Replies to the questions from Szabolcs Mészáros

1. In the last decade multiple high-resolution spectroscopic surveys, such as APOGEE, GALAH and Gaia-ESO determined the chemical composition of hundreds of thousands of stars. Could you please give a short overview of how these large surveys contributed to understanding the slow neutron capture process in general?

ANSWER: High-resolution spectroscopic surveys have included some of the elements heavier than iron and have provided therefore new constraints on the *slow* neutron-capture process in the Galaxy. These observations do not compare directly to models of AGB stars, but to models of galactic chemical evolution (GCE). These models convolve the AGB yields together with the yields from all the other stellar sources to determine the evolution of the elements in the interstellar medium from which the observed stars formed. On top of all the stellar yields, many more parameters need to be considered in GCE models, which makes this field of research particularly rich. Some of the added complexities are, for example, the initial mass function, the star formation rate, the presence of galactic in-fall episodes and their timing, as well as processes such as stellar migration. Within this framework, several debated topics can be found in the current literature based on new data from the APOGEE, GALAH and Gaia-ESO surveys. I provide a brief summary and references for the most relevant here.

1) **The evolution of neutron-capture elements over time**. Large surveys in combination with better age determination have opened the possibility to study the evolution of the elemental abundances both with metallicity [Fe/H] and stellar age (see also Point I of answer to Question 2). For example, Horta et al. (2022, MNRAS, 513, 5477 *Neutron-capture elements record the ordered chemical evolution of the disc over time*) used GALAH DR3 data to map the evolution of Ba over time in different locations in the Galaxy. They concluded that to explain the various trends a different initial mass function is required in different parts of the Milky Way disk.

2) **The reliability of nuclear clocks, such as [Y/Mg].** As discussed in detail by Hayden et al. (2022, MNRAS, 517, 5325 *The GALAH survey: chemical clocks),* there are opportunities to use ratios of elements produced by stellar sources on different timescales as a proxy to derive stellar ages accurate to the level of 1-2 Gyr. For example, [Y/Mg] must trace time because Y is produced by long-lived AGB stars while Mg is produced by short-lived massive stars. However, some of these clocks may be more uncertain than expected (see, e.g., Casali et al. 2020, A&A, 639, A127 *The Gaia-ESO survey: the non-universality of the age–chemical-clocks–metallicity relations in the Galactic disc*), also due to the unclear behaviour of the *slow* neutron-capture elements at young ages discussed in the next point.

3) **The evolution of slow neutron-capture elements with age and radial distance as sampled by observations of Open Clusters.** The possible increase of the abundances of *slow* neutron-capture elements in very young clusters (with ages down to a few tens of Myr) has been debated now for more than two decades. Different studies do not agree with each other on which elements vary and the magnitude of the variations. Furthermore, some of these variations may be related to the modelling the atmospheres of young stars. For recent contributions to this problem by high-resolution spectroscopic surveys see, e.g.:
- Magrini et al. (2018, A&A, 617, id.A106): *The Gaia-ESO Survey: the origin and evolution of s-process elements*;

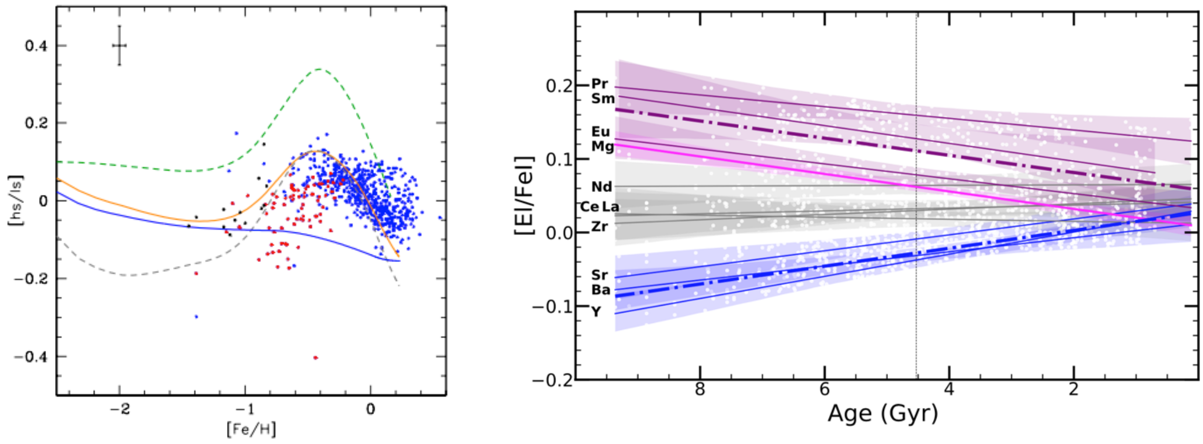
- Baratella, … , Lugaro, …, et al. (2021, A&A, 653, A67): *The Gaia-ESO Survey: a new approach to chemically characterising young open clusters II. Abundances of the neutron-capture elements Cu, Sr, Y, Zr, Ba, La, and Ce.*
- Sales-Silva et al. 2022 (ApJ, 926, 154): *Exploring the S-process History in the Galactic Disk: Cerium Abundances and Gradients in Open Clusters from the OCCAM/APOGEE Sample.*

One example to highlight the ongoing debate is that the data presented in last paper in the list above confirm the decrease of [Ce/Fe] versus [Fe/H] predicted by GCE models, which reproduce the trend of the AGB models and Ba stars data presented in the thesis. However, the data show an increase of Ce for clusters of young ages, at odds with the more limited results of Baratella et al. (2021) but also with the recent Ce analysis based on 30,000 stars from Gaia DR3 (Contursi et al. 2022, A&A, accepted December *The cerium content of the Milky Way as revealed by Gaia DR3 GSP-Spec abundances).* More analysis and data are needed to address the problem of young open clusters.

2. What are the most important elements for understanding the slow and intermediate neutron capture process that do not have detailed abundances determined by these surveys (or by individual studies) and how could we get them using high resolution spectroscopy? What wavelength region should we observe and with what resolution and signal-to-noise to reliable measure the absorption lines of these elements?

ANSWER: I reply to this question in two parts: first, in relation to the previous question and therefore focusing on the understanding the *slow* and *intermediate* neutron-capture process in the Milky Way Galaxy as a whole; second, in relation to direct observations of the abundances predicted by the *slow* and *intermediate* neutron-capture processes in AGB stars, their progenies and their binary companions. I can suggest to experimental colleagues what would be my wish list as a theoretician as the determination of related wavelength regions, resolution, and signal-to-noise is beyond my expertise.

I) Indirect observations involving GCE: In my opinion, more analyses need to be made from already available data on the evolution of the *slow* neutron-capture process elemental ratios versus age in the Milky Way. As shown in the thesis, the AGB models predict and the Ba star data show that in AGB stars the second-to-first peak ratios decrease with increasing metallicity. This is reflected in GCE models, as shown, e.g., in left panel of the figure below. In a simple GCE model, older stars have less Fe, so [Fe/H] decreases with increasing age, therefore the second-to-first peak ratios should increase with age. However, observations indicate that it is not that simple. Tautvaišienė et al. (2021, A&A, 649, A126) analysed data for about 500 stars (from the 1.65 m telescope at the Molėtai Astronomical Observatory) and showed that there are different trends for different *slow* neutron-capture elements as function of both [Fe/H] and age (right panel of the figure below). For example, [Ba/Zr] behaves in the opposite way as predicted and there are clear differences even for elements that belong to the same peak, such as between Sr+Y and Zr, and Ce+La and Ba, as clearly highlighted by the fact that the elements are grouped in the figure differently than according to the peaks that they belong to. If these trends are confirmed, they may represent crucial indications for GCE models and for the study of the *slow* and *intermediate* neutron-capture processes in the Galaxy.



Left panel: Figure 17 of Prantzos et al. (2018, MNRAS, 476, 3432). Heavy-s (hs: Ba, Ce, Nd) to light-s (ls: Sr, Y, Zr) ratio versus [Fe/H]. Blue and red dots are stars in the thin and thick disk, respectively. The lines show GCE models with different massive stars yields. They all show the decrease of [hs/ls] with [Fe/H] predicted by the AGB models - unless of course the AGB stars are excluded from the GCE models, as in the case of the blue line. Right panel: Figure 11 of Tautvaišienė et al. (2021, A&A, 649, A126). Compilation of [El/Fe] trends as a function of age for the thin-disk stars. The shadowed areas show the 95% confidence interval for the regressions.

Another related, exciting topic are the P-rich stars recently discovered thanks to the APOGEE survey by Masseron et al. (2020a, Nature Communications, 11, 3759). These stars are very puzzling as their P-richness, together with their enhanced Si/S ratios, are in disagreement with any current nucleosynthesis site. Masseron et al. (2020b, ApJ, 904, L1) also reported analysis of elements heavier than iron in two of these stars, which show a pattern that cannot be explained by the *slow* neutron-capture process. In fact, their Ba/La ratio is almost ten times higher than solar, while both these elements are produced in the Galaxy by the *slow* neutron-capture process in the same proportion as solar. Further investigations of more elements in more of these P-rich stars are currently ongoing.

II) Direct observation of stars enhanced in the elements heavier than iron: My main interest from a theoretical point of view is in the detection of specific elemental ratios that are predicted to be very different in the case of the *slow* and the *intermediate* neutron-capture processes. Useful in this respect are the relative ratios of elements belonging to the same peaks, e.g. Sr, Y, Zr; and Ba, La, and Ce. As mentioned above, the *slow* neutron-capture process can only predict solar values for such ratios; therefore, ratios different from solar and well beyond the error bars (e.g., the Ba/La ratios of the two P-rich stars mentioned above), must have been produced by a different process. The abundances of the element between the peaks (e.g., Nb, Mo, Ru, Pd, as well as Sm, Nd, W, Hf) relative to the elements belonging to the peaks listed above plus the third peak at Pb, are also among the most important signatures of the *intermediate* neutron-capture process (as demonstrated in Section 3.2 of the thesis). Of course, the smaller the error bar on the data (ideally $< \pm 0.1$ dex), the more robust is the interpretation. Rb is another crucial element, as it is also expected to be strongly produced by the *intermediate* neutron-capture process. In fact, our current interpretation of recent analysis of Ba stars indicated that there is friction between their low Rb abundances and trying to explain the Nb, Mo, and Ru enhancements in some of these stars with a pure *intermediate* neutron-capture process model (den Hartogh et al. 2023, accepted for publication in A&A, arxiv.org/abs/2212.03593). The situation, even for Ba stars, appears more complex with possibly different *slow* and *intermediate* neutron fluxes acting on each other products in the same AGB star.

Other elements of interest are those for which we can derive information complementary to that from the elements listed above from the emission (rather than absorption) lines observed in planetary nebulae. These are, e.g., the noble gases Kr and Xe (Manea et al. 2022, ApJ, 164, 185), where Kr is predicted to be strongly produced by the *intermediate* neutron-capture process.

Another strong constrain would be represented by the isotopic ratios, for example, of Ba, since ^{135}Ba is the isotope of Ba by far the most produced by the *intermediate* neutron-capture process. However, most astronomer colleagues have told me that it is almost impossible to derive isotopic ratios using current resolution because the spectral changes are too small - unless of course the isotopes are present in relatively high abundance in molecules, which is not the case for the elements heavier than iron.