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The [α/Fe] bimodality in the Milky Way disc with chemical evolution models

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Abstract. The analysis of recent high-resolution spectroscopy data has highlighted the existence of a clear distinction between two sequences of stars in the Galactic disc (high- and low-α) in the space of abundance ratios [α/Fe] and [Fe/H]. Chemical evolution models designed to reproduce such a bimodality suggested that APOGEE stars carry the signature of a delayed gas-rich merger, with chemical dilution being the main process determining the shape of low-α stars in the abundance ratios space.

Key words. Galaxy: disc, Galaxy: abundances, Galaxy: evolution

1. Introduction

The purpose of Galactic Archaeology is to reconstruct the formation and evolution of our Galaxy by interpreting the properties observed in the chemical abundances and kinematics of resolved stellar populations. The analysis of recent high-resolution spectroscopy data (APOGEE, Gaia ESO, GALAH, AMBRE) have highlighted the existence of a clear distinction between two sequences of stars of the Galactic disc (high- and low-α) in the space of abundance ratios [α/Fe] and [Fe/H] and would be connected to the thick and thin components of the galactic disc (Recio-Blanco et al. 2014; Hayden et al. 2015; Queiroz et al. 2020). Asteroseismology has played a fundamental role in shading light on the nature of these two populations by providing precise stellar ages for these stars. With the APOKASC catalogue (Silva Aguirre et al. 2018) we can see in action the synergy between asteroseismic observations and high-resolution spectroscopy measurements (combining the atmospheric parameters of APOGEE with data from the Kepler satellite). It was possible to determine the stellar properties for about 1200 red giants in the solar vicinity highlighting that the high- and low-α sequences mentioned (see discussion in Silva Aguirre et al. 2018 for the applied chemical separation criteria) above are also characterized by different age distributions. The age distribution of the "low-α" sequence reaches its maximum at around 2 Gyr, while the "high-α" one at roughly 11 Gyr. This was the first confirmation by asteroseismology of the age gap between these chemically selected populations.

In this paper, we will show results of chemical evolution models designed to reproduce the above mentioned disc sequences. In Section 2, we will focus on the modeling of bimodality observed in the solar vicinity in the APOKASC sample. In Section 3, the disc dichotomy observed in APOGEE DR16 (Ahumada et al. 2020) in [Mg/Fe] and [Fe/H] at different Galactocentric distances will be discussed. Finally, in Section 4 new models for the vertical distribution of [Mg/Fe] will be presented. Some final conclusions will be drawn in Section 5.

2. The delayed infall scenario and [α/Fe] bimodality in the solar neighbourood

In Spitoni et al. (2019), it was presented the first chemical evolution model designed to reproduce the high-α and low-α stars sequences presented in the APOKASC sample. To this aim, the authors updated the classical two-infall model proposed by Chiappini et al. (1997). In this Galactic formation scenario, the disc components were created from two independent primordial gas accretion episodes. The high-α sequence was formed on a shorter time scale than the low alpha sequence in accordance with previous studies.

The novelty of Spitoni et al. (2019) model compared to the original formulation presented by (Chiappini et al. 1997), lies in the fact that in order to explain both the abundance ratios and the age distributions of the two sequences, as suggested by the APOKASC catalogue, a significant delay of about 4.3 Gyr between the two episodes of growth of gas should have occurred, whereas previously a value of 1 Gyr was found.

In Fig. 1, we compare the model predictions of Spitoni et al. (2019) with the APOKASC high- and low- α sequence stars as presented by (Silva Aguirre et al. 2018) in the [α/Fe] versus [Fe/H] space. Here, it is assumed that α abundances are given by the sum of the individual Mg and Si abundances. The delayed accretion of gas with primordial chemical composition has the effect of decreasing the metallicity of each simple stellar population (SSP) born immediately after the beginning of the second infall and has a negligible effect on the [α/Fe] ratio since both α and Fe are diluted in the same measure. When star formation resumes, Type II SNe inject into the ISM α elements on short time-scales, thus producing a steep rise of the [α/Fe] ratio, which is subsequently reduced when higher metallicities are reached due to pollution from type Ia SNe. This sequence produces a characteristic loop in the [α/Fe] plane versus [Fe/H] of the chemical evolution track, which nicely overlaps the region spanned by the observed low-α population of the APOKASC data.

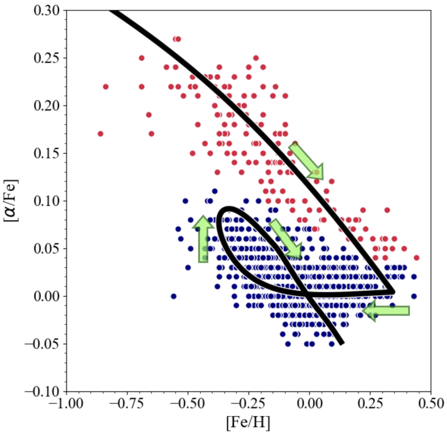

Fig. 1. [α/Fe] vs. [Fe/H] for the APOKASC stars by Silva Aguirre et al. (2018), compared with our chemical evolution model (black solid line) in the solar neighbourhood proposed by Spitoni et al. (2019). The green arrows indicate how the predicted chemical evolution evolves in time in the [α/Fe] versus [Fe/H] space. The red and blue filled circles are the observed high- and low-α stars, respectively.

In the above-mentioned study, the authors presented the comparison between the results of the model with the inclusion of errors in the ages and in the chemical abundances (model defined as synthetic) with the observational data for different stellar ages, as shown in Fig. 2. From Fig. 6 of Spitoni et al. (2019), we note that the errors in the stellar age determination are strongly dependent on the Galactic age: between σ_{Age}=0.13 Gyr (at the Galactic age of 0.25 Gyr) and σ_{Age}=4.93 Gyr (at a Galactic age of 14 Gyr). On the other hand, the considered error on the abundance ratio [M/H] is $\sigma_{[M/H]} \sim$ 0.118 dex.

Spitoni et al. (2019) highlighted that the APOKASC stars of the low-alpha sequence older than 11 Gyr lie on a horizontal sequence corresponding to an approximately constant [α/Fe] ratio (see upper panel in Fig. 2), thus showing the effects of the dilution in the [α/Fe] vs. [Fe/H] relationship created by the delayed primordial gas accretion.

Large surveys and observational campaigns in the contemporary era provide a huge amount of information. Hence, it is critical to properly exploit the data to constrain the parameters of Galactic chemical evolution models and compute the associated uncertainties. To this purpose, in Spitoni et al. (2020), a Bayesian analysis with MCMC methods has been introduced to constrain the two-infall model introduced above for the solar annulus using the measured chemical abundance ratios and the seismically inferred age of the stars in the APOKASC sample. In Spitoni et al. (2020) it was confirmed the presence of the significant delay between the two gas infalls proposed by Spitoni et al. (2019) concluding that dilution is the main process that determines the shape of the sequence of low-α stars in the abundance ratio space. The importance of a delayed gas infall has been also confirmed by Spitoni et al. (2022a) analysing Gaia DR3 data (Gaia Collaboration et al. 2022; Recio-Blanco et al. 2022).

This delay could be the consequence of the late, gas-rich merger episode that gave rise to the low-α sequence. This scenario has been suggested by early chemical evolution works in a cosmological context (Calura & Menci 2009) and more recently confirmed by cosmological simulations (Buck et al. 2021; Agertz et al. 2021). In Vincenzo et al. (2019), it was also mentioned the possibility of a merging event between our Galaxy and a massive system such as Enceladus that could have heated-up the gas in the halo and thus inhibited the growth of matter onto the disc of the Galaxy at high redshifts. This scenario is able to explain the long period of quiescence in the star formation activity predicted by the aforementioned chemical evolution models of the Milky Way.

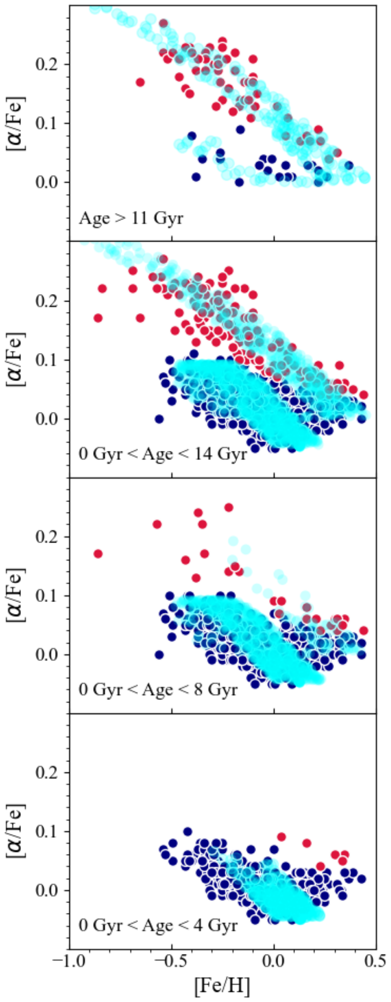

Fig. 2. The [α/Fe] abundance ratios as a function of [Fe/H] predicted by the "synthetic" - considering observational errors on age and metallicity - two-infall chemical evolution model of Spitoni et al. (2019) (cyan circles) computed for different age ranges. APOKASC data (Silva Aguirre et al. 2018) are reported with same color coded filled circles as in Fig. 1.

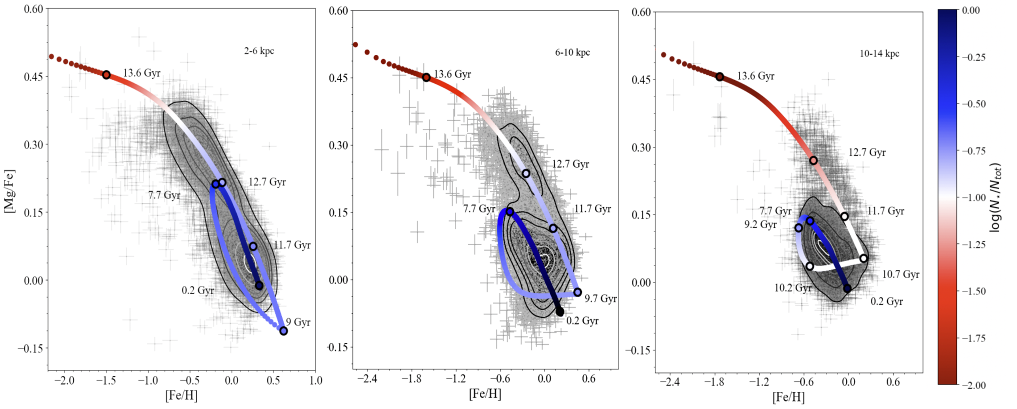

Fig. 3. Multi-zone chemical evolution model for the Galactic disc. Observed [Mg/Fe] vs. [Fe/H] abundance ratios from APOGEE DR16 (grey points with associated errors) in the Galactocentric regions between 2 and 6 kpc (left panel), 6 and 10 kpc (middle panel), and 10 and 14 kpc (right panel) compared with the best-fit chemical evolution models of Spitoni et al. (2021) in the different regions. The color coding represents the cumulative number of stars formed in the Spitoni et al. (2021) model during the Galactic evolution. The open circles label the predicted abundance ratios of SSPs with different ages.

3. Disc bimodality at different Galactocentric distances

Spitoni et al. (2021) extended the aforementioned results to the entire Galactic disc presenting a new multi-zone chemical evolution model using a Bayesian analysis. Indeed, the two sequences in the APOGEE DR16 (Ahumada et al. 2020) data, evident in the relationship [α/Fe] vs. [Fe/H], have different characteristics throughout the galactic disc. Spitoni et al. (2021) found that the internal Galactic regions have been assembled on shorter time scales than the external ones (a result in agreement with the "inside-out" disc formation scenario already known in previous models of chemical evolution, (see Matteucci 2012). In the outermost disc (with Galactocentric distances R > 6 kpc), the chemical dilution due to a late accretion event of a gas with a primordial chemical composition is the main factor influencing the relationship [Mg/Fe] with respect to [Fe/H] in the low-α sequence. In the internal disc, in the framework of the two-infall model, it is instead necessary that the accreted gas in the low-α sequence be chemically enriched as suggested by chemodynamical models (Agertz et al. 2021; Khoperskov et al. 2021) and the pure chemical evolution model of Palla et al. (2020). In particular, Palla et al. (2020) suggested that an enriched accretion event could be originated by the gas lost from the formation of the thick disc, Galactic halo or the Galactic bar which then gets mixed with a larger amount of infalling primordial gas.

In Fig. 3, we report Spitoni et al. (2021) model predictions for three concentric annular regions, 4 kpc wide compared with APOGEE DR16 data. Cescutti et al. (2022) showed the predictions of the two-infall model of Spitoni et al. (2021) for different α elements (O, Si, Ca, ti, Mg) but also for some elements of the iron peak (Sc, Co, Mn, Zn) in the solar neighborhood.

4. The vertical [Mg/Fe] distribution

Vincenzo et al. (2021) highlighted the presence of a clear bimodality in the vertical [α/Fe] distribution of APOGEE data. In the models presented in Sections 2 and 3, the high-α low-α disc bimodality was analysed making pre-

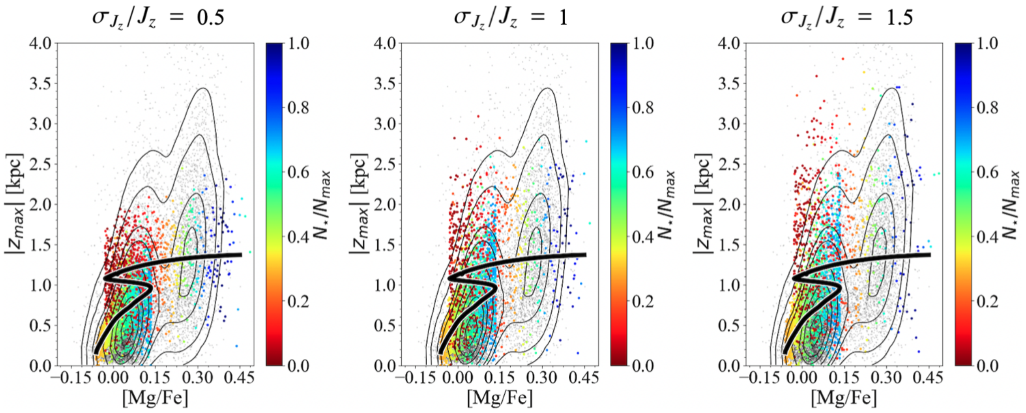

Fig. 4. Vertical distribution of [Mg/Fe] predicted by the chemical evolution model of Spitoni et al. (2022b). The grey points indicate APOGEE DR16 stars within the Galactocentric region between 6 and 10 kpc as reported in the astroNN catalogue. The black lines represent model predictions using the Ting & Rix (2019) relation. Color-coded points refer to the total number of stars predicted by the Spitoni et al. (2022b) model in that region where a Gaussian error in the vertical action J_z estimates in the Ting & Rix (2019) was considered. In the first two panels the model results of Spitoni et al. (2022b) with standard deviation $\sigma_{Jz} = 0.5 \cdot J_Z$ and $\sigma_{J_z} = 1 \cdot J_Z$ are presented. In the right one we show the case with $\sigma_{J_z} = 1.5 \cdot J_Z$ not included in the Spitoni et al. (2022b) study.

dictions just on projected quantities on the Galactic plane. In Spitoni et al. (2022b), this has been solved presenting the vertical distribution of chemical elements assuming simplified dynamical prescriptions in the chemical evolution models.

Ting & Rix (2019), studying the history of the vertical heating of the galactic disc for red-clump stars in APOGEE, proposed an analytical expression of J_Z vs. stellar ages. This relation computed in the solar vicinity can be written as:

$$J_z = 0.91 + 1.81 \cdot \left(\frac{\tau}{1\mathrm{Gyr}}\right)^{1.09} \quad [\mathrm{kpc\ km\ s^{-1}}]. \quad (1)$$

In Spitoni et al. (2022b), stellar orbits were integrated for different simple stellar populations (SSPs) born at different evolutionary times considering as an integral of motion the vertical action J_Z described by eq. (1) using the gravitational potential from Bovy (2015).

Hence, for each SSP along with the chemical composition predicted by Spitoni et al. (2021), the computed $|z_{max}|$ value has been provided. Spitoni et al. (2022b) presented results also assuming the dispersion in the J_z determination of $\sigma_{J_z}/J_z = 1$, and the case with $\sigma_{J_z}/J_z = 0.5$ (Gandhi & Ness 2019 suggested the value of $\sigma_{J_z}/J_z = 1.13$).

They compared model predictions with Mg and Fe abundances provided by APOGEE (Ahumada et al. 2020) in the solar vicinity and the maximum disc height $|z_{max}|$ reported in the value-added catalogue astroNN[1] catalogue.

In Fig. 4, we show Spitoni et al. (2022b) predictions in the [Mg/Fe] vs. $|z_{max}|$ plane. With the black lines we show model results with no dispersion in J_z. The clear transition between high-α and low-α sequence stars is quite evident. Moreover, it is possible to appreciate that the distributions of the predicted SSPs in the $|z_{max}|$ vs. [Mg/Fe] space including the observed dispersion of $\sigma_{J_z}/J_z = 1$ show the best agreement with APOGEE DR16 data. In Fig. 4, we also consider the $\sigma_{J_z}/J_z = 1.5$ case not included in the Spitoni et al. (2022b)

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[1] https://data.sdss.org/sas/dr16/apogee/vac/apogee-astronn

study, where it is still clear the presence of the disc dichotomy signature.

5. Conclusions

In this article, we presented the results of recent chemical evolution models designed to reproduce the disc bimodality in the chemical space. In particular, the main findings can be summarised as follows:

- In Spitoni et al. (2021), it was pointed out that in the outer disc regions with Galactocentric distances $R > 6$ kpc, the chemical dilution originating from a late gas accretion event with pristine composition is the principal cause of the [Mg/Fe] versus [Fe/H] abundance pattern in the low-α phase observed in APOGEE DR16 data. These results are in agreement with findings of the previous models by Spitoni et al. (2019, 2020) for the APOKASC data in the solar neighbourhood.
- In the inner disc ($R < 6$ kpc), an enriched gas infall for the formation of low–α sequence stars is required to reproduce the observed data (Spitoni et al. 2021; Palla et al. 2020).
- The vertical distribution of the [Mg/Fe] abundance ratio predicted by the two-infall model of Spitoni et al. (2022b) shows the presence of the disc dichotomy signature, in good agreement with APOGEE DR16 data.

In conclusions, the signatures i) of a delayed gas infall and ii) the hiatus in the star formation history of the Galaxy are imprinted both in the [Mg/Fe] vs. [Fe/H] relation (see Sections 2 and 3) and in vertical distribution of [Mg/Fe] abundances in the solar vicinity (see Section 4).

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References

Agertz, O., Renaud, F., Feltzing, S., et al. 2021, MNRAS, 503, 5826

Ahumada, R., Prieto, C. A., Almeida, A., et al. 2020, ApJS, 249, 3

Bovy, J. 2015, ApJS, 216, 29

Buck, T., Rybizki, J., Buder, S., et al. 2021, MNRAS, 508, 3365

Calura, F. & Menci, N. 2009, MNRAS, 400, 1347

Cescutti, G., Bonifacio, P., Caffau, E., et al. 2022, arXiv:2211.06086

Chiappini, C., Matteucci, F., Gratton, R., 1997, ApJ, 477, 765

Hayden, M. R., Bovy, J., Holtzman, J. A., et al. 2015, ApJ, 808, 132. doi:10.1088/0004-637X/808/2/132

Gaia Collaboration, Recio-Blanco, A., Kordopatis, G., et al. 2022, arXiv:2206.05534

Gandhi, S. S. & Ness, M. K. 2019, ApJ, 880, 134

Hayden, M. R., Bovy, J., Holtzman, J. A., et al. 2015, ApJ, 808, 132. doi:10.1088/0004-637X/808/2/132

Khoperskov, S., Haywood, M., Snaith, O., et al. 2021, MNRAS, 501, 5176

Matteucci, F. 2012, Chemical Evolution of Galaxies: , Astronomy and Astrophysics Library. ISBN 978-3-642-22490-4. Springer-Verlag Berlin Heidelberg, 2012.

Palla, M., Matteucci, F., Spitoni, E., et al. 2020, MNRAS, 498, 1710.

Queiroz, A. B. A., Anders, F., Chiappini, C., et al. 2020, A&A, 638, A76.

Recio-Blanco, A., de Laverny, P., Kordopatis, G., et al. 2014, A&A, 567, A5.

Recio-Blanco, A., de Laverny, P., Palicio, P. A., et al. 2022, arXiv:2206.05541

Silva Aguirre, V., Bojsen-Hansen, M., Slumstrup, D., et al. 2018, MNRAS, 475, 5487.

Spitoni, E., Silva Aguirre, V., Matteucci, F., et al. 2019, A&A, 623, A60

Spitoni, E., Cescutti, G., Minchev, I., et al. 2019, A&A, 628, A38

Spitoni, E., Verma, K., Silva Aguirre, V., et al. 2020, A&A, 635, A58

Spitoni, E., Verma, K., Silva Aguirre, V., et al. 2021, A&A, 647, A73

Spitoni, E., Aguirre Børsen-Koch, V., Verma, K., et al. 2022, A&A, 663, A174

Spitoni, E., Recio-Blanco, A., de Laverny, P., et al. 2022, arXiv:2206.12436
Ting, Y.-S. & Rix, H.-W. 2019, ApJ, 878, 21
Vincenzo, F., Spitoni, E., Calura, F., Matteucci, F., Silva Aguirre, V., Miglio, A., Cescutti, G., 2019, MNRAS, 487, L47
Vincenzo, F., Weinberg, D. H., Miglio, A., et al. 2021, MNRAS, 508, 5903