Abundance gradients along the Galactic disc from chemical evolution models

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ABSTRACT
In this paper, we study the formation and chemical evolution of the Milky Way disc with particular focus on the abundance patterns ([α/Fe] vs. [Fe/H]) at different Galactocentric distances, the present-time abundance gradients along the disc and the temporal evolution of abundance gradients. We consider the chemical evolution models for the Galactic disc developed by Grisoni et al. (2017) for the solar neighborhood, both the two-infall and the one-infall, and we extend our analysis to the other Galactocentric distances. In particular, we examine the processes which mainly influence the formation of abundance gradients: i) the inside-out scenario for the formation of the Galactic thin disc, ii) a variable star formation efficiency, and iii) radial gas flows. We compare our model results with recent abundance patterns along the Galactic disc from APOGEE survey and with abundance gradients observed from Cepheids, open clusters, HII regions and PNe. We conclude that the inside-out scenario is a key ingredient, but cannot be the only one to explain abundance patterns at different Galactocentric distances and abundance gradients. Further ingredients, such as radial gas flows and variable star formation efficiency, are needed to reproduce the observed features in the thin disc. In particular, the model with a variable star formation efficiency is in very good agreement with the observational data, both the abundance patterns at different Galactocentric distances and abundance gradients. The model with variable star formation efficiency predicts a flattening of the gradient with time, which is in agreement with other chemical evolution models and cosmological simulations, but it does not allow the inversion of gradients, observed at high redshift.

Key words: galaxies: abundances - galaxies: evolution - galaxies: gradient

1 INTRODUCTION

In order to study the formation and chemical evolution of our Galaxy, a fundamental constraint is represented by abundance gradients along the Galactic thin disc. Furthermore, recent observational data of abundance patterns at various Galactocentric distances represent another important constraint for understanding the formation and evolution of the Milky Way disc (Hayden et al. 2015).

Abundance gradients have been observed in many spiral galaxies and show that the abundances of metals decrease outward from the Galactic center. Generally, a good agreement between observational properties of the Galaxy and model predictions is obtained by assuming that the disc formed by infall of gas (Chiosi 1980; Matteucci and Francois 1989; Chiappini et al. 1997, 2001; Cescutti et al. 2007; Colavitti et al. 2009; Spitoni and Matteucci 2011; Mott et al. 2013). In particular, a good assumption for reproducing abundance gradients is that the timescale for the formation of the Galactic thin disc increases with Galactocentric radius according to the inside-out scenario (Matteucci and Francois 1989; Chiappini et al. 2001). Cescutti et al. (2007) showed that a two-infall model with inside-out scenario gives a very good agreement with the data on Cepheids in the Galactocentric distance range 5-17 kpc for many of the studied elements (Andrievsky et al. 2002a,b,c, 2004; Luck et al. 2003).

Colavitti et al. (2009) showed that it is fundamental to assume an inside-out scenario, but also a threshold in the gas density for the star formation rate in order to reproduce the present day gradients in the outer disc. However, even with-
out the threshold in the surface gas density, Colavitti et al. (2009) could reproduce the gradients in the outer disc by assuming a variable star formation efficiency, higher in the inner region than in the outer ones. More recently, Pilkington et al. (2012) have supported the conclusion that spiral discs form inside-out. To maintain consistency, also radial gas flows have to be taken into account as a dynamical consequence of infall (Spitoni and Matteucci 2011; Bilitewski and Schönrich 2012; Wang and Zhao 2013; Spitoni et al. 2013; Mott et al. 2013; Cavichia et al. 2014; Pezzulli et al. 2017). The infalling gas has a lower angular momentum than the circular motions in the disc, and mixing with the gas in the disc induces a net radial inflow. Lacey and Fall (1985) estimated that the gas inflow velocity is up to a few km s\(^{-1}\) and at 10 kpc is \(v_R=1\) km s\(^{-1}\). Goetz and Koeppen (1992) studied numerical and analytical models including radial gas flows and they concluded that radial flows alone cannot explain the abundance gradients, but are an efficient process to amplify the existing ones. Portinari and Chiosi (2000) implemented the radial flows of gas in a detailed chemical evolution model characterized by a single infall episode. More recently, Spitoni and Matteucci (2011) and Spitoni et al. (2013) have taken into account inflows of gas in detailed one-infall models for the Milky Way and M31 respectively, treating the evolution of the thin disc independently from the halo and thick disc. Spitoni and Matteucci (2011) tested also the radial flows in a two-infall model, but only for the oxygen. They found that the observed gradient of oxygen can be reproduced if the gas inflow velocity increases in modulus with the Galactocentric distance, in both the one-infall and two-infall models. A similar approach was followed also by Mott et al. (2013), who studied also the evolution in time of the gradients. At variance with the previous papers, where the velocity patterns of the inflow were chosen to produce a best-fit model, Bilitewski and Schönrich (2012) presented a chemical evolution model where the flow of gas is directly linked to physical properties of the Galaxy like the angular momentum budget. The resulting velocity patterns of the flows of gas are time dependent and show a non-linear trend, always decreasing with decreasing Galactocentric distance. At a fixed Galactocentric distance, the velocity flows decrease in time.

The temporal evolution of abundance gradients has been studied in several works and in literature various predictions have been made by chemical evolution models. Some authors predicted that the gradient steepens in time (Chiappini et al. 2001; Mott et al. 2013), whereas others suggested that the gradient flattens in time (Prantzos and Boissier 2000; Molla and Diaz 2005; Vincenzo et al. 2018; Minchev et al. 2018). The discrepancy between different model predictions is due to the fact that chemical evolution is very sensitive to the prescriptions of the physical processes that lead to the differential enrichment of inner and outer discs, and the flattening or steepening of gradients in time depends on the interplay between infall rate, star formation rate along the disc and also on the presence of a threshold in the gas density for the star formation (Kennicutt 1998a,b). Different recipes of star formation or gas accretion mechanisms can provide different abundance gradients predictions. From the observational point of view, there have been some studies in order to infer the temporal evolution of gradients from planetary nebulae (PNe) of different ages (Maciel and Costa 2009, 2013), but no firm conclusion could be derived. The first observational papers which could clarify the issue of the temporal evolution of abundance gradients are from Cresci et al. (2010), Jones et al. (2010), Contini et al. (2011) and Yuan et al. (2011). More recently, Xiang et al. (2015) studied the evolution of stellar metallicity gradients of the Milky Way disk from LSS-GAC main sequence turn-off stars, and concluded that the radial gradients, after being essentially flat at the earliest epochs of disc formation, steepen with time, reaching a maximum at age 7-8 Gyr, and then they flatten again, suggesting a two-phase disc formation history (see also Huang et al. 2015, Xiang et al. 2017). Furthermore, Anders et al. (2017) measured the age dependence of the radial metallicity distribution in the Galactic thin disc over cosmic time from CoRoT and APOGEE red giants, and concluded that the slope of the radial iron gradient was compatible with a flat distribution for older ages, then it steepens and finally flattens again. These results are in agreement with the one of the Geneva-Copenhagen survey (Nordström et al. 2004; Casagrande et al. 2011), but there are differences with the LAMOST study of Xiang et al. (2015), possibly due to systematic shifts in the distance and age scales. Forthcoming data from asteroseismic and spectroscopic observations will be fundamental to further constrain the temporal evolution of the radial abundance gradients.

This paper is organized as follows. In Section 2, we show the observational data which have been considered to make a comparison with the predictions of our chemical evolution models. We consider the recent chemical evolution models for the Galactic thin disc developed by Grisoni et al. (2017) for the solar neighborhood and we extend our analysis to other Galactocentric distances. In particular, we examine the processes which mainly influence the formation of abundance gradients: i) the inside-out scenario for the formation of the Galactic thin disc, ii) a variable star formation efficiency (SFE), and iii) radial gas flows along the Galactic disc.

This paper is organized as follows. In Section 2, we show the observational data which have been considered to make a comparison with the predictions of our chemical evolution models. In Section 3, we describe the chemical evolution models used in this work. In Section 4, we present the comparison between observations and model predictions. Finally, in Section 5, we summarize our results and conclusions.

2 OBSERVATIONAL DATA

Abundance gradients can be studied by using several tracers, such as HII regions, planetary nebulae (PNe), Cepheids and open clusters.

In this paper, we adopt the Cepheids data by Luck and Lambert (2011) and Genovali et al. (2015), and the open clusters data from Magrini et al. (2017).

We adopt the HII region data by Deharveng et al. (2000), Esteban et al. (2005), Rudolph et al. (2006) and Balser et al. (2011), and the PNe data by Costa et al. (2005).

We also look at how the abundance patterns of \([\alpha/Fe]\) vs. \([Fe/H]\) vary with Galactocentric distance and we consider the APOGEE data of Hayden et al. (2015) for comparison with our models.
3 THE MODELS

The chemical evolution models adopted here are the ones developed in Grisoni et al. (2017):

- a two-infall model (Chiappini et al. 1997, Romano et al. 2010) revisited and applied to the thick and thin discs, and
- a new parallel model adopting two one-infall approaches for the thick and thin discs, respectively.

3.1 The two-infall model

The two-infall model adopted here is the one presented in Grisoni et al. (2017), which is a revision of the model developed by Chiappini et al. (1997) and Romano et al. (2010), but applied to the thick and thin discs. This model assumes that the discs form as a result of two main infall episodes. During the first one, the thick disc formed, whereas during the second one a much slower infall of gas, delayed with respect to the first one, gives rise to the thin disc. Here, we focus only on the evolution of the thick and thin discs. The evolution of the halo is not taken into account, but applied to the thick and thin discs. This model assumes that the discs form as a result of two main infall episodes.

During the first one, the thick disc formed, whereas during the second one, a much slower infall of gas, delayed with respect to the first one, gives rise to the thin disc. Here, we focus only on the evolution of the thick and thin discs. The origin of the gas in the infall episodes is extragalactic and its composition is assumed to be primordial. The Galactic thin disc is approximated by several independent rings, 2 kpc wide, whereas the evolution of the thick disc evolves as a one-zone with radius of 8 kpc (see Haywood et al. 2018). The basic equations that describe the time evolution of $G_i$, namely the mass fraction of the element $i$ in the gas, are (see Matteucci, 2012):

$$G_i(r, t) = -\psi(r, t)X_i(r, t) + \int_{M_{Bm}}^{M_{Bm}} \psi(r, t - \tau_m)Q_{mi}(t - \tau_m) \phi(m) dm$$

$$+ A \int_{M_{Bm}}^{M_{Bm}} \phi(m) \left[ \int_{m_{in}}^{0.5} f(\mu) \psi(r, t - \tau_{m2})Q_{mi}(t - \tau_{m2}) d\mu \right] dm$$

$$+ (1 - A) \int_{M_{Bm}}^{M_{Bm}} \psi(r, t - \tau_m)Q_{mi}(t - \tau_m) \phi(m) dm$$

$$\left[ \int_{M_{Bm}}^{M_{Bm}} Q_{mi}(t - \tau_m) \phi(m) dm \right] + G_i(r, t)_{\alpha f}$$

$$\tag{1}$$

The first term in the right hand side of Eq. (1) represents the rates at which the chemical elements are subtracted from the ISM to be included into stars, whereas the various integrals represent the rate of restitution of matter from the stars of different masses into the ISM. In particular,

- The first integral represents the material restored by stars in the mass range $M_{L}(t) - M_{Bm}$, where $M_{L}(t)$ is the minimum mass dying at the time $t$ and its minimum value is $\approx 0.8M_\odot$ with a lifetime corresponding to the age of the Universe. The stellar lifetime of a star of mass $m$ is defined as $\tau_m$, and $\tau_{m2}$ is the lifetime of the secondary star of those binary systems giving rise to SNe Ia, whose assumed model is the single degenerate one (see next). In fact, the clock to the explosion of these systems is given by the lifetime of the secondary star in the single degenerate model (Matteucci and Greggio 1986). The term $Q_{mi}$ represents both the new and already present fraction of an element $i$, which is restored into the ISM by a star of mass $m$.

- The second integral corresponds to the contribution of Type Ia SNe, as first introduced by Matteucci and Greggio (1986). Here, the rate is calculated by assuming the single-degenerate model for the progenitor of these SNe, namely a CO WD plus a red giant companion. The extremes of this integral correspond to the minimum mass $M_{Bm}$ and the maximum mass $M_{Bm}$ of the entire systems which give rise to Type Ia SNe. The minimum mass $M_{Bm}$ is set equal to $3M_\odot$, in order to ensure that both the primary and the secondary star would be massive enough to allow the WD to reach the Chandrasekhar mass $M_{Ch}$, after accretion from the companion. The maximum mass is fixed by the requirement that the mass of each component cannot exceed $M_{up} = 8M_\odot$, which is the assumed maximum mass giving rise to a CO WD, and so $M_{Bm} = 16M_\odot$. The parameter $A$ represents the fraction of binary systems with the right properties to give rise to SNe Ia and it is assumed $A=0.035$. The time $\tau_{m2}$ is the lifetime of the secondary star in the binary system giving rise to a SN Ia, and represents the clock of the system in the single degenerate scenario. In Matteucci et al. (2009), it has been demonstrated that this scenario is equivalent to the double degenerate one as the effects on Galactic chemical evolution are concerned.

- The third integral is defined as $\Psi(r, t)X_i(r, t)$ and represents the gas accretion rate. In particular, we adopt the Kroupa et al. (1993) IMF that is the life-time of the secondary star of those SNe (those with $M > M_{up}$ which is assumed to be $8M_\odot$).

- The fourth integral represents the material restored by core-collapse SNe (Type II, Ib and Ic).

The star formation rate (SFR) is the Schmidt-Kennicutt law (Kennicutt 1998a):

$$\psi(r, t) = \nu \sigma_{gas}^4(r, t) = \nu \sigma_{gas}^{1.5}(r, t),$$

where $\sigma_{gas}$ is the surface gas density, $k$ is the law index and $\nu$ the star formation efficiency, which is tuned to reproduce the present time SFR.

The initial mass function (IMF) can be parameterized as a power law of the following kind:

$$\phi(m) = am^{-(1+\alpha)},$$

where $\alpha$ is generally defined in the mass range of 0.1-100 $M_\odot$. In particular, we adopt the Kroupa et al. (1993) IMF that corresponds to:

\begin{align*}
\alpha &= 0.3 \text{ for } M \leq 0.5M_\odot \\
\alpha &= 1.2 \text{ for } 0.5M_\odot < M \leq 1.0M_\odot \\
\alpha &= 1.7 \text{ for } M > 1.0M_\odot
\end{align*}

(5)

The last term in the equation is the gas accretion rate. In
particular, the gas infall law is described as:

\[ G_i(r,t)_{\text{inf}} = A(r)(X_i)_{\text{inf}} e^{-\frac{t-t_{\text{max}}}{\tau_i}} + B(r)(X_i)_{\text{inf}} e^{-\frac{t-t_{\text{max}}}{\tau_i}} , \]

where \( G_i(r,t)_{\text{inf}} \) is the infalling material in the form of element \( i \) and \( (X_i)_{\text{inf}} \) is the composition of the infalling gas which is assumed to be primordial. The parameter \( t_{\text{max}} \) is the time for the maximum mass accretion onto the disc and roughly corresponds to the end of the thick disc phase. The parameters \( \tau_1 \) and \( \tau_2 \) are the timescales for mass accretion in the thick and thin disc components, respectively; they are the e-folding times of the mass accretion law and represent the times at which each component accumulated roughly half of its mass. These timescales are free parameters of the model and they are constrained mainly by comparison with the observed metallicity distribution of long-lived stars in the solar vicinity. In the solar vicinity, Grisoni et al. (2017) found that the best values for these timescales are \( \tau_1 = 0.1 \) Gyr and \( \tau_2 = 7 \) Gyr. In this paper, we assume that the surface mass density in the Galactic thin disc changes with the Galactocentric distance according to the inside out scenario (see Chiappini 2001):

\[ \tau_2 = 1.033r - 1.267 , \]

whereas the timescale of the thick disc is fixed and so there is no inside-out scenario for the thick disc (see also Haywood et al. 2018). The quantities \( A(r) \) and \( B(r) \) are two parameters fixed by reproducing the present time total surface mass density in the solar neighborhood as taken from Nesti and Salucci (2013), which gives results in agreement with the values provided by other studies (Bovy and Rix 2013; Zhang et al. 2013; McKee et al. 2015). In particular, in the solar vicinity the surface mass density is equal to 65 M⊙ pc⁻² for the thin disc, and 6.5 M⊙ pc⁻² for the thick disc. In this paper, we assume that the timescale for mass accretion in the Galactic thin disc changes with the Galactocentric distance according to:

\[ \sigma(r) = \sigma_0 e^{-\frac{r}{r_D}} , \]

where \( \sigma_0 = 143 M_\odot \text{pc}^{-2} \) is the central total surface mass density and \( r_D = 2.6 \) kpc is the scale length. In the case of the thick disc, it is constant and equal to 6.5 M⊙ pc⁻² up to 8 kpc and then it decrease with the inverse of the Galactocentric distance (see Chiappini et al. 2001).

### 3.2 The parallel model

We consider also the possibility of abandoning a sequential scenario like the one of the two-infall, in favour of a picture which treats the thick and the thin disc stars as formed in two distinct evolutionary phases, which evolve independently. In the light of these considerations, we develop two distinct one-infall models: one for the thick disc and the other for the thin disc.

As in the previous model, the material accreted by the Galactic discs comes mainly from extragalactic sources, and the basic equation is the same seen before, i.e. Eq. (1). Since this model assumes two distinct infall episodes, the gas infall is described as:

\[ (\dot{G}_i(r,t)_{\text{inf}})_{\text{thick}} = A(r)(X_i)_{\text{inf}} e^{-\frac{t}{\tau_i}} , \]

\[ (\dot{G}_i(r,t)_{\text{inf}})_{\text{thin}} = B(r)(X_i)_{\text{inf}} e^{-\frac{t}{\tau_i}} , \]

for the thick disc and for the thin disc, respectively. The quantities \( A(r) \) and \( B(r) \) and the parameters \( \tau_1 \) and \( \tau_2 \) have the same meaning as discussed for Eq. (6). Actually, the exponential form is similar to the case of the two-infall model, but the novelty introduced here concerns the fact that the infall rate of the thin and thick discs are now totally disentangled. In fact, as mentioned above, we want to treat the thick and the thin disc as two truly distinct evolutionary phases.

For the SFR and the IMF, the functional forms are the same of the two-infall model (Eq. (2) and Eq. (5), respectively).

### 3.3 Nucleosynthesis prescriptions

The nucleosynthesis prescriptions and the implementation of the yields in the model are fundamental ingredients for chemical evolution models. In this work, we adopt the same nucleosynthesis prescriptions of model 15 of Romano et al. (2010), where an exhaustive description of the adopted yields can be found.

For the computation of the stellar yields, one has to distinguish between different mass ranges as well as single stars versus binary systems:

- low and intermediate mass stars (0.8 M⊙ - 8 M⊙), which are divided into single stars and binary systems which can give rise to Type Ia SNe,
- massive stars (M > 8 M⊙).

Single stars in the mass range 0.8 M⊙ - 8 M⊙ contribute to the Galactic chemical enrichment through planetary nebula ejection and quiescent mass loss along the red giant and asymptotic branches. They enrich the interstellar medium mainly in He, C, and N, but they can also produce some amounts of Li, Na and s-process elements. For these stars, which end their lives as white dwarfs, the adopted nucleosynthesis prescriptions are from Karakas (2010).

Type Ia SNe are considered to originate from carbon deflagration in C-O white dwarfs in binary systems. These stars contribute a substantial amount of iron (0.6 M⊙ per event) and non negligible quantities of Si and S. They also contribute to other elements, such as O, C, Ne, Ca, Mg and Mn, but in negligible amounts with respect to the masses of such elements ejected by Type II SNe. The adopted nucleosynthesis prescriptions are from Iwamoto et al. (1999). Massive stars with masses M > 8 M⊙ are the progenitors of Type II, Ib and Ic SNe; if the explosion energies are much higher than 10⁵¹ erg, hypernova events can occur (SNe Ic).

For these stars, the adopted nucleosynthesis prescriptions are from Kobayashi et al. (2006) for the following elements: Na, Mg, Al, Si, S, Ca, Sc, Ti, Cr, Mn, Co, Ni, Fe, Cu and Zn. As for the He and CNO elements, we consider the results of Geneva models for rotating massive stars (see Romano et al. 2010). However, for Mg which is one the relevant element in this study, we adopted the Kobayashi yields multiplied by a factor 1.2 in order to obtain a better agreement with the data. It is well known, in fact, that Mg yields have been underestimated in many nucleosynthesis studies (see François et al. 2004 for a discussion of this point), and although the
most recent ones have improved nonetheless the Mg production in massive stars is still underestimated.

3.4 Implementation of radial inflows

We implement radial inflows of gas in our reference model following the prescriptions described in Spitoni and Matteucci (2011).

We define the $k$-th shell in terms of the Galactocentric radius $r_k$, its inner and outer edge being labeled as $r_{k-\frac{1}{2}}$ and $r_{k+\frac{1}{2}}$. Through these edges, gas inflow occurs with velocity $v_{k-\frac{1}{2}}$ and $v_{k+\frac{1}{2}}$, respectively. The flow velocities are assumed to be positive outward and negative inward.

Radial inflows with a flux $F(r)$, contribute to altering the gas surface density $\sigma_{kh}$ in the $k$-th shell in accordance to:

$$\left[\frac{d\sigma_{kh}}{dt}\right]_{rf} = -\frac{1}{\pi(r_{k+\frac{1}{2}}^2 - r_{k-\frac{1}{2}}^2)}[F(r_{k+\frac{1}{2}}) - F(r_{k-\frac{1}{2}})],$$

(11)

where

$$F(r_{k+\frac{1}{2}}) = 2\pi r_{k+\frac{1}{2}} v_{k+\frac{1}{2}} [\sigma_{g(k+1)}],$$

(12)

and

$$F(r_{k-\frac{1}{2}}) = 2\pi r_{k-\frac{1}{2}} v_{k-\frac{1}{2}} [\sigma_{g(k-1)}].$$

(13)

We take the inner edge of the $k$-shell, $r_{k-\frac{1}{2}}$, at the midpoint between the characteristic radii of the shells $k$ and $k - 1$, and similarly for the outer edge $r_{k+\frac{1}{2}}$;

$$r_{k-\frac{1}{2}} = \frac{r_{k-1} + r_{k}}{2},$$

(14)

and

$$r_{k+\frac{1}{2}} = \frac{r_{k} + r_{k+1}}{2}.$$  

(15)

We find that:

$$(v_{k+\frac{1}{2}}^2 - v_{k-\frac{1}{2}}^2) = \frac{r_{k+1} - r_{k-1}}{2} [r_{k} + \frac{r_{k-1} + r_{k+1}}{2}].$$

(16)

Therefore, by inserting these quantities into Eq. 11, we obtain the radial flow term to be added in Eq. 1:

$$\left[\frac{dG_{i}(r_{k}, t)}{dt}\right]_{rf} = -\beta_{k} G_{i}(r_{k}, t) + \gamma_{k} G_{i}(r_{k+1}, t),$$

(17)

where $\beta_{k}$ and $\gamma_{k}$ are, respectively:

$$\beta_{k} = -\frac{2}{r_{k} + \frac{r_{k-1} + r_{k+1}}{2}} [v_{k-\frac{1}{2}} r_{k-1} + r_{k}],$$

(18)

and

$$\gamma_{k} = -\frac{2}{r_{k} + \frac{r_{k-1} + r_{k+1}}{2}} [v_{k+\frac{1}{2}} r_{k+1} + r_{k} - \frac{r_{k+1}}{2} \sigma_{k}.$$

(19)

where $\sigma_{k}$ are the present time total surface mass density profile at the radius $r_{k+1}$ and $r_{k}$, respectively. We assume that there are no flows from the outer parts of the disc where there is no SF. In our implementation of the radial inflow of gas, only the gas that resides inside the Galactic disc within the radius of 16 kpc can move inward by radial inflow.

We adopt a variable velocity for the radial gas flows. In particular, the modulus of the radial inflow velocity as a function of the Galactocentric distance is assumed to be:

$$|v_R| = \frac{R_0}{4} - 1,$$

(20)

where the range of the velocities span the range 0-3 km s$^{-1}$, in accordance with other previous works (Wong et al. 2004; Schönrich and Binney 2009; Spitoni and Matteucci 2011; Mott et al. 2013). Furthermore, our radial inflow patterns are in agreement with the ones computed by Bildtewski and Schönrich (2012), imposing the conservation of the angular momentum.

4 MODEL RESULTS

We consider the chemical evolution models for the Galactic disc developed by Grisoni et al. (2017) and we study the radial abundance gradients along the Galactic thin disc and its dependence upon several parameters: i) the timescale for the formation of the thin disc, increasing with Galactic radius according to the inside-out scenario (Matteucci and Francois 1989; Chiappini et al. 2001); ii) the star formation efficiency of the thin disc (Colavitti et al. 2009); iii) the radial gas flows, with a variable gas speed (Spitoni and Matteucci 2011).

In Table 1, we summarize the input parameters of the chemical evolution models. In the first column, we write the name...
of the model. In the second column, there is the star formation efficiency of the thin disc at different radii (4-6-8-10-12-14-16 kpc from the Galactic center). Finally, in the last column, we indicate the presence or the absence of radial gas flows. In each model, we adopt Kroupa et al. (1993) IMF and the inside-out law for the timescale of mass accretion in the thin disc, as expressed by Eq. (8). 2IM A is the two-infall model with inside-out scenario for the Galactic thin disc. Similarly, 1IM A is the one-infall model for the thin disc with inside-out scenario. 1IM B is the one-infall model for the Galactic thin disc with inside-out and also a variable star formation efficiency. 1IM C is the one-infall model for the Galactic thin disc with inside-out and also the implementation of radial gas flows. 1IM D is the one-infall model for the Galactic disc with inside-out and both a variable star formation efficiency and radial gas flows.

Before discussing the abundance patterns and gradients for these models, in Fig. 1 we show the temporal evolution of the SFR as predicted by the 2IM A at various Galactocentric distances: 4, 6, 8, 10, 12, 14 kpc. The SFR during the thick disc phase is the same for every Galactocentric distance up to 8 kpc, because the assumed thick disc mass density in this model is constant up to 8 kpc. However, for R>8 kpc the thick disc mass density is assumed to go with the inverse of the distance and this is reflected into the SFR which is damped at large Galactocentric distances. We note that there is no real gap between the thick and thin disc phases due to the fact that there is no assumed threshold for the star formation, but still there is a quenching of star formation between the two phases. In the thin disc phase, the SFR is much higher at smaller Galactocentric distances since the total surface mass density is higher (see Eq. (8)).

In the following, we show the results for the abundance patterns ([Mg/Fe] vs. [Fe/H]) at various Galactocentric distances, for the present-day gradients and for the temporal evolution of gradients.

### 4.1 Abundance patterns

Our starting point is represented by the study of Grisoni et al. (2017), which explored the two different scenarios for the Galactic thick and thin discs in the solar neighborhood: the two-infall and the parallel one. In Fig. 2, we report the predictions of the two different theoretical approaches, i.e. the two-infall and the parallel models. In the case of the two-infall model (left panel), we predict an overabundance of Mg relative to Fe almost constant until [Fe/H] < -1.5 dex and then for [Fe/H] ~ -1.5 dex the trend shows a decrease due to the delayed explosion of Type Ia SNe. This behaviour of the abundance patterns of α-elements such as Mg is well-interpreted in terms of the time-delay model due to the delay of iron ejection from Type Ia SNe relative to the faster production of α-elements by core-collapse SNe (see Matteucci 2001; 2012). Then, there is a gap, which marks the transition between the thick and thin disc phases, and then the thin disc phase starts. On the other hand, in the case of the parallel model (right panel), we have two distinct evolutionary paths for the thick and thin discs, with the thick disc being more α-enhanced due to the faster timescale of formation (see Grisoni et al. 2017 for further discussion on the two approaches).

Now, we focus on how the tracks in the abundance patterns vary with the Galactocentric distance and we compare our model predictions with APOGEE data (Hayden et al. 2015).
Figure 3. Observed and predicted abundance patterns of $[\text{Mg}/\text{Fe}]$ vs. $[\text{Fe}/\text{H}]$. The data are from Hayden et al. (2015) and are color-coded as follows: 3-5 kpc (magenta dots), 5-7 kpc (green dots), 7-9 kpc (light-blue dots), 9-11 kpc (orange dots), 11-13 kpc (yellow dots), 13-15 kpc (blue dots). The predictions are from model 2IM A (first panel), 1IM A (second panel), 1IM B (third panel), 1IM C (fourth panel), 1IM D (fifth panel) at the various distances: 4 kpc (magenta line), 6 (green line), 8 (light-blue line), 10 (orange line), 12 (yellow line), 14 (blue line).
In Fig. 3, we show the abundance patterns of [$\text{Mg/Fe}$] vs. [$\text{Fe/H}$] at different radii in the case of the models of Table 1. In the upper panel, we show the prediction of the two-infall model 2IM A. We note that the various tracks overlap in the thick disc phase, because we do not assume an inside-out formation for the thick disc (see also Haywood et al. 2018). Then, there is a dilution which is due to the second infall episode. In the thin disc phase, we can see that there is a slight difference between the various tracks due to the inside-out scenario for the thick disc, but the effect is not very noticeable. Similarly, for the 1IM A for the Galactic thin disc with only inside-out, the various tracks at different radii are almost overlapping and there is not so much difference between them. On the other hand, in the case of the 1IM B with variable star formation efficiency, the tracks are different, as the variable star formation efficiency increases the spread among them and the agreement with the data is good, in particular for the outer radii: for example, in the third panel of Fig. 3 we can see that the track at 14 kpc (orange line) has a very good match with the data relative to 13-15 kpc (blue dots). Similarly, Spitoni et al. (2015) found that a variable star formation efficiency can reproduce the spread in the [$\alpha$/Fe] vs. [Fe/H] plot. Then, we show the results for the 1IM C with radial gas flows. Also in this case, we have a much larger spread among the various tracks due to the presence of radial gas flows, even if the effect is different with respect to the previous case. In fact, in the case of radial gas flows, the various tracks overlap at low metallicities, then radial gas flows become relevant for larger metallicities and the spread between the tracks appears. Finally, in the lowest panel of Fig. 3, we show the results for the 1IM D with both variable star formation efficiency and radial gas flows. In this case, the spread among the various tracks is present both at low and high metallicities, due to the fact that we have combined the two effects: on one hand, the variable star formation efficiency, which acts at lower metallicities, and on the other, the radial gas flows, which act at higher metallicities. We can see that the combined effects are too strong, since the law for the variable star formation efficiency and the radial gas flows have been fine-tuned sepa-
Figure 6. Temporal evolution of the radial abundance gradient for magnesium. The data are from Luck and Lambert 2011 (light-blue dots) and Genovali et al. 2015 (blue dots) for Cepheids, and from Magrini et al. 2017 (black dots) for open clusters. The predictions are from models 2IM A, 1IM A, 1IM B, 1IM C and 1IM D at different time.
rately to best fit the data. Other combinations of the radial gas flows and variable efficiency of star formation, including the ones of Spitoni et al. (2015) (with constant radial gas flows and variable efficiency), have been tested and they produce results in between model IIM C and IIM D.

4.2 Present-day gradients

Here, we consider the present-day abundance gradients. In Fig. 4, we show the observed and predicted radial abundance gradient for Mg from Cepheids and open clusters. The data are from Luck and Lambert 2011 (light-blue dots) and Genovali et al. 2015 (blue dots) for Cepheids, and from Magrini et al. 2017 (black dots) for open clusters. The predictions are from the one-infall model for the Galactic thin disc in the three different cases summarized in Table 1: IIM A with only inside-out (light-blue line), IIM B with variable star formation efficiency (blue line), IIM C with radial flows (red line) and IIM D (magenta line). We can see that the model with only inside-out scenario predicts a very flat gradient, whereas to steepen the gradients we need more ingredients such as a variable star formation efficiency or radial gas flows, and by combining the two ingredients we get an even steeper gradient. As we have noted in the case of abundance patterns at different Galactocentric distances, only inside-out does not seem to be sufficient to explain entirely the observations.

In Fig. 5, we show the observed and predicted radial abundance gradient for oxygen from HII regions and Planetary Nebulae. The data are from Deharveng et al. 2000 (blue dots), Esteban et al. 2005 (black dots), Rudolph et al. 2006 (green dots), Balser et al. 2011 (orange dots) for HII regions, and from Costa et al. 2004 (red dots) for PNe. The predictions are from the same models, but compared with data from HII regions and PNe. Also in this case and even more evidently, the model with only inside-out is not sufficient to explain the steep abundance gradient: we need a variable star formation efficiency or radial flows to explain the observational data. Therefore, a variable star formation efficiency or radial flows are important ingredients for obtaining a steeper gradient (see also Spitoni and Matteucci 2011).

4.3 Temporal evolution of the gradients

We focus here on the temporal evolution of the abundance gradients and show how abundance gradients vary with time in the various scenarios. In Fig. 6, we show the temporal evolution of the radial abundance gradient for Mg. The predictions are from models 2IM A, IIM A, IIM B, IIM C and IIM D at different time (2 Gyr, 7 Gyr and 13.6 Gyr).

In the first panel, we show the predictions of the 2IM A. We can see that the two-infall model predicts a gradient inversion at early times: the gradient has a positive slope (at 2 Gyr), and then it flattens and reaches a slightly negative slope (at 13.6 Gyr). This gradient inversion was observationally claimed by Cresci et al. (2010), who have found an inversion of the O gradient at redshift z=3 in some Lyman-break galaxies. They showed that the O abundance decreases going toward the Galactic center, thus producing a positive gradient. This inversion was already noted theoretically by Chiappini et al. (2001) and studied by Mott et al. (2013) in terms of the two-infall model. This is a characteristic feature of the two-infall model, with its second infall episode of primordial gas which dilutes the gas in the inner regions in spite of the chemical enrichment.

In the second panel, we show the predictions of the IIM A. At variance with the previous case, in the one-infall approach we have no gradient inversion due to the fact that we have no second infall episode of primordial gas which provokes the dilution. The slope of the gradient slightly steepens with time, but the effects is not noticeable, since in the IIM A we assume only inside-out.

In the third panel, we show the predictions of IIM C with inside-out and also radial gas flows. The models with radial gas flows predict that the gradient steepens noticeably in time as was found by Mott et al. (2013), but then we have no gradient inversion because it is a one-infall model and not a two-infall one.

In the fourth panel, we show the predictions of the IIM B with inside-out and also variable star formation efficiency. In this case, the temporal evolution of the gradient is different than in the previous case and the gradient flattens in time. This result is in agreement with other studies which predict a flattening of the gradient with time (Prantzos and Boissier 2000; Molla and Diaz 2005; Vincenzo and Kobayashi 2018; Minchev et al. 2018).

Finally, in the last panel, we show the predictions of the IIM D with inside-out and also both the variable star formation efficiency and radial gas flows. We can see that the gradient starts steep due to the variable star formation efficiency at different distances and then it becomes even steeper in time due to the effect of radial gas flows, which becomes dominant at later time.

The discrepancy between different model predictions is due to the fact that the gas chemical evolution is very sensitive to the prescriptions of the physical processes that lead to the enrichment of inner and outer discs, and the flattening or steepening of gradients in time depends on the interplay between infall rate and star formation rate along the Galactic disc. Different recipes of the star formation process or gas accretion mechanisms can provide very different predictions for the abundance gradients. Only future observations of high redshift gradients will shed light on this point.

5 CONCLUSIONS

In this paper, we have studied the formation and chemical evolution of the Milky Way discs with particular focus on the abundance patterns at different Galactocentric distances, the present-time abundance gradients along the disc and the temporal evolution of abundance gradients. We have considered the chemical evolution models developed by Grisoni et al. (2017) for the solar neighborhood, both the two-infall and the one-infall, and we have extended our analysis to the other Galactocentric distances. In particular, we have examined the processes which mainly influence the formation of the Galactic thin disc: i) the inside-out scenario for the formation of the Galactic thin disc, ii) a variable star formation efficiency (SFE), and iii) radial gas flows along
the Galactic disc. Our main conclusions are as follows.

- As regard to the abundance patterns (in particular [Mg/Fe] vs. [Fe/H]) at different Galactocentric distances, the inside-out scenario for the thin disc is a key element, but provides only a slight difference between the various tracks at different radii and so it is not sufficient to explain the data at various radii. In order to have a more significant spread among the various tracks, we need further ingredients such as a variable star formation efficiency or radial gas flows: the variable star formation efficiency produces a spread at lower metallicities, whereas the radial gas flows become significant at higher ones. The case with a variable star formation efficiency provides a very good agreement with the observational data, in particular for the outer radii.

- Also concerning the present-day abundance gradients along the Galactic thin disc, the inside-out scenario provides a too flat gradient and cannot explain the observational data, neither of Cepheids, open clusters, PNe and HII regions which show a steeper gradient. To recover the steeper gradient, we need the variable star formation efficiency or radial gas flows.

- As regard to the temporal evolution of abundance gradients, the one-infall model with only inside-out or radial gas flows predicts a steepening of the gradient with time, whereas the case with variable star formation efficiency predicts a flattening of the gradient with time. In the case of the two-infall model, we predict a gradient inversion which is due to the dilution of the second infall episode of primordial gas, an effect not seen in the one-infall case.

- In our scenario, the Galactic thick disc formed on a very short timescale ($\tau = 0.1$ Gyr, see Grisoni et al. 2017), which is assumed to be constant with radius. Therefore, there is no inside-out scenario for the thick disc, in agreement with Haywood et al. (2018).

In summary, we conclude that the inside-out scenario is a key ingredient for the formation of Galactic discs, but cannot be the only one to explain abundance patterns at different Galactocentric distances and abundance gradients. Further ingredients are needed, such as radial gas flows and variable star formation efficiency. In particular, the model with a variable star formation efficiency is in very good agreement with the observational data, both the abundance patterns at different Galactocentric distances and abundance gradients. The model with variable star formation efficiency predicts a flattening of the gradient with time, which is in agreement with other chemical evolution models and cosmological simulations (Prantzos and Boissier 2000; Molla and Diaz 2005; Vincenzo and Kobayashi 2018; Minchev et al. 2018), but it cannot predict the gradient inversion at high redshift.

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