understanding and Exploration (SEGUE) survey, including 13 that were directed at stellar Galaxy clusters. Focusing on five spectral lines of europium in the visible window, our procedure ranked the stars by their likelihood of having enhanced content of this atomic species and identifies the objects that exhibit signs of being rich in neutron-capture elements as those scoring in the upper 2.5%. We find that several of the cluster plates contain relatively large numbers of stars with significant absorption around at least three of the five selected lines. The most prominent is the globular cluster M3, where we measured a fraction of stars that are potentially rich in heavy nuclides, representing at least 15%.

CONTEXT OF THE RESEARCH

- The aim of this work is to provide a tool to locate regions of our Galaxy whose stars show signs of being rich in rapid neutron capture (r-process) elements.

- The r-process is a primary process that only occurs in environments with extremely large neutron densities (~ 1020–1028 cm^{-3}). The astrophysical sources are still not definitely identified. Traditionally, the most probable candidate site for the r-process have been assumed to be the large regions swept by the ejecta of core-collapse supernovae, but other scenarios seem feasible such as binary neutron star mergers and collapsars.

- We want to look for the presence of neutral or singly ionized Europium (Eu) in stellar spectra since this element is among the best indicators of enrichment by rapid n-capture reactions (Argast et al. 2004). In particular, Eu is an element synthesized practically on its totality through the r-process (97% at solar metallicity according to Burris et al. 2000).

- Eu has several strong absorption lines in the optical part of the electromagnetic spectrum. These sub-angstrom-wide lines fall within the wavelength coverage of existing spectroscopic surveys whose spectral resolution is, however, too coarse to allow the direct detection of the lines.

- In this work, we provide an automated method to find stars that show evidence of possessing significant amounts of Eu relying on a large sample of medium-resolution spectra.

METHODOLOGY

- We work with ~70,000 spectra of F- and G-type stars distributed among 215 plates from the Sloan Extension for Galactic Understanding and Exploration (SEGUE) survey, 13 of them directed at stellar Galaxy clusters.
- The first step of our procedure consists on averaging the spectra for all the stars with the same spectral type.
- Next, we compare each spectrum with the inferred mean to identify the most discordant ones in several narrow spectral bands that encompass strong absorption lines of Eu (Table 1).
- The differences for each spectral range are then ranked in increasing order and those included in the upper 2.5% are considered to be indicators of an enhancement.
- For a star to be considered a potential candidate rich in n-capture elements, it must have produced positive results in, at least, three of the five spectral ranges (see Table 1).

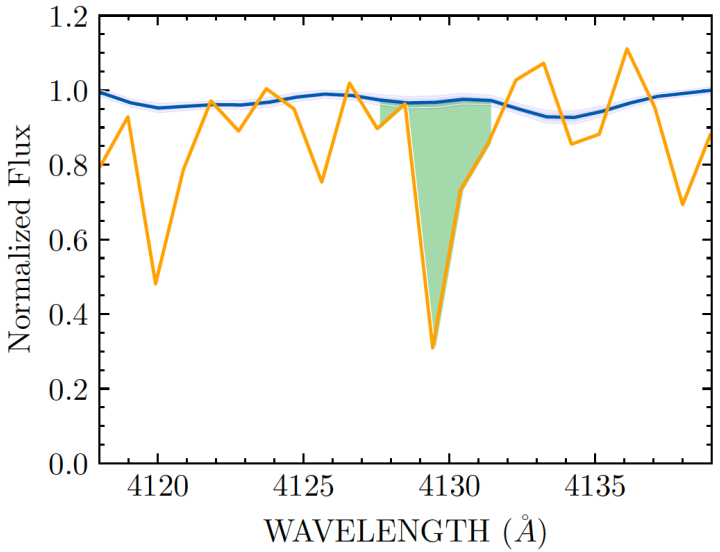

Figure 1: Example of F5 star (orange curve) which shows a significant flux deficiency with respect to the average flux inferred from the whole spectral class (blue curve).

Nuclide	Spectral line (Å)	Spectral range (Å)
EuI	4594	4592-4596
	4627	4625-4629
	4661	4659-4663
EuII	4129	4127-4131
	4205	4203-4207

Table 1: Strongest lines from Eu in the optical window and assigned spectral ranges for detection.

RESULTS

SEGUE program	Plate ID	l (°)	b (°)	Cluster ID	$N_{\geqslant 3}$	N_3	N_4	N_5	Q	F_r
Segue2	3304	132.06	62.00	–	3	3	0	0	0.1	0.08
Segcluster	2667	132.82	10.94	M67	6	4	2	0	0.5	0.03
	1961	54.00	−35.43	M2	6	4	1	1	0.3	0.03
	2476	199.03	17.01	NGC5053	10	8	2	0	0.3	0.07
	2475	42.31	78.70	M3	18	13	4	1	0.2	0.15

Table 2: SEGUE plates with at least three candidate stars rich in n-capture elements. From "G. Navó, J. L. Tous and J. M. Solanes, 2019, A&A, 631, A93".

- These plates correspond to regions of the sky that include at least three stars with a likely Eu enhancement, which is the minimum number required, in the present work, to consider that this part of the Galaxy would merit being explored in the search of n-capture enriched stars.

- Table 2 also reports the number of stars per plate whose spectrum produces evidence that is favorable to the existence of significant amounts of elements arising from n-capture nucleosynthesis in exactly 3, 4, and 5 of the narrow spectral ranges investigated and given by N_3, N_4, and N_5 (Cols. 7–9), respectively.

- Q is the fraction of stars within each plate whose spectrum complies our quality requirements, while F_r is the frequency of candidate stars per plate.

RESULTS (Cont.)

- Comparing F_r table values with its probability distribution:
  - Median $\bar{F}_r$=0.0 and mean $\langle F_r \rangle$= 0.004.
  - All of the frequencies are well within its upper decile, $F_r > 0.014$.
- Q values are very close to the average of the whole set, $\langle Q \rangle \simeq 0.2$. This excludes the possibility that the amount of Eu-rich stars found in a plate depends on the fraction of spectra analyzed.
- All but one of these plates are devoted to star clusters. Besides, the only field halo (segue2) plate in this list contains the lowest total number of stars with an enhanced content in heavy elements in at least three lines, $N_{\geq 3}$ (Col. 6).
- These findings are consistent with the expectation that most targets included in the tiles of segcluster program should be stars created in a common formative environment; while the presumably disparate birth places of the objects observed in the segue2's tiles should contribute to blur any signature that might exist from past heavy-element nucleosynthesis events in the targeted regions of our Galaxy.
- By considering only the 43 candidate stars contained the five plates listed in Table 2, the probability of obtaining by chance this number of positive signals from a sample of 70, 000 stars is extremely low (in the order of 10^{-57}). Besides, the fact that these 43 candidate stars show indications of a heavy nuclide boost not only in three, but also in four (on 9 occasions) and even in all five lines (on 2 occasions), reinforces the robustness of the detections.
- NGC5053 and M3 are the two globular clusters with the highest fractions of r-process enriched stars: 7% and 15%, respectively.

IMPACT AND PROSPECTS FOR THE FUTURE

- We have devised a fast and reliable automated procedure that enables the detection of the fine absorption lines from using data from large surveys whose spectral resolution is too coarse to approach this problem in a traditional way.

- When applied to SEGUE data it has enabled the identification of sites within our Galaxy where it should be possible to find a good number of stars that exhibit enhancement in such elements, avoiding the time-consuming searches through thousands of candidates that are currently being carried out to find these precious objects in the Galactic halo.

- The SDSS spectroscopic identifiers (specobjID), together with the spectral subclasses and metallicities of all candidate stars enriched in Eu detected in the SEGUE plates can be found in Table A.1 of Appendix A in Navó et al. (2019). These data should benefit future high-resolution stellar spectral abundance surveys that search for clues to the astrophysical origin of the r-process nuclides by facilitating the identification of the sites where it should be possible to find a good number of stars that exhibit an enhancement in such elements. We encourage the astronomical community to use them.