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Chemical evolution of the Galaxy estimated by distributions of elemental abundance

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Abstract. One of the consequences of stellar evolution is the enrichment of the Milky Way gas. New chemical elements synthetized within stars are mixed into the interstellar gas after the death of the star. Therefore, stars born when the Glaxy was younger are supposed to have a lower proportion of heavy chemical elements than stars born later. We also know that the enrichment rate of each particular chemical element depends on the nucleosynthetic processes that produce it. So, they are associated with stars at certain evolutionary stages. This is reflected in the distribution of the abundance of these elements, and this is our object of study. We use chemical evolution models to obtain additional information about the abundance distributions of the elements, understanding what information their statistics can give us about their formation process.

Resumo. Uma das consequências da evolução estelar é o enriquecimento do gás da Via Láctea. Novos elementos químicos gerados no interior de estrelas são misturados ao gás interestelar com a morte da estrela. Dessa forma, estrelas nascidas quando a Galáxia era mais jovem terão uma menor proporção de elementos químicosn pesados do que as estrelas que nasceram posteriormente. Sabemos também que a taxa de enriquecimento em cada elemento químico em particular depende dos processos nucleossíntéticos que o produzem; por isso são associados a estrelas em determinados estágios evolutivos. Isso se reflete na distribuição da abundância desses elementos e esta é nosso objeto de estudo. Utilizamos modelos de evolução química para obter informações adicionais sobre as distribuições de abundância dos elementos, entendendo o que informações suas estatísticas podem nos dar a cerca de seu processo de formação.

Keywords. Chemical Evolution – Nucleosynthetic processes – Elemental Abundance

1. Introduction

The chemical enrichment of the Milky Way gas occurs progressively as a result of stellar evolution. The elements synthesized by stars are released into the interstellar medium upon their death. Therefore, the rate of enrichment of a chemical element depends on its formation process, and its abundance serves as a summary of the element evolution. The present work aims to compile general information about the nucleosynthesis of specific elements based on parameters that describe their abundance distribution. In particular, we explore how the mean and dispersion (i.e., the standard deviation) reveal common behaviors among elements originating from the same nucleosynthetic processes.

We consider the following nucleosynthetic processes which forms the bulk of the chemical elements:

- Hydrogen burning and odd-Z elements: N, Na, Al, K, P;
- Helium burning and α Process: C, O, Ne, Mg, Si, S, Ca, Ti;
- e-Process: Fe, Sc, V, Cr, Mn, Co, Ni, Cu, Zn;
- Slow Neutron Capture Process (s-Process): Sr, Y, Zr, Mo, Ba, La, Ce, Pr, Nd, Sm;
- Rapid Neutron Capture Process (r-Process): Eu.

2. Analytical model

A more refined analysis of Galactic chemical evolution requires the use of numerical models with several free parameters. In our project, to establish the relationship between the mean and dispersion of elements as a consequence of the characteristic lifetimes of stars that dominate their formation processes, we employed the analytical model developed by Pagel & Tautvaišienė (1995). Unlike other analytical models that consider stellar ejection contributions as instantaneous, this model introduces the concept of delay, which is associated with the time it takes for a star, the producer of a specific element, to release it upon its death. The presence of this delay (Δ) allows for the possibility that the element's yield can be formed either instantly (p_1) or with a delay (p_2). From this model, the average abundance of an element Z, where $Z = Z_1 + Z_2$, is determined by the following equations:

$$u \equiv \int_0^t \omega(t')\, dt' \tag{1}$$

$$\frac{dZ_1}{du} + \frac{F}{\omega g} Z_1 = p_1 \tag{2}$$

$$\frac{dZ_2}{du} + \frac{F}{\omega g} Z_2 = \begin{cases} 0, & \text{if } u < \omega\Delta \\ p_2 \frac{g(u-\omega\Delta)}{g(u)}, & \text{if } u \geq \omega\Delta \end{cases} \tag{3}$$

In the above equations g is the mass of gass, F the mass inflow rate, ω the transition probability for diffuse material ('gas') to change into stars in unit time at time t and u is a dimensionless time-like variable.

3. Data

To identify similarities among elements formed through the same nucleosynthetic processes, we employed four catalogs, each containing abundance data for various stars. These catalogs include Hypatia (Hinkel et al. 2014) with 15 elements and 3,127 stars, GALAH (Buder et al. 2021) with 34 elements and 588,571 stars, APOGEE (Jönsson et al. 2020) with 21 elements and 472,306 stars, and Gaia-ESO (Worley et al. 2024) with 31 elements and 114,916 stars.

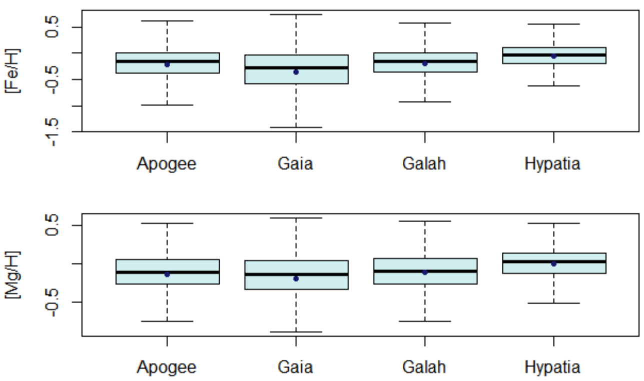

Figure 1. The box plot displays the distributions of Fe and Mg for each catalogue. Each of these catalogues cover a different range of abundances, but their bulk distribution is somewhat similar. This gives us confidence that we are comparing more or less the same Galactic regions.

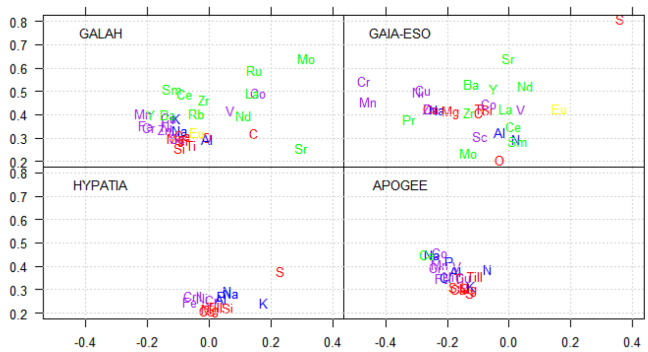

Figure 2. Expected value and dispersion of the abundance distribution of several elements. Elements formed by similar nucleosynthetic processes are generally clustered together. Color codes show elements formed by: helium-burning and alpha elements (red), hydrogen burning and odd-Z (blue), e-process (purple), and s-process (green).

We collected the metallicities of different chemical elements found in stars from the disk region of the Galaxy (as we will see below), with the data from each catalogue, and compared their means and dispersions, noticing how the elements behave similarly to those produced in the same nucleosynthetic processes.

4. Results

4.1. Mean and standard deviation

After analyzing the metallicity data, we made plots using the mean and dispersion to understand how elements from the same nucleosynthetic processes behaved. We also compared the results for each catalogs, observing the presence of a certain pattern of element positionn in the plot.

4.2. Model

The Delayed Production model (Pagel & Tautvaišienė 1995) was used to test how changes in the instantaneous and delayed yields, respectively, p_1 and p_2, as well as on the delay Δ can produce the observed differences in the expected value and dispersion of the abundance distribution of different elements.

Table 1. When $p_1 = 0$, production is instantaneous, resulting in no variation in deviation or mean. However, as p_2 varies and introduces a significant delay, the mean tends to decrease because the production of that element becomes increasingly delayed. The same principle applies when we change the delay: this leads to changes in the standard deviation due to an increase in time of mixing the stellar ejecta into the interstellar medium.

CONSTANTS	VARIABLES 2	MEAN	STANDARD DEVIATION
P2= 0, DELTA = 0	P1 = 0,3	-0.1092	0.185
	P1 = 0.7	-0.1092	0.185
	P1 = 0,9	-0.1092	0.185
P2= 0.1, DELTA = 0.3	P2 = 0.3	-0.7241	0.185
	P2 = 0.5	-0.9016	0.185
	P2 = 0.7	-1.0272	0.185
P1= 0.3 P2 = 0.7	DELTA = 0.4	-0.687	0.226
	DELTA = 0.6	-0.6194	0.347
	DELTA = 0.9	-0.5946	0.493

5. Conclusions

We present preliminary results with the aim of gaining an analytical insight into the chemical evolution of the galaxy and the processes of element formation. Thus, what we have obtained so far shows us that there is a relationship in how the elements are formed and in their distribution in the intergalactic medium. In this way, we can advance our studies, aiming to use more sophisticated and numerical chemical evolution models to obtain more specific results.

References

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