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Constraining the formation of the Milky Way: Ages

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Abstract. We present a new approach for studying the chemodynamical evolution of the Milky Way, which combines a thin disk chemical evolution model with the dynamics from N-body simulation of a galaxy with properties similar to those of our Galaxy. A cosmological re-simulation is used as a surrogate in order to extract ∼11 Gyrs of self-consistent dynamical evolution. We are then in a position to quantify the impact of radial migration at the Solar Vicinity. We find that the distribution of birth radii, r0, of stars ending up in a solar neighborhood-like location after ∼11 Gyr of evolution peaks around r0 = 6 kpc due to radial migration. A wide range of birth radii is seen for different age groups. The strongest effect from radial migration is found for the oldest stars and it is connected to an early merger phase typical from cosmological simulations. We find that while the low-end in our simulated solar vicinity metallicity distribution is composed by stars with a wide range of birth radii, the tail at larger metallicities (0.25 <[Fe/H]< 0.6) results almost exclusively from stars with 3 < r0 < 5 kpc. This is the region just inside the bar's corotation (CR), which is where the strongest outward radial migration occurs. The fraction of stars in this tail can, therefore, be related to the bar's dynamical properties, such as its strength, pattern speed and time evolution/formation. We show that one of the main observational constraints of this kind of models is the time variation of the abundance gradients in the disk. The most important outcome of our chemodynamical model is that, although we used only a thin-disc chemical evolution model, the oldest stars that are now in the solar vicinity show several of the properties usually attributed to the Galactic thick disc. In other words, in our model the MW "thick disc" emerges naturally from stars migrating from the inner disc very early on due to strong merger activity in the first couple of Gyr of disc formation, followed by further radial migration driven by the bar and spirals at later times. These results will be extended to other radius bins and more chemical elements in order to provide testable predictions once more precise information on ages and distances would become available (with Gaia, asteroseismology and future surveys such as 4MOST).

1. INTRODUCTION

The power of Galactic Archaeology has been threatened both by observational and theoretical results, showing that stars most probably move away from their birthplaces, i.e, migrate radially. Observational signatures of this radial migration (or mixing) have been reported in the literature since the 1970's, with the pioneering works by [11] and [12]. Grenon identified an old population of *super-metal-rich stars* (hereafter SMR), presently at the Solar vicinity, but with kinematics and abundance properties indicative of an origin in the inner Galactic disc (see also [30]). These results were extended by [13], who showed, by re-analyzing the Geneva-Copenhagen Survey data, that the low- and high-metallicity tails of the thin disc are populated by objects, whose orbital properties suggest origin in the outer and inner Galactic disc, respectively. In particular, the so-called SMR stars show metallicities which exceed

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the present day ISM and those of young stars at the solar vicinity. As discussed by [8] (see also Table 5 of [1]), the metallicity at the solar vicinity is not expected to increase much since the Sun's formation, i.e., in the last ∼4 Gyr, due to the rather inefficient star formation rate at the solar radius during this period, combined with continuous gas infall into the disc. Hence, as summarized in [9], pure chemical evolution models for the MW thin disc cannot explain stars more metal rich than ∼0.2 dex with respect to the Sun and radial migration has to be invoked. N-body simulations have also long shown that radial migration is unavoidable (e.g. [24], [28], [25], [23], [21]), although its main driver is still a hot debated topic in the literature (see [5], [20], and references therein).

It thus seems that the only way to advance in this field is by developing chemodynamical models tailored to the Milky Way (MW), in the cosmological framework. Only then, a meaningful comparison with the large amounts of current and forthcoming observational data (RAVE, SEGUE, APOGEE, Gaia-ESO and future planned surveys such as 4MOST), can be carried out. This was the main goal of the our work Minchev, Chiappini and Martig [19] (where more details can be found), namely, to develop a chemodynamical model for the MW, to be able to quantify the importance of radial mixing throughout the evolution of our Galaxy.

2. A NEW APPROACH FOR BUILDING A CHEMO-DYNAMICAL MODEL

Despite the recent advances in the general field of galaxy formation and evolution, there are currently no self-consistent simulations, that have the level of chemical implementation required for making detailed chemical predictions. This situation has led us to look for a novel way to approach this complex problem. We will show that our new approach works encouragingly well, explaining not only current observations, but also leading to a more clear picture regarding the nature of the MW thick disc.

The novelty of our approach is: a) we assume that each particle in our N-body simulation represents one star. Dynamically, this is a good assumption, since the stellar dynamics is collisionless; and b) we implement the exact star formation history and chemical enrichment from a thin disk chemical model into our simulated galactic disc. This is done by, at each time output, randomly selecting newly born stars in a way to match the star formation history corresponding to our chemical evolution model, at each radial bin. In this way we are able to insert the dynamics of our simulation into the chemical model.

For the chemical evolution model we assume a thin disk only model. For a detailed description see [19]. Here we just recall a few important points, namely: a) our code follows in detail a large number of chemical evolution elements by properly taking into account the stellar lifetimes and the type Ia supernovae rate; b) we assume an exponentially decreasing gas accretion in time, which, combined with a star formation law dependent on the gas density, produces a star formation history for the solar vicinity which is agreement with observations. In other words, given our star formation history, we predict the observed gas and mass stellar densities at the present time; c) our star formation history leads to predicted type Ia, type II and deuterium abundances in agreement with observations. Outside the solar vicinity we have much less constraints and this is the reason why different chemical evolution models that otherwise agree at the present time, diverge in their predictions of, for instance, the abundance gradients evolution (see [7] for a discussion). As the purpose here is to use a pure thin disk chemistry, we assume a chemical evolution model without pre-enrichment from a thick disk, but just primordial composition gas accretion, which as a consequence leads to gradients which flatten with time, similar to other pure thin-disk chemical evolution models in the literature (e.g. [14]). The impact of other alternative chemical evolution models will be studied in forthcoming papers.

The simulation used in this work is part of a suite of numerical experiments first presented by [17], where the authors studied the evolution of 33 simulated galaxies from $z = 5$ to $z = 0$ using the zoom-in technique described in [16]. The galaxy we have chosen has a number of properties consistent with the MW, namely: *(i)* it has an approximately flat rotation curve with a circular velocity $V_c \sim 210\,\mathrm{km/s}$ at 8 kpc (slightly lower than the MW); *(ii)* the bulge is relatively small, with a bulge-to-total ratio of $\sim 1/5$; *(iii)* it contains an intermediate size bar at the final simulation time, which develops early on and grows

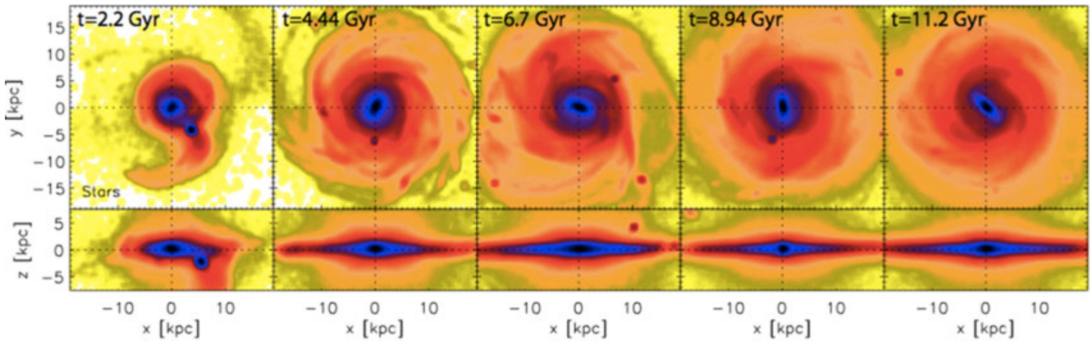

Figure 1. Face-on (upper row) and edge-on (bottom row) density maps of the stellar component of the simulated galaxy for different times, as indicated. The contour spacing is logarithmic (see [19] for details).

in strength during the disc evolution; *(iv)* the disc grows self-consistently as the result of cosmological gas accretion from filaments and (a small number of) early-on gas-rich mergers, as well as merger debris, with a last significant merger concluding $\sim 9-8$ Gyr ago; *(v)* the disc gas-to-total mass ratio at the final time is $\sim$0.12, consistent with the estimate of $\sim$0.14 for the solar vicinity, and *(vi)* the radial and vertical velocity dispersions at $r \approx 8$ kpc are $\sim$40 and $\sim$20 km/s, in good agreement with observations. Maps of the density distribution of our simulated galaxy, at different times, are shown in Fig. 1. A full description of our new approach can be found in Minchev, Chiappini and Martig [19]. Here we just concentrate on its limitations and advantages.

The main limitations of our approach from the chemical-evolution point of view are: *i)* we neglect radial gas flows and the SN-driven galactic winds, possibly resulting in flatter abundance gradients than we currently find. In a forthcoming paper, we show that gas flows are important mostly at the disc boundaries and do not affect significantly the present results, *ii)* we assume that stars do not contribute to the chemical evolution outside the zone where they are born, but either contribute only to the chemical enrichment within 2 kpc from their birth place, or never die. The latter assumption is valid for most of the stars because (a) the massive stars die essentially where they were born, due to their short lifetimes and (b) low mass stars live longer than the age of the galaxy (never die). We do not expect this simplification to affect our results by more than 10% for chemical elements made in low and intermediate mass stars, and even less for those coming from massive stars, as it is the case for Oxygen.

From the dynamical point of view the limitations are: *i)* the resampling of the simulation star formation history according to the chemical evolution model, and *ii)* the difference between the gas-to-total mass ratio expected from the chemical model and attained by the simulation. Although the discs in both the chemical and dynamical models grow inside-out, there are some offsets at particular times. These differences in the star formation histories are unavoidable, since the chemical and dynamical models are not tuned to reproduce the same star formation, although they are quite similar for most of the evolution. While the difference between the assumed (chemical model) and actual (dynamical model) stellar and gas densities can introduce some inconsistencies in the resulting dynamics (see details in [19]), this would generally have the tendency of bringing more stars from the inner disc out, due to a larger bar expected at earlier times. As it will become clear later, a larger fraction of old stars coming from the bar's CR region to the solar vicinity would only strengthen our results.

Overall, we do not anticipate the simplifications of our approach to affect significantly any of our results. On the other hand, what we gain with the above simplifications is a new tool to study the chemodynamics of our Galaxy, which is complementary to fully self-consistent models, and where the overall complex problem of galaxy assembly and evolution can be understood by pieces (i.e., same chemistry applied to different simulations and different chemistry applied to the same simulation). We

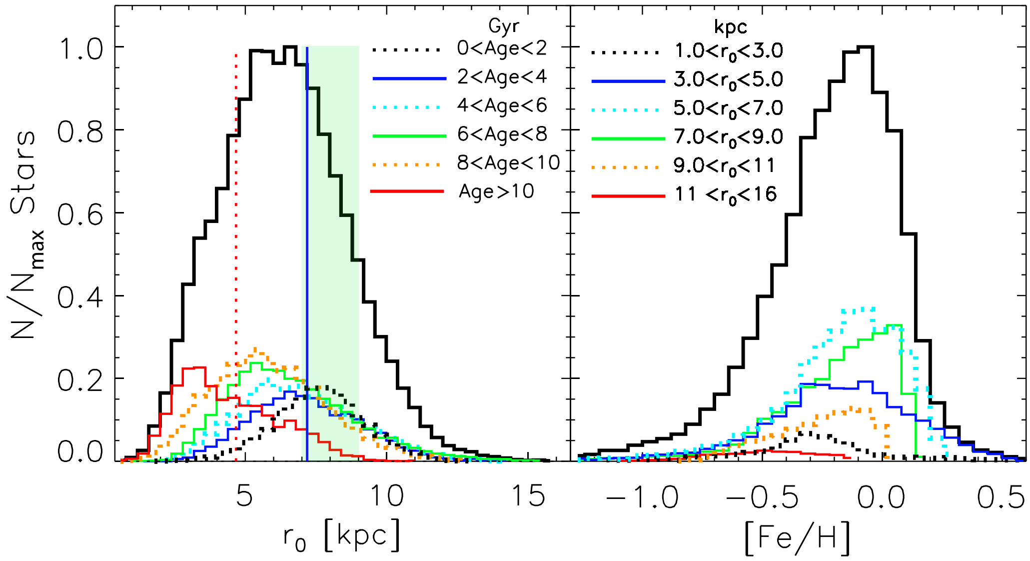

Figure 2. *Left*: Birth radii of stars ending up in the "solar" radius (green bin) at the final simulation time. The solid black curve plots the total r_0-distribution, while the color-coded curves show the distributions of stars in six different age groups, as indicated. The dotted-red and solid-blue vertical lines indicate the positions of the bar's CR and OLR at the final simulation time. A large fraction of old stars comes from the inner disc, including from inside the CR. *Right*: [Fe/H] distributions for stars ending up in the green bin (left) binned by birth radii in six groups, as indicated. The total distribution is shown by the solid black curve. The importance of the bar's CR is seen in the large fraction of stars with $3 < r_0 < 5$ kpc (blue line).

anticipate that this new approach will also be very useful to gain insights that can later be used in fully self-consistent simulations. Finally, our approach certainly represents an improvement over previous models parameterized chemodynamical models (e.g. [27]), as we extract dynamics from a state-of-the-art simulation of a disc formation and use it to fuse with a chemical model tailored for the MW.

3. IMPACT ON THE MAIN CONSTRAINTS OF CHEMICAL EVOLUTION MODELS: THE AMR, ABUNDANCE GRADIENTS AND [O/FE] VS. [FE/H]

Here we focus on the main results of our chemodynamical model that are more related to age and chemistry.

The distribution of birth radii, r_0, of stars ending up in a solar neighborhood-like location after ~11 Gyr of evolution peaks around $r_0 = 6$ kpc due to radial migration (left panel of Fig. 2). The strongest effect from radial migration is found for the oldest stars and it is connected to an early merger phase in our simulation, where the last important merger happened ~9 Gyr ago. Locally born stars of all ages can be found in the solar neighborhood. While a wide range of birth radii is seen for different age groups, the majority of the youngest stars are born at, or close to, the solar neighborhood bin. While the low-end in our simulated metallicity distribution is composed by stars with a wide range of birth radii, the tail at larger metallicities (0.25 <[Fe/H]< 0.6) results almost exclusively from stars with $3 < r_0 < 5$ kpc. This is the region just inside the bar's CR, which is where the strongest outward radial migration occurs. The fraction of stars in this tail can, therefore, be related to the bar's dynamical properties, such as its strength, pattern speed and time evolution/formation. For this reason it is crucial to have a better knowledge of the properties of the Milky Way bar at present time (see Section 5).

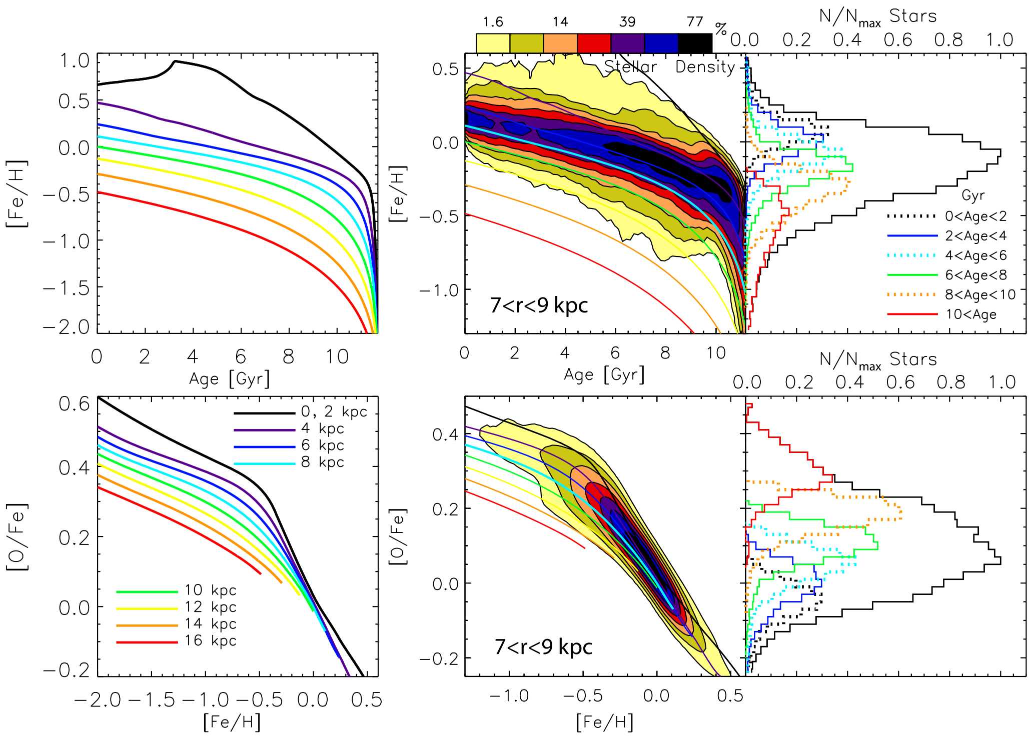

Figure 3. *Top*: The left panel plots age versus [Fe/H] for different radii, resulting from our input chemical model (left). The middle panel shows stellar density contours of the resulting relation after fusing with dynamics, for the "solar" radius ($7 < r < 9$ kpc). The overlaid lines show the input chemistry for the same radii as in the left. The right panel plots the metallicity distributions for different age bins. *Bottom*: Same as above but for the [Fe/H]-[O/Fe] relation. There is some contribution from stars born ~2 kpc and hardly any from $r > 14$ kpc, consistent with the birth radii distributions shown in Fig. 2.

Examining the effect on the age-metallicity relation (AMR), we find that some flattening is observed, mostly for ages $\gtrsim 5$ Gyr (Fig. 3). More interestingly, although significant radial mixing is present, a slope in the AMR is preserved, with a scatter compatible with recent observational work (e.g. [6]).

We found a strong flattening in the [Fe/H] radial profiles of the older populations, however, the younger ones are much less affected (see Fig. 4). For stars younger than 2 Gyr the final gradient is very similar to the initial one out to ~12 kpc, justifying its use as a constraint for our chemical model.We predict that the [O/Fe] radial profiles are essentially preserved for the chemical model we use. The [O/Fe] profiles for different age groups result straightforwardly from the adopted variation of the infall-law with radius (and hence the SFHs at different positions) and, thus, provide a way to constrain different chemical evolution models. In the near future, these would be possible to measure by combining the good distances and ages expected from the CoRoT mission (see [18] for a first step in this direction), with abundance ratios obtained by spectroscopic follow-up surveys. For the young populations, this should be already possible to be obtained from the observations of open clusters, e.g., with the ongoing Gaia-ESO or APOGEE surveys.

We find no bimodality in the [Fe/H]-[O/Fe] stellar density distribution. However, when selecting particles according to kinematical criteria used in high-resolution samples to define thin and thick discs, we recover the observed discontinuity in the [O/Fe]-[Fe/H] plane (Fig. 5). This is in agreement with the recent observational results by [4], where a smooth [Fe/H]-[O/Fe] distribution was obtained, after correcting for the spectroscopic sampling of stellar sub-populations in the SEGUE survey. By separating

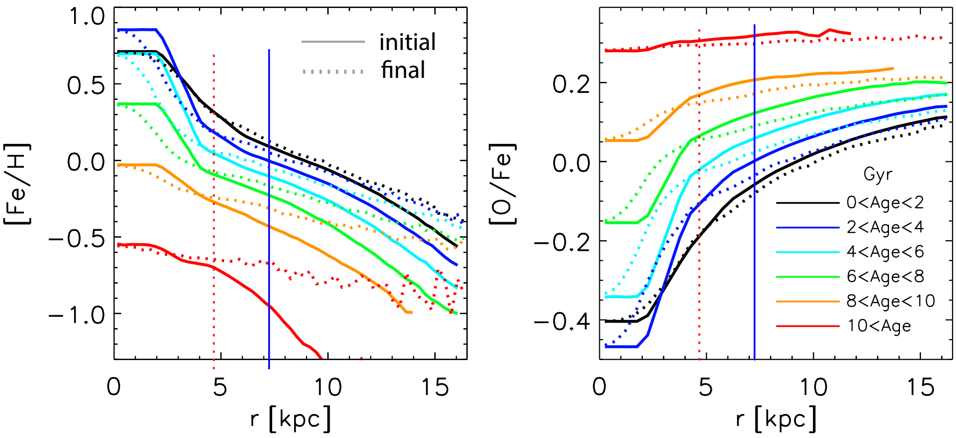

Figure 4. The effect on the initial [Fe/H] (top) and [O/Fe] (bottom) gradients for different stellar age groups. The solid and dotted color curves show the initial and final states, respectively. Note that, while strong flattening is observed for the older populations, the metallicity gradient for the youngest stars ($age < 2$) is hardly affected at $r \lesssim 12$ kpc, thus justifying the use of our chemical model, which uses this as a constraint.

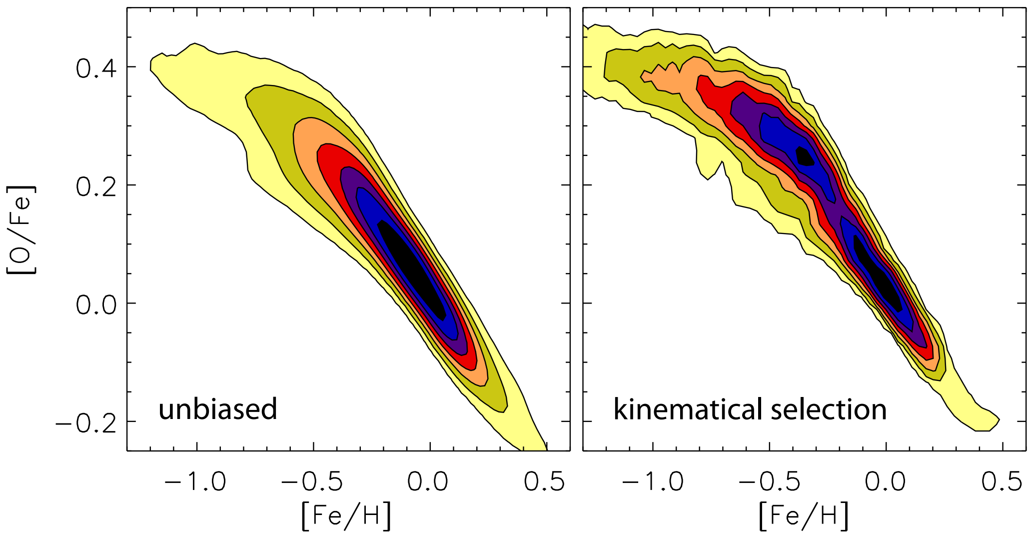

Figure 5. Selection effects can result in a bimodality in the [Fe/H]-[O/Fe] plane. The top panel show the unbiased stellar density distribution, as in Fig. 3. In the bottom plot we have applied the selection criteria used by [2].

our simulated local sample into narrow bins of age, [O/Fe], and [Fe/H], we found that the vertical scale-height of each component can be fitted well by a single exponential, with values growing with increasing age, increasing [O/Fe], and decreasing metallicity. The vertical velocity dispersions for each of these subpopulation was found to exhibit smooth variations with height above the disc plane, strongly flattening for old, high-[O/Fe], and metal-poor stars.

Due to the lack of good age estimates, the [α-elements/Fe] ratios, such as [O/Fe], are often used as proxies of age. To see how well age and [O/Fe] relations match, we plot in Fig. 6 the [O/Fe] ratio versus age for each population of same birth radii that are now found in the solar vicinity. The total relation is shown by the solid curve. [O/Fe] appears to follow age closely at the α-rich end, but is less

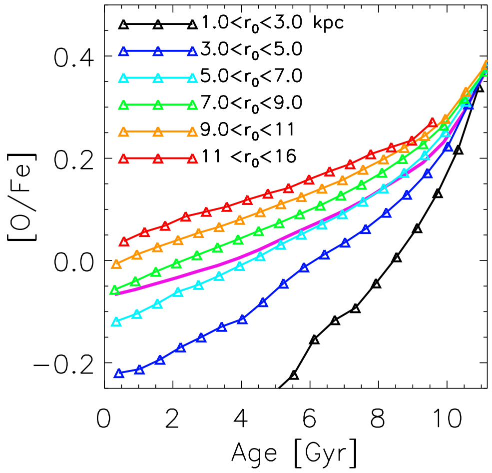

Figure 6. [O/Fe] versus age for different groups of particles with same birth radii, r0. The solid line represents the total relation found once all stars now located at the solar vicinity are combined.

sensible to age at low [O/Fe] values. Note that stars with [O/Fe]< -0.1 are born at $r_0 < 7$ kpc and have age $\lesssim 8$ Gyr, correlating inversely with birth radius. Therefore, the majority of stars with [O/Fe]< -0.1 currently in the local bin, should have ages< 4 Gyr. Such a mixture of ages would naturally result in higher velocity dispersions. Indeed, the mean σ_r and σ_z for stars of age < 4 Gyr (see Fig. 5 for the σ_z case), match well the corresponding, approximately constant, values at [O/Fe]< -0.1 in Fig. 6.

4. THE FORMATION OF THE THICK DISK

When focusing on the properties of the oldest stars in our model that at present time are found in the solar neighbourhood (age$\gtrsim$ 10 Gyr) we find:

- a metallicity distribution which peaks at [Fe/H]~ -0.5 and has a metal-poor tail down to [Fe/H]~ -1.3 (Fig. 3, upper right panel).
- [O/Fe]-values spanning the range $0.2 - 0.4$, with a peak around 0.3 (Fig. 3, lower right panel).
- a lag in the rotational velocity by $\sim$50 km/s compared to the young stars (Fig. 7, dashed red line).
- large velocity dispersions (Fig. 7 - red solid line).
- a large scale-height (see [20]).

All of these properties are strikingly reminiscent of what we call the "thick disc" of our Galaxy, despite the fact that we have used pure thin-disc chemistry. Within the frameworks of the model we present here, the MW thick disc has emerged from (i) stars born hot and heated by mergers at early times and (ii) radial migration (from mergers at early times and bar/spirals later on) transporting these old stars from the inner disc to the solar vicinity.

To illustrate this in a more clear way, we performed another model where we start the implementation with chemistry 2.7 Gyr later, thus avoiding the early massive merger phase. We then integrate the simulation for additional 2.7 Gyr so that we again have 11.2 Gyr of evolution. To keep the correct location with respect to the bar's resonances, we downscale the disc radius by a factor 2.1 to account for the bar's slowing down. Figure 7 shows a comparison of the vertical velocity dispersion, $\sigma_z(r)$ (solid lines), and rotational velocity, $V_\phi(r)$ (dashed lines) evolution resulting from the new realizations (black and blue lines) with our standard model (red curves). The oldest stars have σ_z about a factor of two smaller than when the merger is present. The maximum radial velocity dispersion values (not shown) also drop to $\sim$43 km/s, which is reflected in the higher V_ϕ-values. These smaller velocity dispersions

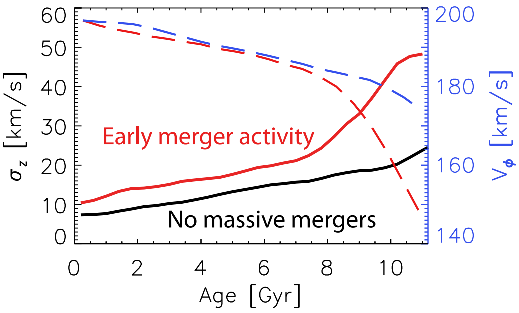

Figure 7. Vertical velocity dispersion $\sigma_z(r)$ (solid lines), and rotational velocity, $V_\phi(r)$ (dashed) evolution for a) our standard model, where an early merger phase plays an important role in the formation of the thick disk (red curves), and b) a model where the radial migration is driven essentially by internal evolution (dark and blue curves).

and rotational velocity difference between young and old stars is unlike the observed values in the solar neighborhood. This again suggests that an early phase of mergers is a crucial step in developing thick disks.

Such a conclusion is in agreement with most (seemingly contradicting) models of thick-disc formation, which expect contribution from only/mostly one of the following: (i) mergers, (ii) early formation in gas-rich, turbulent clumpy discs, or gas rich mergers, and (iii) radial migration driven by internal instabilities. A combination of these mechanisms working together is required, where strong heating and migration occurs early on form external perturbations (our case) and/or turbulent gas clumps, followed by radial migration taking over the disc dynamics at later times. Yes, mergers are important, but we also need radial migration (unavoidable if a bar, spiral structure and/or mergers are present) to transport out old, hot stars, with thick-disc chemical characteristics. Yes, migration is important, but the old stars need to be "preheated" by being born hot and/or were heated by mergers at high redshift (also unavoidable from our current understanding of cosmology). The high stellar birth velocity dispersions at high redshift we find in our simulation (∼30–50 km/s) is consistent with recent works [10] [3]. An important dynamical consequence of this is that the disc becomes less susceptible to satellite perturbations (common at high redshift), making it easier to survive until today.

A different conclusion has been reached by [27] who proposed that pure stellar radial migration can provide a mechanism for the formation of thick discs. They have assumed a certain migration efficiency and chemical enrichment scheme in order to fit the current ISM gradient in the MW, the metallicity distribute function (MDF), and the stellar velocity dispersions. This work suggested for the first time that galactic discs can be heated by radial migration, thus, excluding the need for merger activity during the MW disc evolution. It is important to note that the heating in this model was achieved by the explicit assumption that migrating stars preserved their vertical energy, thus outward migrators populated a thick disc component. Following [27], the increase of disc thickness with time found in the simulation by [25] was attributed to migration in the work by [15].

However, how exactly radial migration affects disc thickening in dynamical models had not been demonstrated until the work by [22] where it was shown for the first time that the conserved quantity for a migrating population is not the energy, but the vertical action. More recently, [20] presented an extensive study of six galaxy models using two completely different simulation techniques to show that internally driven radial migration does not contribute significantly to the increase in disc thickness (except in the disc outskirts), regardless of the migration efficiency. The authors showed that, while outward migrators contribute to some disk heating, inward ones cool the disk so the overall effect is negligible for most of the disk extent. It was thus concluded that radial migration in the absence of external perturbations fails to produce discs thick enough to explain observations and results instead in substantial flaring.

The recent work by [26] also considered the effect of migration on disc thickening, by analyzing the N-body/SPH simulation previously studied by [25] and [15]. The authors concluded that radial migration and internal heating thicken coeval stellar populations by comparable amounts, thus challenging the results by [20]. However, in [26]'s analysis the authors focused only on the outward migrators, i.e., the ones which contribute to some disc thickening in agreement with what was found in [20]. As shown in the latter paper, it is the overall contribution from migrators that should be considered in a given radial bin, not the time evolution of a given population, if one were to tackle the question of how much migrators contribute to the thickening of the disc. Notice that both groups find a similar radial variation of the disk scale height, indicating that when all the migrators are taken into account, flaring thus result and thickening is not enough to make a thick disk.

It is clear that more observational constraints are needed in order to shed light on the disk thickening mechanism and the role of the bar and mergers in the formation and evolution history of our Galaxy. So far most of the observational constraints are confined to a small volume around our Sun. A first step in overcoming this limitation was taken by RAVE, SEGUE, and APOGEE which sample a larger region of our Galaxy (although most of the data is still confined to ∼2–3 kpc from us).

5. FUTURE OBSERVATIONS: WHAT WILL WE LEARN?

Tighter constraints on the formation of the MW disk can only be obtained through kinematical and metallicity data, covering as large a disk area as possible. In the near future, Gaia will deliver large astrometric accuracies for a large volume of our galaxy, providing direct distance estimates out to 10 kpc with roughly 10% accuracy. However, Gaia needs to be complemented by multi-object spectroscopy. This is one of the aims of the 4-m multi-object spectroscopic telescope (4MOST) to be installed at the VISTA telescope, currently in a conceptual design selection phase for ESO, with a decision in Spring 2013.

With 4MOST we aim at maximizing the scientific return of Gaia, thanks to additional chemical abundance information for stars fainter than ∼14 mag, and radial velocities with a precision better then 2 km/s for stars in the $14 < V < 20$ range. By coupling Gaia proper motions and parallaxes with radial velocity, metallicity and detailed chemical abundances information provided by the 4MOST low- ($R = 5000$) and high-resolution ($R = 20\,000$) modes, we will be in a position to fully trace the position-metallicity-velocity space throughout the disk, finally providing stringent constraints to chemodynamical models of the Milky Way. With its large number of fibers (around 1600 for low-resolution and 800 for high-resolution), 4MOST will be able to obtain spectra of around 30 million objects, with large impact both in Galactic and extra-galactic sciences.

Finally, asteroseismology can also bring crucial information to this field. Thanks to asteroseismology, solar-like pulsating red giants turn out to represent a well-populated class of accurate distance indicators, spanning a large age range, which can be used to map and date the Galactic disc in the regions probed by observations made by the CoRoT and *Kepler* space telescopes. When combined with spectroscopic constraints, one can estimate the mass and radius of these evolved stasr and hence obtain also their distances and ages. This data will be very important in providing crucial constraints not only onthe the age-velocity and age-metallicity relations at different at different Galactocentric radii and heights from the plane, but also on the abundance gradients and their time evolution.

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