Beyond the two-infall model

I. Indications for a recent gas infall with Gaia DR3 chemical abundances

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ABSTRACT

Context. The recent Gaia Data Release 3 (DR3) represents an unparalleled revolution in Galactic archaeology, providing numerous radial velocities and chemical abundances for millions of stars as well as all-sky coverage.

Aims We present a new chemical evolution model for the Galactic disc components (high- and low-α sequence stars) designed to constrain the new abundance ratios provided by the General Stellar Parametriser-spectroscopy module for the Gaia DR3 and constrained by the detailed star formation (SF) histories for both the thick and thin disc stars inferred from previous Gaia releases.

Methods Sophisticated modelling based on previous Gaia releases have found evidence for narrow episodes of enhanced SF in recent time. Additionally, Gaia DR3 indicated the presence of young (massive) low-α disc stars that show evidence of a recent chemical impoverishment in several elements. In order to reproduce these observables, we propose a new chemical evolution model in which the low-α sequence is generated by two distinct infall episodes. Hence, in this study we compare Gaia DR3 chemical abundances with the predictions of a three-infall chemical evolution model for the high- and low-α components.

Results The proposed three-infall chemical evolution model nicely reproduces the main features of the abundance ratio [X/Fe] versus [M/H] (X= Mg, Si, Ca, Ti, α) of Gaia DR3 stars in different age bins for the considered α elements. Moreover, the most recent gas infall – which started ∼2.7 Gyr ago – allowed us to predict accurately predict the Gaia DR3 young population which has experienced a recent chemical impoverishment.

Conclusions. We extended previous chemical evolution models designed to reproduce APOGEE and APOKASC data in order to predict new Gaia DR3 chemical abundances. To this aim, we proposed a three-infall chemical evolution model to better trace both (i) the young population in Gaia DR3 with evidence of chemical impoverishment and (ii) the SF history from previous Gaia releases.

Key words. Galaxy: disk – Galaxy: abundances – Galaxy: evolution – Galaxy: kinematics and dynamics – solar neighborhood – evolution

1. Introduction

Unravelling the origin and evolution of our Galaxy’s disc ultimately relies on the study and interpretation of signatures imprinted in resolved stellar populations, such as their chemical and kinematic properties (Freeman & Bland-Hawthorn 2002). Intermediate releases of Gaia data (Gaia Collaboration 2016, 2018) have already dramatically improved the comprehension of the structure and evolution of our Milky Way, mainly through unprecedentedly astrometric and line-of-sight velocity measurements (Gaia Collaboration 2021a; Laporte et al. 2019a).

However, Galactic archaeology relies also on the interpretations of chemical signatures present in the stellar atmospheres (Matteucci 2021, 2012; Freeman & Bland-Hawthorn 2002; Feltzing 2016). In fact, once a star is born, the chemical enrichment history of the interstellar medium (ISM) from which it was formed is imprinted in its atmosphere. For this reason, in the stellar atmospheres, we can find insights into the processes that determined the formation and regulated the evolution of various components of our Galaxy. Hence, previous studies focused on Galactic archaeology have had to complement the intermediate Gaia data releases with chemical data from ground-based observations. However, ground-based surveys like the GALactic Archaeology with HERMES survey (GALAH; Buder et al. 2021), the Apache Point Observatory Galactic Evolution Experiment project (APOGEE; Majewski et al. 2017; Ahumada et al. 2020; Abdurro’uf et al. 2022), Gaia-ESO Survey (Randich et al. 2022), The Radial Velocity Experiment (RAVE; Steinmetz et al. 2020), and Large Sky Area Multi-Object Fibre Spectroscopic Telescope (LAMOST; Yu et al. 2021) continue to have all the issues associated with biased samples, hampering observations from Earth. In this context, Gaia Data Release 3 (DR3; Gaia Collaboration 2023a) and Recio-Blanco et al. (2023) have brought a truly and unprecedented revolution, opening

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a new era of all-sky spectroscopy. With about 5.6 million stars, the Gaia DR3 General Stellar Parameteriser-spectroscopy (GSP-Spec; Recio-Blanco et al. 2023) all-sky catalogue is the largest compilation of stellar chemo-physical parameters and the first from space data.

The analysis of spectroscopic data from ground-based surveys such as the APOGEE (e.g. Hayden et al. 2015; Queiroz et al. 2020), the Gaia-ESO (e.g. Recio-Blanco et al. 2014; Kordopatis et al. 2015a; Rojas-Arriagada et al. 2016, 2017), the AMBRE project (Mikolaitis et al. 2017; de Laverny et al. 2013), and GALAH (Buder et al. 2019, 2021) suggest the existence of a clear separation between two sequences of disc stars in the [α/Fe] versus [Fe/H] abundance ratio space: the so-called high-α and low-α sequences. Several theoretical models of the evolution of Galactic discs have suggested that the bimodality may be strictly connected to a delayed accretion of gas of primordial chemical composition (or with a metal-poor chemical composition). By revising the classical two-infall chemical evolution model by Chiappini et al. (1997) and Grisoni et al. (2017), Spitoni et al. (2019a, 2020, 2022) showed that a significant delay of ∼4 Gyr between two consecutive episodes of gas accretion is needed to explain the dichotomy between the APOKASC (APOGEE+ Kepler Asteroseismology Science Consortium; Pinsonneault et al. 2014) sample for the solar neighbourhood (Silva Aguirre et al. 2018) and APOGEE DR16 stars. In particular, the authors predict that the star formation rate (SFR) has a minimum at the age of ∼8 Gyr. A similar quenching of star formation (SF) at an age of 8 Gyr was derived by Snäith et al. (2015) using the chemical abundances of Adibekyan et al. (2012) and the isochrone ages of Haywood et al. (2013) for solar-type stars. Katz et al. (2021) concluded that in APOGEE data, there is a clear signature of a dilution of interstellar medium from 6 kpc to the outskirts of the disc, which occurs before the onset of the thin disc formation.

By analysing ESO/HARPS spectra of local solar twin stars, Nissen et al. (2020) found that the age-metallicity distribution has two distinct populations with a clear age dissection. The authors suggest that these two sequences may be interpreted as evidence of two episodes of accretion of gas onto the Galactic disc with quenching of SF between them, which is in agreement with the scenario proposed by Spitoni et al. (2019a) and Spitoni et al. (2020, hereafter ES20). Finally, Romano et al. (2020), comparing chemical evolution models with the recent [C/Fe] and [C/O] abundance ratios from high resolution spectra by Amarsi et al. (2019) for dwarf stars, concluded that the delayed gas infall scenario proposed by Spitoni et al. (2019a) fits reasonably well with those [C/Fe] and [C/O] ratios as well.

The new AMBRE:HARPS data were reproduced by Palla et al. (2022) with chemical evolution models characterised by peculiar histories of SF, such as the two-infall model with a significant delay. Xiang & Rix (2022), analysing subgiant stars in LAMOST, confirmed that the stellar age-metallicity distribution splits into two almost disjointed parts, separated at age ∼8 Gyr. The authors in Sahhlholdt et al. (2022) also highlighted the age-metallicity relation characterised by several disconnected sequences, which could be associated to different SF regimes throughout the Milky Way disc evolution. In Spitoni et al. (2022), it was finally shown that the signature of a delayed gas infall episode, which gives rise to a hiatus in the SF history of the Galaxy, is imprinted both in the [Mg/Fe] versus [Fe/H] relation and in the vertical distribution of [Mg/Fe] abundances in the solar vicinity.

Analysing [Ca/Fe] versus [M/H] abundance ratios of Gaia DR3 disc stars, Gaia Collaboration (2023b) found that most of the 7300 massive stars of the sample (young objects selected with the criteria indicated in their Sect. 3.2.2) are Ca poor, with [Ca/Fe] values down to ∼−0.3 dex with [M/H] ∈ [−0.5,+0.0] dex. Hence, young disc stars show, surprisingly, a recent chemical impoverishment in several elements. It is worth mentioning that also in the [Ce/Fe] versus [M/H] ratio, a metal-impoverished population in the low-α sequence exists. The interesting fact is that these stars are exactly the same massive objects mentioned above in the [Ca/Fe] versus [M/H] sample. Only a large number statistics chemical survey, such as the Gaia DR3 GSP-Spec, could clearly provide constraints to this younger population. Many young stars are relatively hot main-sequence objects for which a detailed chemical abundance analysis is not possible (due to a lack of metallic lines in the spectra). However, cool young stars are rare (about 30,000 stars out of 5.5 million in the GSP-Spec catalogue, as shown in Gaia Collaboration 2023b). Even if in this paper we concentrate on the solar neighbourhood, Gaia Collaboration (2023b) shows that the impoverishment of the massive population is apparent at all Galactic radii.

Stellar migration cannot be invoked to explain such a young metal-impoverished stellar population because, due to the decreasing stellar density profile with the galactocentric distance, the inwards stellar migration that decreases the local metallicities should not dominate. However, a more likely physical process responsible for this recent chemical impoverishment could be the dilution caused by a recent gas infall event.

In this article, we present a new chemical evolution model designed to reproduce the abundance ratios for α-elements in Gaia DR3 and, in particular, for the young population that seems to show recent chemical impoverishment in several elements. In addition, our model is constrained by the several brief episodes of enhanced SF that recently occurred (in the last 2 Gyr of disc evolution), as inferred from Gaia DR2-observed colour–magnitude diagrams by Ruiz-Lara et al. (2020). The authors proposed that the timing of these enhanced SF episodes is consistent with the Sagittarius dwarf spheroidal galaxy pericentre passages that triggered the SF in the Galactic disc (e.g., Laporte et al. 2019b; Antoja et al. 2020).

The paper is organised as follows. In Sect. 2, the Gaia DR3 sample in the solar vicinity is presented. In Sect. 3, we describe the main characteristics of the chemical evolution model adopted in this work. In Sect. 4, we present our results, and finally in Sect. 5, we draw our conclusions.

2. The Gaia DR3 sample in the solar vicinity

In this section, we provide all the information on the samples of Gaia DR3 stars adopted in the study. In Sect. 2.1, we present the selection criteria for different chemical elements, and in Sect. 2.2 we briefly explain how the stellar ages proposed by Kordopatis et al. (2023) have been computed.

2.1. Selection of solar vicinity stars and GSP-Spec quality flags

As mentioned in the introduction, Recio-Blanco et al. (2023) has presented the largest homogeneous spectral analysis performed so far. In this work, we are mainly interested in the study of α chemical elements in the solar vicinity. Taking advantage of the large number of stars in Gaia DR3, we were able to limit our analysis to a narrow region centred at the solar vicinity, that is, we consider stars with guiding radii $R_s \in [8.1, 8.4]$ kpc (the motivation for this selection is presented in the next
paragraph). As in Recio-Blanco et al. (2023), we adopted the Sun’s galactocentric position \((R, Z) = (8.249, 0.0208) \) kpc (Gravity Collaboration 2021; Bennett & Bovy 2019), and guiding radii were computed using the rescaled version of the McMillan (2017) axisymmetric Galactic potential considering as inputs the geometric distances by Bailier-Jones et al. (2021) based on high-precision astrometric parameters from Gaia EDR3 (Gaia Collaboration 2021b) and the additional information provided by Gaia DR3 for the radial velocities (Katz et al. 2023; Gaia Collaboration 2023a).

Selecting Gaia DR3 stars based on their guiding radii was motivated by an effort to minimise the ‘blurring’, that is, the orbit scatering due to interactions with disc inhomogeneities and non-axisymmetries (see Lynden-Bell & Kalnajs 1972; Schönrich & Binney 2009) that increase a star’s epicyclic amplitude, potentially without changing its angular momentum. Nevertheless, we are aware that processes like ‘churning’ (Sellwood & Binney 2002; Schönrich & Binney 2009) could still affect our stellar samples selected by their guiding radii. In the presence of churning, the angular momentum of the stars changes, moving them from an almost circular orbit to another almost circular one, thus erasing all memory of the birthplace of the star that could be deciphered based on its kinematics. For instance, in Kordopatis et al. (2015b) it was shown that a significant number of super-solar metallicity stars have clear signatures of migrants into the solar neighbourhood. Those stars have circular orbits and kinematic ages that indicate they are at least a few gigayears old.

It is worth mentioning that the stellar sample selection based on a small range of guiding radii values centred at the solar position also helps to remove the effects of abundance gradients along the Galactic disc (Kordopatis et al. 2020). Furthermore, we selected only giant stars with surface gravities \( g < 3.5, \) \( \text{g in cm s}^{-2}. \) The Kiel diagrams of the medium quality sample selected in different Galactic regions across the Milky Way reported in Fig. 6 of Gaia Collaboration (2023b) clearly show that red giant stars are observed in all the considered vertical height bins above the plane, hence minimising distance-dependent changes in the population being analysed.

The first 13 parameter flags of Table 2 of Recio-Blanco et al. (2023) are shared by all the stars and have been set to be equal to zero, thus imposing the best quality stellar atmospheric parameters. We refer the reader to Recio-Blanco et al. (2023) for all details on the physical meaning of the flags. Concerning the single element quality flags for Si, Ca, and Ti, we imposed only the value zero (best data) both for the flags ‘UpLim’ and ‘Uncer’. Solely for the Mg did we also allow medium quality (zero and one values) for ‘UpLim’ (but still zero for ‘Uncer’) because of the smaller number of stars available for this element (see Recio-Blanco et al. 2023).

The polynomial coefficients as reported in Table 4 of Recio-Blanco et al. (2023) for the \( g \) versus \([X/Fe]\) calibration (see their Eq. (3)) were applied considering the suggested validity domain in gravity. Similarly, the \( g \) versus \([M/H]\) calibration of Eq. (2) in Recio-Blanco et al. (2023, and relative coefficients reported in their Table 3) was also considered.

### 2.2. Stellar ages

Kordopatis et al. (2023) presented four different sets of ages and masses obtained through an isochrone fitting method. They used the PAdova and TRieste Stellar Evolution Code (PARSEC) stellar tracks (Bressan et al. 2012) up to the beginning of the AGB phase and the tracks up to the end of the AGB phase from COLIBRI S37 (see references in Kordopatis et al. 2023). In Sect. 2.2 of Kordopatis et al. (2023), the main methodology of the projection is reported in detail. Here, we just recall that the four following combinations of spectroscopic parameters and broad-band photometric measurements \((J,H,K_s)\) from 2MASS and \(G\) from GDR3) were considered: spec (projects only Teff, \( \log g \) and \([M/H]\)), speck (projects T eff, \( \log g \), \([M/H]\) and \(K_s\)), spech (projects T eff, \( \log g \), \([M/H]\), \(J\), \(H\) and \(K_s\)) and spechkg (projects T eff, \( \log g \), \([M/H]\), \(J\), \(H\), \(K_s\) and \(G\)).

In the study by Kordopatis et al. (2023), they also provided the optimal combination of projection flavour as a function of the line-of-sight extinction in order to get the most reliable ages and masses. In this work, we compare our chemical evolution model predictions with only Gaia DR3 stars with associated ages characterised by relative errors smaller than 0.5, as suggested by Kordopatis et al. (2023).

For our study, it is important to be able to identify young stars as robustly as possible. When Kordopatis et al. (2023) compared the estimated ages of individual stars in open cluster members with the more robust ages from Cantat-Gaudin et al. (2020) which were derived by fitting the entire color-magnitude diagram of the cluster, they found an over-estimation of 0.6 Gyr (inner dispersion of 1 Gyr) for cluster stars younger than 2 Gyr. This approach is a good starting point for our analysis, keeping in mind that some contamination might exist. We are confident that this difference does not affect our conclusions since (i) we include a dispersion in the age estimates of our model results (see Sect. 3.3) and (ii) we compare the model predictions for young sample stellar populations (SSPs) with the massive stars from Gaia DR3.

### 3. The three-infall chemical evolution model for the solar vicinity

In this section, we present the main assumptions and characteristics of the chemical evolution model considered in this work for the Galactic region centred at the solar position. In Sect. 3.1, we briefly provide some details about the revised two-infall model proposed by Spitoni et al. (2019a, 2020, 2021) for the solar neighbourhood. In Sect. 3.2, we postulate that an additional third accretion gas infall episode mimics the recent enhanced SF episodes found analysing Gaia data in the solar vicinity. In Sect. 3.3, we provide all the details of the three-infall chemical evolution model presented in this work.

#### 3.1. The revised two-infall model

Spitoni et al. (2019a) and ES20 presented chemical evolution models designed to fit the observed chemical abundance ratios and asteroseismic ages of the APOKASC stars (Silva Aguirre et al. 2018). The sample contained about 1200 red giants from an annular region of 2 kpc wide centred on the Sun. The stellar properties for this sample were determined by fitting the photometric, spectroscopic, and asteroseismic observables (Silva Aguirre et al. 2017; Aguirre Børsen-Koch et al. 2022). In agreement with the classical two-infall model by Chiappini et al. (1997), the first gas infall was characterised by a short accretion timescale \((t_1 \ll t_2)\); however, the presence of a significant delay \(t_{\text{max}}\) between the two-infall accretion episodes \((\sim 4 \text{ Gyr})\) was highlighted. ES20 later confirmed this delay by using a Bayesian framework based on Markov Chain Monte Carlo methods.

Observational evidence supporting this scenario has been presented by Nissen et al. (2020) through the analysis of the
ESO/HARPS spectra of local solar twin stars. They found that the age-metallicity distribution shows the presence of two diverse populations characterised by a clear age separation. The authors suggested that these two sequences may be interpreted as evidence of two episodes of accretion of gas onto the Galactic disc with quenching of SF between them. More recently, Spitoni et al. (2021) hereafter ES21 presented a multi-zone two-infall chemical evolution model with quantitatively inferred free parameters by fitting the APOGEE DR16 (Ahumada et al. 2020) abundance ratios at different galactocentric distances. In particular, the model computed at 8 kpc constrained by the [Mg/Fe] and [Fe/H] ratios of about 9200 stars located in the annular region enclosed between 6 and 10 kpc and with vertical height |z| < 1 kpc confirmed the previous findings of a significant delay between the two gas infall episodes.

3.2. Beyond the two-infall model: Including a recent episode of SF

As shown hereafter, the classical two-infall model fails to reproduce part of the new Gaia data. The three-infall model for the Galactic chemical evolution was originally introduced by Miceli et al. (2013) in order to study the halo, thick, and thin disc components separately. In this analysis, we adopt a similar formalism but take into account a recent episode with enhanced SF.

In their recent work, Ruiz-Lara et al. (2020) presented the detailed SF history for both the thick and thin disc stars of the 2 kpc bubble around the Sun inferred from Gaia DR2 colour–magnitude diagrams. Several narrow episodes of enhanced SF activity were revealed, with the last two occurring approximately 1.9 and 1.0 Gyr ago, respectively. The authors proposed that the timing of these peaks of star formation coincide with the Sagittarius dwarf spheroidal galaxy pericentre passages that triggered the formation of new stars in the Galactic disc.

In Fig. 1, we show the star formation history proposed by Ruiz-Lara et al. (2020) for both thick and thin disc sequences along with results from Bernard (2017). In fact, we note that Bernard (2017) also highlighted the presence of recent events with enhanced SF activity when analysing the first Gaia data release. This recent event of enhanced SF activity can be easily mimicked in the chemical evolution models by including a recent gas infall episode. In Sect. 4.5, we discuss how this assumption is also consistent with the abundance ratios observed in Gaia DR3 for massive stars and young objects.

3.3. The three-infall model details

In this paper, we extend the two-infall chemical evolution models presented in Sect. 3.1 while taking into account the recent constraints imposed by the star formation history (SFH) and GDR3 chemical abundances. Using the models of Sect. 3.1 as a reference, we split the low-α sequence into two distinct gas infall episodes in order to mimic the recent enhanced SF activity of Ruiz-Lara et al. (2020) and Bernard (2017). Here, in the framework of the three-infall model, the functional form of the gas infall rate is

\[
I_i(t) = \frac{\sigma_1}{\tau_1} e^{-\left(t - t_{max1}\right)/\tau_1} + \frac{\sigma_2}{\tau_2} e^{-\left(t - t_{max2}\right)/\tau_2},
\]

where \(\tau_1, \tau_2,\) and \(\tau_3\) are the timescales of the three distinct gas infall episodes. The Heaviside step function is represented by \(H(t)\). The quantity \(t_{max1}\) is the time of the maximum infall rate on the second accretion episode, that is, it indicates the delay between the two peaks of the thick disc and the second infall (low-α part I) rates. Similarly, the quantity \(t_{max2}\) is the Galactic time associated to the maximum infall rate of the third accretion episode.

Finally, the coefficients \(A, B,\) and \(C\) were obtained by imposing a fit to the observed current total surface mass density with the following relations

\[
A = \frac{\sigma_1}{\tau_1 \left(1 - e^{-\left(t - t_{max1}\right)/\tau_1}\right)},
\]

\[
B = \frac{\sigma_2}{\tau_2 \left(1 - e^{-\left(t - t_{max2}\right)/\tau_2}\right)},
\]

\[
C = \frac{\sigma_3}{\tau_3 \left(1 - e^{-\left(t - t_{max2}\right)/\tau_3}\right)}.
\]

where \(\sigma_1\) is the present-day total surface mass density of the high-α sequence. The \(\sigma_2\) and \(\sigma_3\) quantities stand for the present-day total surface mass density of the two components of the low-α sequence. Finally, \(t_G\) is the age of the Galaxy. For the total present-day surface density (\(\sigma_1 + \sigma_2 + \sigma_3\)) in the solar neighbourhood, we assumed the value of 47.1 \(\pm 3.4\) \(M_\odot\) pc\(^{-2}\), as provided by McKee et al. (2015) and used previously by ES20 and ES21. The SFR is expressed as the Kennicutt (1998) law,

\[
\psi(t) \propto \nu_{1,2,3} \cdot \sigma_g(t)^k,
\]

where \(\sigma_g\) is the gas surface density and \(k = 1.5\) is the exponent. The quantity \(\nu_{1,2,3}\) is the star formation efficiency (SFE).
associated to different Galactic evolutionary phases. Motivated by the theory of star formation induced by spiral density waves in Galactic discs (Wyse & Silk 1989), we considered a variable SFE as being a function of the Galactic phase already considered in the two-infall model (Chiappini et al. 2001; Grisoni et al. 2017, 2019, 2020; Spitoni et al. 2020). We adopted the Scalo (1986) initial stellar mass function (IMF), constant in time and space. Finally, we adopted the photovspheric values of Grevesse et al. (2007) as our solar reference abundances to be consistent with the Gaia DR3 spectroscopic abundances.

Unlike other studies (e.g. Nidever et al. 2014 for APOGEE data), we ignored the effect of Galactic winds on chemical evolution. In fact, while studying the Galactic fountain originated by the explosions of Type II supernovae (SNe) in OB associations in the solar annulus, Melioli et al. (2008, 2009) and Spitoni et al. (2008, 2009) found that the ejected metals fall back to approximately the same galactocentric region where they were ejected and consequently do not significantly modify the chemical evolution in this area. Furthermore, the typical delay, as computed by Spitoni et al. (2009) of 0.1 Gyr (due to the orbit time of the clouds subject on the Galactic potential) also produces a negligible effect on the chemical evolution of the Galaxy in the solar neighbourhood.

In Sect. 4, we show the model results considering, a posteriori, the dispersion in the abundance ratios and ages for the predicted SSPs (see also Spitoni et al. 2019a). At each Galactic time, we added a random error to the ages and ratios ([M/H], [X/M]) of the SSPs formed at Galactic evolutionary time $t$ as follows:

$$\text{Age}_{\text{new}}(t) = \text{Age}(t) + \delta t(\text{Age}); \quad \delta G(\text{Age}) \sim N(0, \sigma_{\text{Age}}),$$

where $\delta t$ is a perturbation that follows a normal distribution $N(0, \sigma_{\text{Age}})$ with the standard deviation fixed at the value of $\sigma_{\text{Age}} = 30\%$Age and where Age $(t) = (13.7-t)$ Gyr. Similarly, for [M/H] and [X/M] we have, respectively:

$$\delta G([M/H]) \sim N(0, \sigma_{\text{M/H}}),$$

$$\delta G([X/M]) \sim N(0, \sigma_{\text{X/M}}).$$

In Eqs. (7) and (8), we imposed that $\sigma_{\text{M/H}} = \sigma_{\text{X/Fe}} \equiv 0.05$ dex. In the remainder of this paper, we refer to this chemical evolution model as our ‘synthetic model’.

Although stellar migration has undeniably played an important role in Galactic evolution, such as in radial metallicity profiles (e.g. Kordopatis et al. 2015a), and affected the [$\alpha$/Fe] relation of thin disc stars (Vincenzo & Kobayashi 2020), we decided to ignore stellar migration effects in the solar vicinity. Indeed, by means of a self-consistent chemodynamical model for the Galactic disc evolution, Khoperskov et al. (2021) concluded that radial migration has a negligible effect on the [α/Fe] versus [Fe/H] distribution over time, suggesting that the $\alpha$-dichotomy is strictly linked to different star formation regimes over the Galaxy’s lifetime. The only effect of stellar migration from the inner and outer disc Galactic regions would be to smear and smooth the disc bimodality.

Despite the presence of important signatures of stellar migration, Vincenzo & Kobayashi (2020) stressed that two distinct enriched gas accretion episodes with primordial, or poorly enriched, chemical composition occurred at 0–2 and 5–7 Gyr ago, defining the shape of the low-$\alpha$ sequence in the [$\alpha$/Fe] versus [Fe/H] plot. It is worth noting that in their Fig. 13, the abundances in stars younger than 8 Gyr in the solar neighbourhood perfectly trace the gas phase abundances in the same region.

Hence, we investigate a scenario complementary to that proposed by Sharma et al. (2021) and Chen et al. (2022) and in which the dichotomy visible in [$\alpha$/Fe] versus [Fe/H] abundance in the solar neighbourhood is entirely explainable by the stellar migration. The observed chemical impoverishment does not naturally appear in the sense of radial migration, which would favour a majority of stars coming from the chemically enriched inner galactic regions.

3.4. Nucleosynthesis prescriptions

In this paper, we assumed the same stellar nucleosynthesis prescriptions as in ES20 and ES21, that is the ones of François et al. (2004). However, in the last part of the results (Sect. 4.6), we also test the effects of the nucleosynthesis prescriptions suggested by Romano et al. (2010).

3.4.1. François et al. yields collection

As for the models of ES20 and ES21, we adopted the same nucleosynthesis prescriptions proposed by François et al. (2004) for Fe, Mg, Si, Ca, and Ti. The authors artificially increased the Mg yields for massive stars from Woosley & Weaver (1995) to reproduce the solar Mg abundance. The Mg yields from stars in the range 11–20 $M_{\odot}$ were increased by a factor of seven, whereas yields for stars with mass >20 $M_{\odot}$ were on average a factor of ~two larger. No modifications were required for the yields of Fe and Ca computed for solar chemical composition. Concerning Si, only the yields of very massive stars ($M > 40 M_{\odot}$) were increased by a factor of two. For the modification of Ti yields, we refer the reader to Fig. 7 of François et al. (2004) where the ratios between the revised yields to the data of Woosley & Weaver (1995) for massive stars are indicated. It is possible to note that Ti yields have been substantially increased. Concerning Type Ia SNe, in order to preserve the observed [Mg/Fe] and [Ti/Fe] versus [Fe/H] pattern, the yields of Iwamoto et al. (1999) for Mg and Ti were increased by a factor of five and two, respectively. The choice of such ad hoc nucleosynthesis prescriptions is supported by the fact that stellar yields are still a relatively uncertain component of chemical evolution models (e.g. François et al. 2004; Romano et al. 2010; Côté et al. 2017; Prantzos et al. 2018). This set of yields has been widely used in the literature (Cescutti et al. 2007, 2022; Spitoni et al. 2014, 2015, 2017, 2019b; Mott et al. 2013; Vincenzo et al. 2019; Pallà et al. 2022) and has been shown to be able to reproduce the main features of the solar neighbourhood.

3.4.2. Romano et al. yields collection

We also adopted (see Sect. 4.6) an alternative set of stellar yields coming from full stellar evolution and nucleosynthesis computations, i.e. those suggested by Romano et al. (2010, their model 15) and recently used in several Galactic archaeology studies with chemical evolution models (i.e. Brusadin et al. 2013; Micali et al. 2013; Spitoni et al. 2016, 2018). We decided to include these stellar yields in our analysis because, in contrast to François et al. (2004), Romano et al. (2010) suggested a collection of yields without applying any modifications or tuning.
Table 1. Summary of the main parameters of the best model presented in this study.

|      | $t_1$ [Gyr] | $t_2$ [Gyr] | $t_3$ [Gyr] | $t_{\text{max} 1}$ [Gyr] | $t_{\text{max} 2}$ [Gyr] | $\sigma_{2+3}/\sigma_1$ | $\sigma_2/\sigma_3$ | $\nu_1$ [Gyr$^{-1}$] | $\nu_2$ [Gyr$^{-1}$] | $\nu_3$ [Gyr$^{-1}$] |
|------|-------------|-------------|-------------|--------------------------|--------------------------|--------------------------|--------------------------|------------------|------------------|------------------|
| Model | 0.103       | 4.110       | 0.150       | 4.085                     | 11.000                   | 3.472                    | 2.33                      | 2.0              | 1.3              | 0.5              |
| ES21  | ES21        | ES21        | ES20        | ES21                     | ES20                     |                           |                           |                  |                  |                  |

Notes. The accretion timescales $(t_1, t_2, t_3)$, time-delays $(t_{\text{max} 1}, t_{\text{max} 2})$, the present-day total surface mass density ratios $(\sigma_{2+3}/\sigma_1$ and $\sigma_2/\sigma_3)$ and the SFEs $(\nu_1, \nu_2,$ and $\nu_3)$. We also indicate the values that are identical to the ones adopted in the previous two-infall chemical evolution models of ES20 and ES21.

For low- and intermediate-mass stars (0.8–8 $M_\odot$), the metallicity-dependent stellar yields of Karakas (2010) with thermal pulses were included. For the progenitors of either Type II SNe or HNe (massive stars >11–13 $M_\odot$, depending on the explosion energy), they used the metallicity-dependent He, C, N, and O yields coupled with the Geneva stellar evolution code, which takes into account the combined effect of mass loss and rotation (Meynet & Maeder 2002; Hirschi 2005, 2007; Ekström et al. 2008). For all the elements heavier than O, they used the stellar evolution calculations by Kobayashi et al. (2006).

3.5. Best-fit model parameters

As explained in Sect. 3.2, our main goal is to extend the previous models presented in ES20 and ES21 (for the solar vicinity) regarding the new constraints given by the SF history (from Gaia DR1 and Gaia DR2 data) and the new RVS chemical abundance ratios provided by Gaia DR3. In Table 1, we summarise the main parameters of the best model presented in this study. Because the models ES20 and ES21 were already able to successfully reproduce data from high-resolution surveys, such as APOKASC and APOGEE DR16, we tried to keep most of the model parameters similar to the values proposed in those studies.

For the sake of clarity, in Table 1 we indicate which parameters have not been modified: the infall timescales, $t_1 = 0.103$ Gyr (high-$\alpha$) and $t_2 = 4.110$ Gyr (low-$\alpha$, part I); the delay between the first and the second infall, $t_{\text{max} 1} = 4.085$ Gyr; and the star formation efficiency of the high-$\alpha$ sequence, $\nu_1 = 2$ Gyr$^{-1}$. These parameters are all taken from ES21 model. Defining $\sigma_{2+3}/\sigma_1$ as the ratio between the low-$\alpha$ and high-$\alpha$ present-day total surface mass densities, we assumed $\sigma_{2+3}/\sigma_1 = 3.472$, as prescribed by ES20. Concerning the present-day ratio between low-$\alpha$ and high-$\alpha$ stars, the actual observed value is still uncertain. We highlight that Fuhrmann et al. (2017) derived a local mass density ratio of 5.26 in the solar vicinity between the thin and thick disc stars, which becomes as low as 1.73 after correction for the difference in the scale height. Finally, the SFE of the low-$\alpha$ part I sequence was also taken from the ES20 model ($\nu_2 = 1.3$ Gyr$^{-1}$).

As discussed in Sect. 4, the radial velocity spectrometer (RVS) chemical abundance shows the presence of a population composed of massive stars with a deficiency in metallicity [M/H], i.e. sub-solar values not explainable with standard chemical evolution or stellar migration processes. The same behaviour is seen in young objects with Kordopatis et al. (2023) ages smaller than 1 Gyr. It is important to note that this population has been found to trace the spiral arms.

In order to correctly model this population, we need the third infall (low-$\alpha$, part II) associated with lower SFE to be compared with the first component of the low-$\alpha$ phase that is coupled with enough gas infall to produce sufficient dilution on short timescales. In fact, we fixed the SFE at the value of $\nu_3 = 0.5$ Gyr$^{-1}$, imposing that the mass of the part II is $\sigma_3 = 0.3 \cdot \sigma_{2+3}$ and $t_3 = 0.15$ Gyr (see Table 1 and the discussion in Sect. 4 with the effects on the chemical evolution of this set of model parameters). Finally, in order to better reproduce the Gaia DR3 abundance ratios, we imposed for the two low-alpha components that the infalling gas has a mild chemical enrichment obtained from the model fixed at the value of the high-$\alpha$ disc phase corresponding to [Fe/H] $= -0.75$ dex divided by a factor of five.

4. Results

In this section, we show the results of the new three-infall chemical evolution model introduced in Sect. 3 for $\alpha$-elements. In Sect. 4.1, we compare Gaia DR3 data with the previous two-infall models regarding different chemical species. In Sect. 4.2, the main features of the proposed three-infall chemical evolution in the [X/Fe] versus [M/H] (X=Mg, Si, Ca, Ti, $\alpha$) plane are discussed. In Sect. 4.3, we present results of the temporal evolution of the SF and other Galactic disc observables. In Sect. 4.4, we compare the model predictions with Gaia DR3 data for different age bins. In Sect. 4.5, we show the dilution signature present in Gaia DR3 massive stars.

4.1. The two-infall model and Gaia DR3 abundance ratios

In the right panels of Fig. 2, we present the predictions of the reference two-infall ES21 model compared with Gaia DR3 data. As illustrated in ES20 and ES21, the gas dilution originated by a strong second gas infall is a key process for explaining APOKASC and APOGEE DR16 abundance ratios. In particular, the second accretion event of pristine gas (or with a metal-poor chemical composition) decreases the metallicity of the stellar populations born immediately after the event, keeping a roughly constant [X/Fe] ratio where X is the $\alpha$-element. When star formation resumes, Type II SNe pollutes the ISM, producing a steep rise in the [X/Fe] ratio that subsequently decreases at higher metallicities due to the bulk of Fe injection from Type Ia SNe (Matteucci et al. 2009; Bonaparte et al. 2013; Palla 2021). This sequence produces the characteristic ‘loop’ feature in the chemical evolution track of [X/Fe] versus [Fe/H].

In Fig. 2, we also report the predictions of the two-infall ES21 synthetic model, including errors for ages younger than 1 Gyr and the whole age range for the [Si/Fe] and [Mg/Fe] versus [M/H] relations. We included Si and Mg because (i) in ES20 with they approximate the global $\alpha$ and (ii) in ES21 the chemical evolution of Mg was studied.

Concerning the whole-ages case (reported in the right panels), the general trend of the data is well reproduced for the high-$\alpha$ and low-$\alpha$ phases. This agreement is quite reassuring because...
The presence of a young metal deficient population in these stars should predominantly migrate from the outer disc, to explain this population either because, in such a scenario, by Gaia Collaboration (2023b), stellar migration will not be able to sagittarius, as suggested by Ruiz-Lara et al. (2020). As stated of the dynamical interaction between the Milky Way and In the proposed scenario, the third infall can be the result with our three-infall model, as we explain in Sects. 4.4 and 4.5. All of the parameters are the same as in ES20 and ES21 for the first two gas infall episode (see Table 1).

However, it is clear from Fig. 2 that the ES21 model is not capable of reproducing the young population centred at under-solar [M/H] values, predicting SSPs with a too-high metallicity. The presence of a young metal deficient population in Gaia DR3 data is discussed in more detail in Section 4.5. For the moment, we just mention that Gaia Collaboration (2023b) pinpointed low [Mg/Fe], [Ca/Fe], and [Ti/Fe] ratios in the range of \(-0.5 \text{ dex} < [\text{M/H}] < 0 \text{ dex}\) for evolved massive stars near the disc plane.

This range seems to indicate that the young stellar populations are chemically impoverished, which can be explained with our three-infall model, as we explain in Sects. 4.4 and 4.5. In the proposed scenario, the third infall can be the result of the dynamical interaction between the Milky Way and Sagittarius, as suggested by Ruiz-Lara et al. (2020). As stated by Gaia Collaboration (2023b), stellar migration will not be able to explain this population either because, in such a scenario, these stars should predominantly migrate from the outer disc, but the decreasing stellar density with galactocentric radius cannot allow them to dominate the star counts.

4.2. The three-infall model and the dilution features

In Fig. 3, we show the chemical enrichment history in the [Si/Fe] versus [M/H] plane for the three-infall model without the inclusion of errors. We highlight different phases associated to the distinct infall episodes to better visualise the main trends. The dilution phase begins soon after injection of the infalling gas associated with the first component of the low-\(\alpha\) sequence (low-\(\alpha\) part I in Eq. (1)) into the Galactic system. In particular, and as mentioned for the ES20 and ES21 model, the second accretion event of metal-poor gas decreases the metallicity of the stellar populations that are born immediately after, keeping a roughly constant [Si/Fe] ratio. Once the SF resumes, the predicted Galactic chemical evolution follows the characteristic loop feature in the [Si/Fe] versus [Fe/H] plane. In Johnson & Weinberg (2020) and Lian et al. (2020a,b), the effects of a recent gas-rich merger or violent dynamical disturbance on the chemical evolution have been discussed as producing features in the chemical space similar to the ones described above.

In Fig. 3, the effects of the third accretion event (with model parameters reported in Table 1) on the chemical enrichment of the Galactic disc can be seen. This accretion episode begins after 11 Gyr of evolution (Galactic age of 2.7 Gyr) and produces a much smaller loop feature compared to the second infall. As clearly indicated by the light-blue line in Fig. 3, the principal effects of the third gas infall are: (i) keeping the present-day
metallicity [M/H] at a value smaller than the previous chemical evolution model proposed by Spitoni et al. (2019a, 2020, 2021), and (ii) maintaining low values of [Si/Fe]. As shown in the first upper panel of Fig. 4, this third infall allows our synthetic model to reproduce even the observed stars younger than 1 Gyr.

We have mentioned in Sect. 3.5 that the total baryonic mass in the low-alpha sequence (i.e. the $\sigma_{2+3}$ quantity in Table 1) is distributed as follows: 70% in the low-\(\alpha\) part I and 30% low-\(\alpha\) part II phases. Hence, the smaller mass associated to the third infall combined with the low SFE ($v_3 = 0.5 \text{ Gyr}^{-1}$) is mainly responsible for the small loop in the [Si/Fe] versus [M/H] relation. However, the dilution required to reproduce the young population at sub-solar metallicity may be in place, imposing a short timescale $t_3$ for the gas accretion. This particular combination of parameters allows us to predict the young sub-solar metallicity population, as we show in Sects. 4.4 and 4.5.

For the sake of completeness, in Fig. 5 we show a chemical evolution model constrained by an SF history similar to the one reported in the inset panel of Fig. 3 and that presents a different chemical enrichment in the [Si/Fe] versus [M/H] space. We imposed a smaller gas infall mass for the third infall. In this case, it accounts for 15% of the total low-\(\alpha\) sequence baryonic mass – and a larger SFE ($v_3 = 0.8 \text{ Gyr}^{-1}$). The inset also reports the normalised star formation history with the different evolutionary phases coloured as in the main plot [Si/Fe] versus [M/H]. The value of the SFE associated to the low-\(\alpha\) phase I (indicated with the blue dashed line) is $v_2 = 1 \text{ Gyr}^{-1}$. Vertical dashed lines indicate the ages corresponding to yellow points.
ponent was required in order to impose a lower mass associated to the third infall. Hence, we were able to reproduce the SF history of Fig. 3 by assuming a smaller SFE value of the low-\(\alpha\) sequence in the [Si/Fe] versus [M/H] space compared to the model of Fig. 3 during the third infall phase, showing a chemical evolution track very similar to the ES20 and ES21 models. It is worth mentioning that the models presented in Figs. 3 and 5 are also able to reproduce the data studied in ES20 and ES21. The proposed three-infall model with strong dilution has been used to interpret in the [M/H] versus [Ce/Fe] Gaia DR3 abundance ratios in Contursi et al. (2023).

Future Gaia data releases, as well as other surveys, might revise the properties and significance of the young metal-impoverished population of stars found by Gaia Collaboration (2023b). However, the three-infall model presented in this paper, constrained by the recent local SFH derived from Gaia data, would still remain a viable scenario for the local disc formation. It could be necessary, though, to assume a higher or smaller amount of accreted gas. In this respect, it also has to be mentioned that the identification of the young, metal-poor component could suffer from biases related to the adoption of the standard spectroscopic local thermodynamic equilibrium (LTE) analysis for those stars (see discussions in Magrini et al. 2023). Furthermore, the parameterisation of young stars from high-resolution spectra (\(R \sim 100\,000\)) could also be affected by a combination of intrinsic factors, such as activity, fast rotation, and magnetic fields (Zhang et al. 2021; Spina et al. 2020, 2022). Nonetheless, Gaia Collaboration (2023b) pointed out that the above-mentioned processes should be important in young stars with ages younger than 200 Myr, thus not affecting the Gaia RVs parameterisation, which is performed at medium resolution (\(R \sim 11\,500\)).

4.3. The Galactic star formation history and other disc observables

In Fig. 1, we compare the predicted SF history by the model with parameters given in Table 1 with the parameters of Ruiz-Lara et al. (2020) and Bernard (2017). The figure shows that our three-infall model approximately traces the main feature of the observed SF history by Gaia and that the recent narrow SF peaks can be well mimicked by a low-\(\alpha\) sequence formed by two independent episodes of gas infall. Concerning the high-\(\alpha\) sequence, the predicted SF is in very good agreement with the thick disc part of Bernard (2017). However, in Ruiz-Lara et al. (2020), we notice that the thick disc has a more extended evolution in time.

We want to recall here that the Milky Way-like galaxy simulations in the cosmological framework presented by Vincenzo & Kobayashi (2020) show important signatures of two gas accretions of metal-poor gas as occurring about 0–2 and 5–7 Gyr ago, respectively, which is in very good agreement with the scenario we propose with the three-infall model. These events are responsible for the shape of the low-\(\alpha\) sequence in the \([\alpha/Fe]–[Fe/H]\) diagram for the neighbourhood.

As mentioned in Sect. 3.5 of this study, we want to retain, especially for the high-\(\alpha\) sequence, the model parameters of previous chemical evolution models already capable of appropriately reproducing abundance ratios of APOGEE and APOKASC data.

As anticipated in Sect. 3.3, we imposed that the total (sum of high- and low-\(\alpha\) sequence contributions) surface mass density in the local disc is the same as the one suggested by McKee et al. (2015) i.e. \(47.1 \pm 3.4\, M_\odot\, pc^{-2}\). In the same article, the authors provide the values for the present-day total local surface density of stars, \(\sigma_g(t_p) = 33.4 \pm 3\, M_\odot\, pc^{-2}\). In the left panel of Fig. 6, we draw the temporal evolution of the surface density of stars predicted by our three-infall chemical evolution model. With this model, we have \(\sigma_g(t_p) = 31.2\, M_\odot\, pc^{-2}\), which is in agreement with the above mentioned value proposed by McKee et al. (2015). In the same panel of Fig. 6, we show the predicted temporal evolution of the surface gas density. In particular, the computed present-day value of \(\sigma_g(t) = 11.0\, M_\odot\, pc^{-2}\) is shown to be higher than the value computed by Palla et al. (2020) of \(8.4^{+4.9}_{-4.2}\, M_\odot\, pc^{-2}\) (averaging between the Dame (1993) and Nakanishi & Sofue (2003, 2006) dataset as presented by Palla et al. (2020) (here shown only at 8 kpc). Middle panel: the SFR time evolution predicted by the model is shown to be in agreement with the blue line. The red shaded area indicates the measured range in the solar annulus suggested by Prantsos et al. (2018). Right panel: evolution of the Type Ia SN (dashed line) and Type II SN (solid line) rates predicted by model for whole Galactic disc. The magenta star stands for the observed Type Ia SN rate observed by Cappellaro & Turatto (1997), whereas the purple one stands for Type II SN rates observed by Li et al. (2011). The 1\(\sigma\) and 2\(\sigma\) errors are reported with grey and yellow bars, respectively.
Fig. 7. Same as in Fig. 4 but for Mg. In this case, the empty grey hexagons contain between one and three Gaia DR3 stars, the light-blue hexagons contain between three and 10, and the blue ones indicate regions with more than 10 stars.

and Nakanishi & Sofue 2003, 2006 datasets) but still within 1σ uncertainty.

In the middle panel of Fig. 6, we present the time evolution of the SFR in our model, which predicts a present-day value of 2.63 $M_\odot$ pc$^{-2}$ Gyr$^{-1}$. Hence, it is in excellent agreement with the range usually assumed as a constraint in chemical evolution models in the solar vicinity of 2–5 $M_\odot$ pc$^{-2}$ Gyr$^{-1}$ (Matteucci 2012; Prantzos et al. 2018).

In the right panel of Fig. 6, we report the time evolution of the Type Ia SN and Type II SN rates. The present-day Type II SN rate in the whole Galactic disc predicted by our three-infall model is 1.08 [100 yr], a smaller value (but within 2σ error) than the observations of Li et al. (2011), who yielded a value of 1.54 ± 0.32 [100 yr]. The predicted present-day Type Ia SN rate is 0.29 [100 yr], which is in very good agreement with the value provided by Cappellaro & Turatto (1997) of 0.30 ± 0.20 [100 yr]. Moreover, the computed present-day infalling gas rate is 0.71 $M_\odot$ pc$^{-2}$ Gyr$^{-1}$, consistent with the range 0.3–1.5 $M_\odot$ pc$^{-2}$ Gyr$^{-1}$ suggested in Chapter 5.3.1 of Matteucci (2012) for the solar vicinity.

4.4. Three-infall model predictions in different age bins

In this section, we present the predicted abundance ratios by the three-infall chemical evolution and the associated synthetic models. In Fig. 4, we report the [Si/Fe] versus [M/H] abundance ratios computed in six different age bins. We recall that in GSP-Spec, [M/H] values follow the [Fe/H] abundance with a tight correlation. Hence, in this work we compare [Fe/H] model predictions with [M/H] Gaia DR3 abundance ratios.

We can note that our three-infall synthetic model is able to produce the main features of Gaia DR3 data at different ages. In particular, the model is able to reproduce the youngest stellar population with ages < 1 Gyr.

In Fig. 4, we also indicate the median vertical velocity dispersion $\sigma_Z$ of the Gaia stars in each age bin. As expected, the older age bins are characterised by larger $\sigma_Z$ values.

In the lower right panel, we consider the whole age range, and beside the synthetic model, we show the best-fit three-infall model of Fig. 3. As already discussed in Sect. 4.2, the chemical evolution track is very similar to the one previously proposed by Spitoni et al. (2019a), ES20, and ES21: once the high-α sequence ended (after ~4 Gyr of evolution), the Galactic disc achieved the highest value of metallicity [M/H].

In Fig. 7, we show the model results for the [Mg/Fe] versus [M/H]. In this case, we find a very good agreement between our synthetic model computed at different age bins and the Gaia DR3 data, similar to the results presented for Si. In Fig. 2, we also report ES21 model predictions for Mg compared with Gaia DR3 data.

As for Si, model ES21 (designed to reproduce APOGEE DR16 data in the solar vicinity) is capable of reproducing Gaia DR3 if we consider the whole stellar ages (lower-right panel of Fig. 2).
it cannot predict the Gaia DR3 stars younger than 1 Gyr impoverished in metals [M/H] (lower-left panel).

As shown in Fig. 8, we also have a good agreement between models and data for Ti. Indeed, the synthetic model traces very well the main features of [Ti/Fe] versus [Fe/H] in all the considered age bins. In Fig. 9, we have drawn model results for [Ca/Fe] versus [Mg/Fe]. The model is shown to slightly underestimate [Ca/Fe] and [α/Fe] in all [M/H] bins. Even for the corrected yield, the predicted [Ca/Fe] versus [Fe/H] abundance ratios in Fig. 4 of François et al. (2004) seem to be consistently below our collection of stellar data results, shown in Fig. 9.

In Fig. 10, we report the metallicity distribution function predicted by our synthetic model in comparison with those computed for different stellar samples selected for different elements. Our synthetic model metallicity distribution function is in very good agreement with Ca, α, Si, and Ti stellar samples. Only for Mg does the Gaia DR3 stellar distribution show fewer stars at low metallicity. In the Gaia RVS range, the unique Mg line is very weak, so the abundances have to be treated carefully. The fact that we have a limited number of stars with high-quality values for the flags is the main reason for this slight discrepancy.

### 4.5. Recent dilution signature in Gaia DR3 massive stars

As pointed out by Gaia Collaboration (2023b), the evolved massive stars in the same parameter range as the massive population presented in their Sect. 3 dominate the observed populations visible for X= Mg, Ca, Ti abundances in the range [M/H] ∈ [-0.5, 0] dex, and at low abundance [X/Fe] ratio values near the disc plane at all Galactic radii. In the previous section, we have shown that this population of young stars seems to be impoverished in the solar cylinder, which was also found by Recio-Blanco et al. (2023) when considering a larger number of element abundances. We note that silicon, calcium, and titanium, which have several lines in the RVS wavelength range, were measured in a large sample of stars in the solar cylinder: more than 80 000 for [Ti/Fe] and more than 140 000 for [Si/Fe]. Moreover, in Appendix D of Gaia Collaboration (2023b), the robustness of the massive stars’ chemical impoverishment estimate and its dependence on the different calibrations have been also verified.

In the left panel of Fig. 11, we show the Kiel diagram of massive stars as selected in the $T_{\text{eff}}$ and $\log g$ (calibrated values) space by Gaia Collaboration (2023b, see their Fig. 8) for the subsamples considered in this work for α, Ca, Mg, Si, and Ti. In this particular analysis, including for the Mg sample, the stars have been selected imposing a value of zero for the ‘UpLim’ flag (best quality data).

In Fig. 12, we compare the predicted [X/Fe] versus [Fe/H] abundance ratios for SSPs younger than 1 Gyr (for different α elements) from the synthetic model with the massive stars reported in Fig. 11 which uses calibrations proposed for...
Fig. 9. Same as in Fig. 4 but for Ca. In this case, the empty grey hexagons enclose between five and 15 Gaia DR3 stars, the light-blue hexagons enclose between 15 and 50, and the blue hexagons enclose more than 50.

Fig. 10. Metallicity [M/H] distributions predicted by the synthetic model (light-red histograms) compared with the ones obtained considering the different Gaia DR3 stellar sub-samples for Ca, $\alpha$, Mg, Si, and Ti, respectively (blue histograms). In each plot, the associated median values are indicated by the vertical dashed lines.

by Recio-Blanco et al. (2023). The only predictions that are not in agreement with the data are those for Mg. Although [Mg/Fe] ratios computed by our synthetic model have larger values, the observed [M/H] is well traced in this case. Following Poggio et al. (2022), in the right panel of Fig. 11, we compare the selected massive stars of Gaia DR3 stars with the prediction from the PARSEC isochrones (Bressan et al. 2012; Chen et al. 2014, 2015; Tang et al. 2014; Pastorelli et al. 2019) computed at 1 Gyr, 500 Myr, 300 Myr, 100 Myr, and 30 Myr. These isochrones consider both solar metallicity [M/H] = 0 dex and $-0.25$ dex because, as can be seen in Fig. 12, the range in metallicity of the selected Gaia DR3 stars spanned $\in [-0.25, 0]$ dex. It is clear that the sample mostly contains young stars with ages between 100 Myr and 300 Myr.

An important test for validating the young, chemical-impoverished population identified by the Gaia DR3 involves the comparison of the identified stars with the high-resolution spectroscopic surveys of APOGEE DR17 (Abdurro’uf et al. 2022). In Fig. 13, we show the stars in common between the subsamples of Gaia DR3 and APOGEE DR17, both for the massive stars and for objects younger than 1 Gyr. The stars are shown separately in the [X/Fe] versus [M/X] chemical space (where X = Mg, Si, Ca, Ti). Notwithstanding some differences in the [X/Fe]
Fig. 11. Kiel diagram of massive Gaia DR3 population. Left panel: Kiel diagram for the massive Gaia DR3 star sub-samples selected, as indicated in Sect. 4.5, for α, Ca, Mg, Si, and Ti, respectively. Different point sizes help to visualise the stars in common among different sub-samples. Right panel: PARSEC isochrones for metallicites [M/H] = 0 dex and [M/H] = −0.25 dex compared to the massive Gaia DR3 star sub-samples (black points).

Fig. 12. Comparison between abundance ratios of [α/Fe], [Mg/Fe], [Si/Fe], [Ca/Fe], [Ti/Fe] as a function of [M/H] predicted by the three-infall model for stars younger than 1 Gyr compared and Gaia DR 3 massive stars. Black points indicate observed massive stars selected by Gaia Collaboration (2023b, see text for details) using the calibrations proposed by Recio-Blanco et al. (2023). The contour lines enclose fractions of 0.75, 0.60, 0.45, 0.30, 0.20, and 0.05 of the total number of observed stars. The colour-coded hexagons indicate the model predictions and highlight the total number of stars formed by the fiducial three-infall model in the different regions of the abundance ratio relation.

Fig. 13. Upper panels: comparison between the GSP-Spec chemical abundances ratios of Gaia DR3 younger than 1 Gyr analysed in this work (blue points and associated errors) and their counterparts in APOGEE DR17 (yellow points). Lower panels: same as the upper panels, but for the massive Gaia DR3 stars considered in this work.
Fig. 14. Upper panel: \([\text{Mg/Fe}] \) versus \([\text{Fe/H}]\) abundance ratios for APOGEE DR17 stars with Galactocentric distances between 7 and 9 kpc are reported with the black points. APOGEE DR17 stars that cross-match with the population of massive stars presented by Gaia Collaboration (2023b) characterised by chemical impoverishment with maximum vertical heights \(|z_{\text{max}}| < 0.5\) kpc are indicated with the yellow points. Lower panel: same as the upper panel but for \([\alpha/\text{Fe}]\) versus \([\text{Fe/H}]\).

values, which can be explained by the differences in models and wavelength domain, the metallicities estimated by both surveys are in very good agreement. It is important to note that Gaia DR3 and APOGEE DR17 have only a few stars in common in the selected Galactic region \((R_g \in [8.1, 8.4] \text{ kpc})\); see Sect. 2). As shown in Fig. 12, Gaia DR3 shows a significant number of massive stars even in the narrow region selected around the solar position.

In addition, in Fig. 14 we investigate in more detail the massive, young population introduced in Fig. 11 of Gaia Collaboration (2023b), which is characterised by chemical impoverishment in \([\text{Ca/Fe}]\) versus \([\text{M/H}]\) ratios. We draw the chemical ratios observed in APOGEE DR17 for the same stars as in Gaia Collaboration (2023b) which display chemical impoverishment in their Fig. 11 in the same Galactic region and with maximum vertical heights \(|z_{\text{max}}| < 0.5\) kpc. For the validation of this young chemical impoverished population, from Fig. 14, it is very important to note that all the cross-matched stars (i) are part of the low-\(\alpha\) sequence in APOGEE DR17 and (ii) the majority of them present sub-solar values in metallicity.

Finally, in Fig. 15, we compare the three-infall chemical evolution models presented in this study with APOGEE DR17 data in the \([\text{Mg/Fe}]\) versus \([\text{Fe/H}]\) abundance ratios. Symbols of the APOGEE DR17 stars are as in the upper panel of Fig. 14. Line types and colours of the two chemical evolution models are the ones indicated in Fig. 3 (model with strong dilution created by the third infall) and Fig. 5 (model with a less massive third infall).

Fig. 15. Comparison between the three-infall chemical evolution models presented in this study and APOGEE DR17 data in the \([\text{Mg/Fe}]\) versus \([\text{Fe/H}]\) abundance ratios. Symbols of the APOGEE DR17 stars are as in the upper panel of Fig. 14. Line types and colours of the two chemical evolution models are the ones indicated in Fig. 3 (model with strong dilution created by the third infall) and Fig. 5 (model with a less massive third infall).

4.6. Results with Romano et al. nucleosynthesis prescriptions

In this section, we present the three-infall model results using the nucleosynthesis prescriptions suggested by Romano et al. (2010) (see Sect. 4.6 for details) with the same parameters as in Table 1. In order to be consistent with the Romano et al. (2010) study, we considered the IMF of Kroupa et al. (1993). In the different panels of Fig. 16, we show the results for \([\text{Si/Fe}], [\text{Mg/Fe}], [\text{Ti/Fe}],\) and \([\text{Ca/Fe}]\) versus \([\text{M/H}]\), respectively. We note that for Mg and Ti, the predicted abundance ratios fall substantially below the observation data by more than 0.2 dex. We stress, however, that modeling the galactic chemical evolution of Mg and Ti is challenging, even when adopting the most up-to-date nucleosynthesis prescriptions for massive stars. For instance, Prantzos et al. (2018) presented chemical evolution with metallicity-dependent weighted rotational velocities by Limongi & Chieffi (2018), but the evolution of Mg and Ti substantially underestimated the observational data in the Milky Way.

We want to stress that the largest uncertainties in the model predictions are still due to the adopted stellar nucleosynthesis prescriptions.
5. Conclusions

In this study, we have presented a new three-infall chemical evolution model for the solar vicinity. Our main goal was to extend the previous models presented in Spitoni et al. (2020, 2021) in the light of the new constraints given by the star formation history (from Gaia DR1 and Gaia DR2) and the RVS spectra abundance ratios (Gaia DR3). Because these models were already able to successfully reproduce data from high resolution surveys, such as APOKASC and APOGEE DR16, we kept the parameters proposed by the previous studies unchanged (see Table 1). Our main conclusions are summarised as follows:

1. The new three-infall chemical evolution model, characterised by infall timescales \( t_1 = 0.10 \) Gyr, \( t_2 = 4.11 \) Gyr, and \( t_3 = 0.15 \) Gyr, as well as a strong chemical dilation during the third infall phase, is able to reproduce the main features of the abundance ratio \([X/Fe]\) versus \([M/H]\) \((X=\text{Mg, Si, Ca, Ti, } \alpha)\) of Gaia DR3 stars in different age bins for the considered \( \alpha \) elements.

2. The most recent gas infall, which started \( \sim 2.7 \) Gyr ago, allows us to identify predict the Gaia DR3 young population that has suffered a recent chemical impoverishment. We have shown that the classical two-infall model is not capable of predicting this young population centred at undersolar \([M/H]\) values because too many stars at higher metallicities are formed.

3. Our model also reproduces important observational constraints for the chemical evolution of the Galactic disc, such as the present-day star formation rate, the stellar and gas surface densities, Type II and Ia SN rates, and the infall rate of the accreted gas. In addition, the proposed three-infall model is able to reproduce the solar photospheric abundance values of Grevesse et al. (2007).

4. The stars identified by Gaia Collaboration (2023b) as massive objects, with the above-mentioned signature of chemical impoverishment, are also part of the low-\( \alpha \) sequence that accounts for the associated APOGEE DR17 chemical abundances.

5. The proposed three-infall model with a strong dilution in the chemical abundances ratios caused by a third infall event is capable of reproducing APOGEE DR17 data reasonably well.

6. Future Gaia data releases, as well as other surveys, might revise the properties and significance of the young population of metal-impoverished stars found by Gaia Collaboration (2023b). However, the three-infall model presented here constrained by the recent local SFH derived from Gaia data would remain a viable scenario for the local disc formation. It could be necessary, though, to assume a higher or smaller amount of accreted gas.

The above-mentioned results suggest that the distribution of the stars in high-\( \alpha \) and low-\( \alpha \) sequences is strictly linked to different star formation regimes over the Galaxy’s life. As pointed out by Gaia Collaboration (2023b), stellar migration is not capable of explaining the presence of the significant young stellar population with an impoverished chemical composition. The reason is that inwards migration from outer parts, which favours lower metallicities, should not the dominant process due to the decreasing stellar density with the galactocentric distance. In conclusion, we suggest that the main reason for this peculiar young stellar population is the chemical dilution from a recent gas infall episode.

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