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The Abundance of S-Process Elements: Temporal and Spatial Trends from Open Cluster Observations

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Citation: Magrini, L.; Viscasillas Vázquez, C.; Casali, G.; Baratella, M.; D'Orazi, V.; Spina, L.; Randich, S.; Cristallo, S.; Vescovi, D. The Abundance of S-Process Elements: Temporal and Spatial Trends from Open Cluster Observations. *Universe* **2022**, *8*, 64. https://doi.org/10.3390/universe8020064

Academic Editor: Elisa Delgado Mena

Received: 7 December 2021
Accepted: 17 January 2022
Published: 21 January 2022

Abstract: Spectroscopic observations of stars belonging to open clusters, with well-determined ages and distances, are a unique tool for constraining stellar evolution, nucleosynthesis, mixing processes, and, ultimately, Galactic chemical evolution. Abundances of slow (s) process neutron capture elements in stars that retain their initial surface composition open a window into the processes that generated them. In particular, they give us information on their main site of production, i.e., the low- and intermediate-mass Asymptotic Giant Branch (AGB) stars. In the present work, we review some observational results obtained during the last decade that contributed to a better understanding of the AGB phase: the growth of s-process abundances at recent epochs, i.e., in the youngest stellar populations; the different relations between age and [s/Fe] in distinct regions of the disc; and finally the use of s-process abundances combined with those of α elements, [s/α], to estimate stellar ages. We revise some implications that these observations had both on stellar and Galactic evolution, and on our ability to infer stellar ages.

Keywords: galaxy: abundances; open clusters and associations: general; disk nucleosynthesis

1. Introduction

The production of elements heavier than iron follows a different path from the lighter ones, as they cannot be synthesised through thermonuclear fusion reactions. They are formed by addition of neutrons in various astrophysical contexts, either by rapid (r) or slow (s) processes, depending on whether the neutron-capture is slow or rapid compared to the timescale of the β-decay [1]. The production of s-process elements can occur both in massive stars (the so-called weak process; see, e.g., Heil et al. [2], Pignatari et al. [3,4]) and during the asymptotic giant branch (AGB) phase of low- and intermediate-mass stars (the main process; see, e.g., Busso and Gallino [5], Busso et al. [6], Karakas and Lugaro [7], Cristallo et al. [8], Busso et al. [9]). Here, we focus on the s-process elements produced by the main process. In this contribution, we review the steps done in the last decade to understand the origin and evolution of the s-process elements, and the great contribution given by high-resolution spectroscopic observations of open star clusters.

2. The Open Cluster Samples and the Contribution of the *Gaia*-ESO Survey

Open star clusters are coeval groups of stars, sharing the same chemical composition, and belonging to the Galactic disc. Thanks to photometric observations of several members along the evolutionary sequence of star clusters, it is possible to determine precisely their age and distance. The reached precision is much higher than that achieved when measuring the ages of field stars. In addition, the population of open clusters covers a wide range of ages (from a few Myr to about 7–8 Gyr), and Galactocentric distances (5–20 kpc), thus representing among the best tracers of the kinematics and of the chemistry (including its time evolution) of the Galactic thin disc (see Dias et al. [10], Kharchenko et al. [11] for the two most widely used catalogues before *Gaia*). The *Gaia* mission has given an incredible boost leading to the discovery, confirmation and determination of the properties of thousands of clusters [12–16]. *Gaia* results were amplified by combining them with ground-based large spectroscopic surveys, e.g., APOGEE [17], GALAH [18] and *Gaia*-ESO [19,20]. Among them, the *Gaia*-ESO survey, a large public spectroscopic survey carried on with the spectrograph FLAMES [21] at ESO/VLT [19,20] from the end of 2011 to 2018, devoted about 36% of the 340 allocated observing nights to open clusters. Its cluster sample was designed to cover the whole age-distance-metallicity parameter space, observing in each cluster large and unbiased samples of stars. The *Gaia*-ESO sample thus represents a unique tool for investigating variations in the spatial and temporal properties of s-process abundances in the disc. A description of the survey and of the open cluster sample can be found in Randich et al. (submitted).

3. Age Effects in the Abundances of the S-Process Elements

From an observational point of view, the study of the chemical composition of stellar populations with well-measured ages, i.e., star clusters, has revealed an interesting property of s-process elements related to their main site of production. The pioneering work of D'Orazi et al. [22] indeed noticed a net increase in the abundance of the s-process abundances in the youngest stellar populations of their sample, with Ba abundance noticeably higher in the younger clusters than in the older ones. Subsequent works [23,24] added several other elements with important s-process contributions (yttrium, zirconium, lanthanum, and cerium), confirming the increasing trend of their abundances towards younger ages. Several further works have contributed to the understanding of the origin of this growth, without yet reaching a general consensus, arguing whether the enrichment is due to mixing effects that produce a larger source of neutrons, and hence s-elements, in low-mass stars, or whether it is due to observational effects or related to stellar characteristics, such as chromospheric or magnetic activity (see, e.g., Busso et al. [9], Bisterzo et al. [25], Mishenina et al. [26], Trippella et al. [27], Reddy and Lambert [28], Magrini et al. [29], Spina et al. [30,31], Baratella et al. [32]). Other works used the properties of those abundance ratios as a valuable tool to estimate the ages of stars (see, e.g., Spina et al. [30], Nissen [33], Delgado Mena et al. [34], Casali et al. [35], Horta et al. [36]).

One of the most interesting open topics in chemical evolution is, indeed, to understand the origin of the time-evolution of the s-process abundances, both for its importance in our comprehension of the evolution and nucleosynthesis of the most numerous population, i.e., low- and intermediate-mass stars, and for its application as a tracer of stellar age. Chemical evolution models assuming a decreasing efficiency in the production of s-process elements in low-mass stars (see, e.g., Pagel and Tautvaisiene [37], Travaglio et al. [38]) predict a plateau or even a decrease in the abundances [El/Fe] versus age in the last 4–5 Gyr. In such models, an increase at later times was not expected. However, from an observational point of view, a general consensus of an increasing, though weak, trend in the s-process elements production exists, both from cluster samples (e.g., Maiorca et al. [23,24], Mishenina et al. [26], Yong et al. [39], Jacobson and Friel [40], Mishenina et al. [41], Sales-Silva et al. [42]) and from field stars (e.g., Reddy and Lambert [28], Spina et al. [30], Nissen et al. [43]). The observations of *Gaia*-ESO [29] confirmed with a large statistical sample of open clusters and field stars, homogeneously analysed, the increasing trend of s-process abundance ratios (Y, Zr, Ba, La, Ce) with age, in the solar neighbourhood (see Figure 1). The weighted linear fits shown in Figure 1, computed for stellar ages <8 Gyr, and considering both the open cluster and field star populations, highlight the increase of [El/Fe] at recent epochs. Details and coefficients of the fits can be found in Magrini et al. [29]. In Figure 1, we can notice the so-called barium puzzle, i.e., the over-abundance of Ba with respect to the other elements of the second peak in younger stellar populations, which is probably linked to the effect of stellar activity and how it shapes the strongest spectral lines. For a discussion on this topic, we refer to [31,44] and to the contribution of V. D'Orazi in this volume.

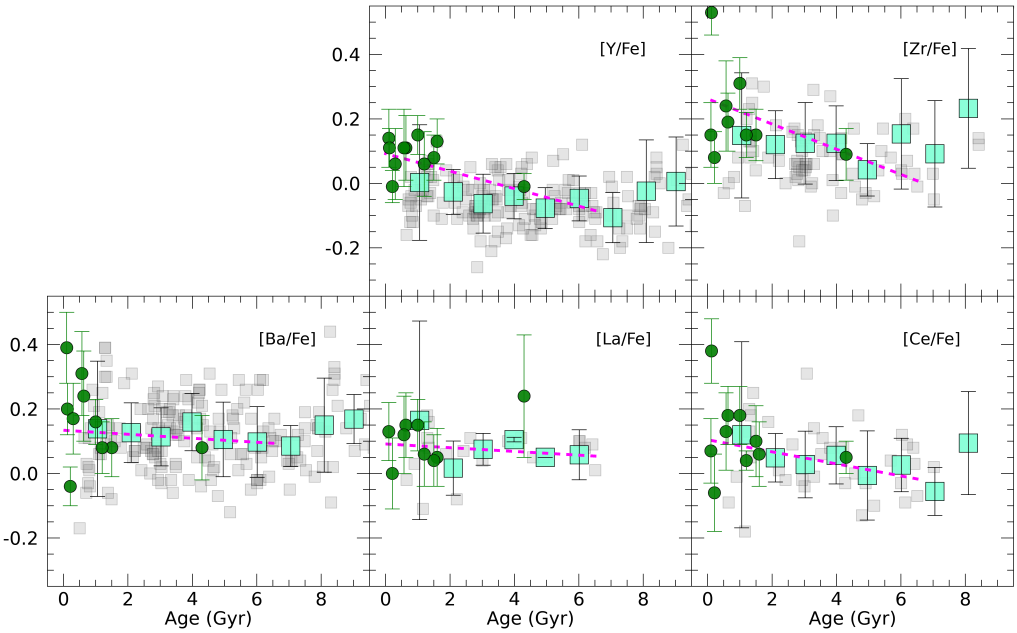

Figure 1. Abundance ratios [El/Fe] vs. age for the thin-disc stars (binned results, bin 0.1 dex wide–cyan squares, and individual stars–grey squares) and the open clusters located in the solar neighbourhood (green circles). The magenta dashed lines are the weighted linear fits to the cumulative sample of solar neighbourhood clusters and thin-disc field stars for stellar ages <8 Gyr (figure adapted from [29]).

From a theoretical point of view, an important step in understanding the late-time increase has been made (first empirically, then quantitatively) by including a higher production of s-elements by low-mass stars ($M < 1.5\ M_{\odot}$), which start contributing later in the lifetime of the Galaxy (see, e.g., D'Orazi et al. [22], Maiorca et al. [24]) and in which larger reservoirs of neutrons from the $^{13}C(\alpha, n)^{16}O$ reaction might be in place. The presence of an extended ^{13}C pocket requires a very efficient mixing episode and the magnetic buoyancy is one of the most conceivable transport mechanisms able to produce it [9,27,45–50]. The result is also confirmed in independent way from the composition of the presolar grains [51–53], confirming the major role played by low-mass AGB stars in the s-process Galactic enrichment. Moreover, to complicate the picture further, the yields of s-process elements are highly dependent on metallicity, in a non-monotonic way (see. e.g., [7,54,55]), and thus varied behaviours are expected at different Galactocentric regions, characterised by diverse star formation history and metallicity, as reflected by the presence of the radial metallicity gradient [56–58].

4. Spatial Effect in the Age-[s/Fe] Relationships

The relation between the abundances of neutron-capture elements and stellar ages in the limited volume around the Sun has been later widely investigated and confirmed [28,30,39–41,59–61]. The work of Viscasillas Vázquez et al. (submitted, hereafter VV22), taking advantage of the last *Gaia*-ESO data release, made use of a sample of open clusters covering a wide range of ages (0.1–7 Gyr) and Galactocentric distances (5–20 kpc), to extend the relationships between age and [s/Fe] in different regions of the disc. The results are summarised in Figure 2 (for full details see VV22), in which the cluster sample is divided in three Galactocentric regions: an outer region of the Galactic disc, which includes 30 OCs located at a Galactocentric distance $R_{GC} > 9$ kpc; a central region, in which our Sun is located, which includes 20 OCs at $7 \leq R_{GC} \leq 9$ kpc; and an inner region, with 12 OCs at $R_{GC} < 7$ kpc. The figure shows some important results: (*i*) the maximum enrichment (intercept of the fit) varies with the Galactocentric distance, and the highest values of [s/Fe] are reached in the outer disc for all the considered elements; (*ii*) although in each radial bin there is a well-defined relation between age and abundance ratios, its slope varies with R_{GC}; (*iii*) there are differences between the elements of the first and second peaks, and, on average, the slope of the relation involving the first-peak elements is flatter than for the second-peak ones; (*iv*) [Ba/Fe] differs from the other two heavy elements, Ce and La (barium puzzle). The radial variations are likely related to the interplay between the metallicity dependence of the s-process yields, which acts differently on the two peaks, and the radial dependence of the star formation history. A possible explanation was proposed by Magrini et al. [62]. They used a new set of yields from FRUITY stellar models in which the magnetic-buoyancy-induced mixing accounts for the formation of the ^{13}C neutron source in AGB stars [52]. The new yields, included in a Galactic chemical evolution model, can qualitatively explain the different time evolution of the s-process elements in the inner part of the disc with respect to the outskirts [62].

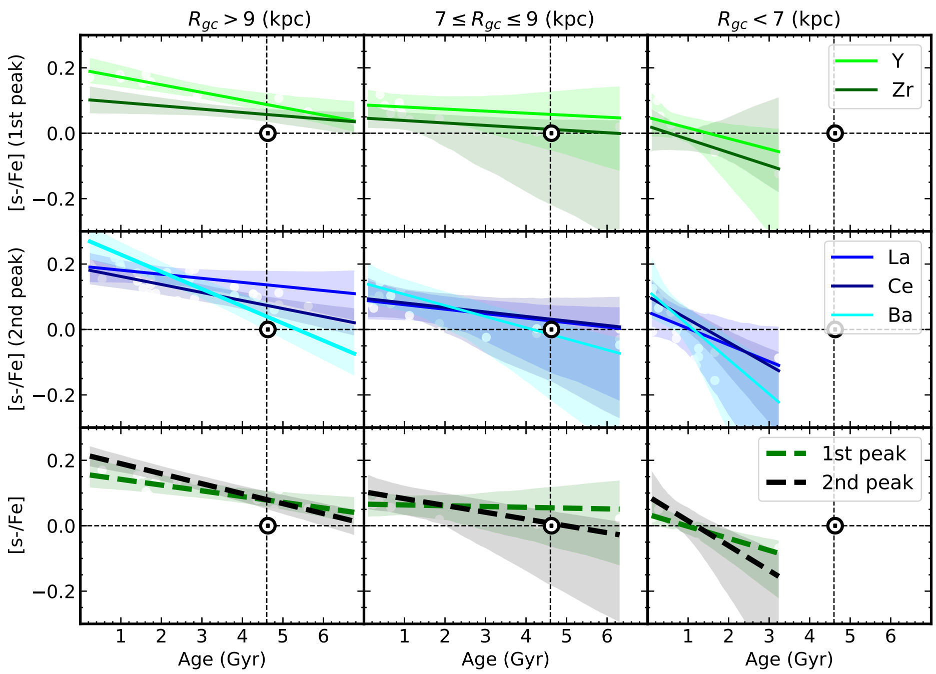

Figure 2. [El/Fe] versus age for the elements of the first peak (Y and Zr, **upper panels**), of the second peak (Ba, La, Ce, **central panels**), and average of first and second peak (**bottom panels**) in three Galactocentric bins (outer disc, $R_{GC} > 9$ kpc; solar neighbdourhood $7 \leq R_{GC} \leq 9$ kpc; inner disc, $R_{GC} < 9$ kpc). The curves are the weighted linear fits to the data. The data of individual clusters are shown in transparency in each panel.

5. The [s/α] Ratios as Age Tracers

One of the hot topics in Galactic Archaeology is the determination of the ages of stars. Stellar ages, in fact, add the temporal dimension to the complex picture outlined by positions, distances, kinematics and chemistry provided by the *Gaia* mission [63–65] and the ground-based spectroscopic surveys [17–19]. In the last decades, the use of chemical indicators for stellar ages, the so-called chemical clocks, has been consolidated (see, e.g., Delgado Mena et al. [34], Casali et al. [35], Casamiquela et al. [61], Spina et al. [66], Jofré et al. [67], Casali et al. [68]), providing alternative and complementary estimates of ages to the classical isochrone fitting. The relation between [s/α] and stellar age is well-established in the solar neighbourhood, and currently the relevant issue is whether it is universally valid, or depends on, e.g., the spectral type considered [61,69,70], the metallicity [35,71], and the stellar population [72–74].

Starting from the work of Casali et al. [35], it was noticed that the relations derived in the solar neighbourhood fail to reproduce the ages of star clusters in the inner disc. They concluded that the relationships between age and abundance-ratios are not universal, and vary with Galactocentric position. In a similar way, Casamiquela et al. [61] noticed that the dispersion in those relations increases adding star clusters with different R_{GC}. Casali et al. [35] attributed the spatial variation of these relations to the change of the star formation history along R_{GC}, coupled with the non-monotonic metallicity-dependence of the s-process stellar yields. This suggestion is later theoretically confirmed by Magrini et al. [62].

The final *Gaia*-ESO data release produced a new momentum for this topic by providing the largest sample of open clusters with abundances from high-resolution spectra, including s-processes. Furthermore, for most of the clusters in *Gaia*-ESO we can benefit from ages and distances measured homogeneously with *Gaia* data [13]. The analysis of VV22, summarised in Figure 3 in which [Y/Mg] and [Ba/Mg] versus cluster age are shown, clearly illustrates the differences in the relationships for the cluster samples located in different Galactocentric regions. The figure shows that there is no single relation that can be adopted in the whole disk, but that it is fundamental to take into account R_{GC} when one wants to estimate the age of a star from its [s/α].

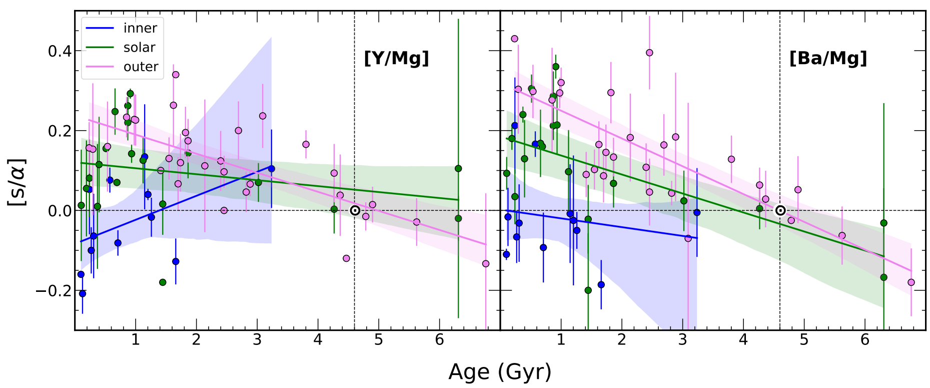

Figure 3. [s/α] versus age in three Galactocentric bins (outer disc in pink, $R_{GC} > 9$ kpc; solar neighbourhood in green, $7 \leq R_{GC} \leq 9$ kpc; inner disc in blue, $R_{GC} < 9$ kpc). The curves are the weighted linear fits to the data. In the left-hand panel we show [Y/Mg] versus ages, and in the right-hand panel [Ba/Mg] versus age. The data of individual clusters (abundance ratios are the mean values of the clusters members, while ages are from Cantat-Gaudin et al. [13], derived from *Gaia* DR2 data) are represented by filled circles, in the same colours as the corresponding fits. The shaded areas indicate the confidence intervals of the fits.

6. Summary, Conclusions and Future Perspectives

Observations of stars in clusters have made an important contribution to our understanding of the evolution and nucleosynthesis of low- and intermediate-mass stars, and their implications in the global chemical evolution of our Galaxy. Since the cluster populations comprise large ranges in age and R_{GC}, they serve as tests for both the temporal and spatial evolution of the products of chemical evolution. In the present work, we have shown some recent observational results which provided strong constraints of the physics of the AGB stars as producers of heavy s-process elements.

- Observations in young clusters have revealed, for the first time, the important role played by low-mass stars during their AGB phase in the s-process Galactic enrichment during recent epochs, providing strong constraints on mixing processes, necessary to produce an enhanced ^{13}C pocket, with consequent effects on nucleosynthesis [9,22–24,48].
- Large samples of open clusters have confirmed the growth with time of the s-process abundances, but showing a different time evolution at different R_{GC}. That difference might be a signature of the non-monotonic metallicity dependence of the AGB yields for the s-process elements. The s-process yields are indeed driven by the neutron-to-seed ratio, which depends on the availability of free neutrons (numerator) and on the abundance of iron seed from which the s-process path starts (denominator). While the first quantity is of primary origin, the latter depends on the initial metallicity. The different time evolution of the elements belonging to the first and second peaks made a further theoretical effort necessary, in which the inclusion of magnetic fields succeeds in qualitatively reproducing the observations [52,62]. Given the great importance of the dependence on mass and metallicity of s-process element yields, it will be necessary in future to produce finer grids of stellar yields, taking also in to account constraints from other elements, like Pb and Rb, which will allow us to distinguish between different scenarios.
- Finally, the ratio between s-process and α elements are considered excellent indicators of stellar age. Observations of these abundance ratios in clusters enabled us to calibrate relationships between ages and so-called chemical clocks. Recent works ([35] VV22), using the cluster sample in *Gaia*-ESO, have revealed that these relationships are not universal, and that they have a high degree of dependence on Galactocentric distance. So special care must be taken when inferring ages from them, and it is essential to take into account the radial region of origin of the stars. This can be particularly relevant for the older stars on which stellar migration has the greatest influence [75–79]. In addition, chemical clocks based on Ba and Y might not work for clusters younger than 150 Myr, since their abundances can be modified for other reasons (see [44]).

Many of the absorption lines produced by heavy elements fall in the blue and ultraviolet (UV) part of the spectrum. Remarkable progress in the study of the formation and evolution of these elements will be achieved with the next generation of spectrographs that will include wavelength ranges towards the blue and UV. Among the future instruments, we recall CUBES (Cassegrain U-Band Efficient Spectrograph), a forthcoming ESO VLT spectrograph with the goal of covering with a high efficiency the UV ground-based region (300–400 nm) with intermediate resolution (about R = 20,000) and HRMOS (High Resolution Multi-Object Spectrograph), a proposed facility instrument for the ESO VLT, with high spectral resolution (R = 60,000–80,000) and multi-object (50–100) capabilities and stability, going to blue wavelengths (from 380 nm). Thanks to its high spectral resolution, HRMOS will be the only instrument that will provide Pb measurements for large samples of stars, which are crucial for a complete understanding of the production of s-elements from the main process.

Author Contributions: Conceptualization, L.M., C.V.V., G.C., L.S., V.D., M.B., S.R., S.C., D.V.; methodology, L.M., C.V.V., G.C., L.S., V.D., M.B., S.C., D.V.; software, L.M., C.V.V., G.C., L.S., V.D., M.B., S.C., D.V.; writing—original draft preparation, L.M.; writing—review and editing, L.M., C.V.V., G.C., L.S., V.D., M.B., S.R., S.C., D.V.; visualization, L.M., C.V.V. All authors have read and agreed to the published version of the manuscript.

Funding: COST Action CA18104: MW-Gaia.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Gaia-ESO data can be accessed from the ESO Archive: http://archive.eso.org/ (accessed on 6 December 2021).

Acknowledgments: The authors acknowledge A. Karakas for useful discussion. G.C. acknowledges support from the European Research Council Consolidator Grant funding scheme (project ASTEROCHRONOMETRY, G.A. n. 772293, http://www.asterochronometry.eu (accessed on 6 December 2021). L.M. and C.V.V. thank the COST Action CA18104: MW-Gaia. D.V. acknowledges financial support from the German-Israeli Foundation (GIF No. I-1500-303.7/2019).

Conflicts of Interest: The authors declare no conflict of interest.

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