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Abstract: We analyse the structure and chemical enrichment of a Milky Way-like galaxy with a stellar mass of $2 \times 10^{10} \, M_{\odot}$, formed in a cosmological hydrodynamical simulation. It is disc dominated with a flat rotation curve, and has a disc scalelength similar to the Milky Way’s, but a velocity dispersion that is ~50 per cent higher. Examining stars in narrow $[\text{Fe/H}]$ and $[\alpha/\text{Fe}]$ abundance ranges, we find remarkable qualitative agreement between this simulation and observations. (a) The old stars lie in a thickened distribution with a short scalelength, while the young stars form a thinner disc, with scalelengths decreasing, as $[\text{Fe/H}]$ increases. (b) Consequently, there is a distinct outward metallicity gradient. (c) Mono-abundance populations exist with a continuous distribution of scaleheights (from thin to thick). However, the simulated galaxy has a distinct and substantive very thick disc ($h_z \sim 1.5 \, \text{kpc}$), not seen in the Milky Way. The broad agreement between simulations and observations allows us to test the validity of observational proxies used in the literature: we find in the simulation that mono-abundance populations are good proxies for single age populations (<1 Gyr) for most abundances.

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MaGICC thick disc – I. Comparing a simulated disc formed with stellar feedback to the Milky Way

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ABSTRACT
We analyse the structure and chemical enrichment of a Milky Way-like galaxy with a stellar mass of $2 \times 10^{10} M_\odot$, formed in a cosmological hydrodynamical simulation. It is disc dominated with a flat rotation curve, and has a disc scalelength similar to the Milky Way’s, but a velocity dispersion that is $\sim 50$ per cent higher. Examining stars in narrow $[\text{Fe/H}]$ and $[\alpha/\text{Fe}]$ abundance ranges, we find remarkable qualitative agreement between this simulation and observations. (a) The old stars lie in a thickened distribution with a short scalelength, while the young stars form a thinner disc, with scalelengths decreasing, as $[\text{Fe/H}]$ increases. (b) Consequently, there is a distinct outward metallicity gradient. (c) Mono-abundance populations exist with a continuous distribution of scaleheights (from thin to thick). However, the simulated galaxy has a distinct and substantive very thick disc ($h_z \sim 1.5$ kpc), not seen in the Milky Way. The broad agreement between simulations and observations allows us to test the validity of observational proxies used in the literature: we find in the simulation that mono-abundance populations are good proxies for single age populations ($<1$ Gyr) for most abundances.

Key words: hydrodynamics – galaxies: formation – galaxies: structure.

1 INTRODUCTION
Ever since the discovery that the luminosity distribution of edge-on S0 galaxies could be well fit by including a thick and thin disc component (Burstein 1979), evidence has accumulated for the ubiquity of thick disc components in galaxies. van der Kruit & Searle (1981) found that the disc of the late-type galaxy NGC 891 required three separate components to fit its vertical profile, a bulge, thick and thin disc. Number counts of dwarf stars in the Solar Neighbourhood found that the Milky Way disc also was well fit using two distinct scaleheights (Gilmore & Reid 1983). Subsequent observations found that every observed disc galaxy is characterized by more than one single vertical scaleheight, but are well fit by two components (van der Kruit & Searle 1982; Dalcanton & Bernstein 2000, 2002; Seth, Dalcanton & de Jong 2005; Yoachim & Dalcanton 2006; de Jong et al. 2007). Recently, large surveys have allowed more extensive examinations of the Milky Way disc structure. With the Sloan Digital Sky Survey, Jurić et al. (2008) confirmed that the spatial structure of the Galactic disc can be well described with two distinct scaleheights.

In addition to the density structure of the stellar discs, observations have also examined the chemical abundances of the stars that make up different sub-populations in the Milky Way. A number of spectroscopic studies have found distinct stellar abundances in stars that are kinematically associated with the thick disc (Majewski 1993; Gilmore, Wyse & Jones 1995; Fuhrmann 1998; Chiba & Beers 2000; Prochaska et al. 2000; Bensby, Feltzing & Lundström 2003; Bensby et al. 2005; Reddy, Lambert & Allende Prieto 2006; Wyse et al. 2006; Fuhrmann 2008; Ruchti et al. 2010). Stars in the thick disc components are more $\alpha$-enhanced than kinematically cooler thin disc stars. It is reasonable to assume that $\alpha$-enhanced stars are older since they formed from gas not yet polluted with the iron rich ejecta of longer lived Type Ia supernovae.

Spectroscopic surveys have begun to assemble more extensive samples and have thus allowed more detailed comparisons between stellar abundance, disc structure and kinematics. The Geneva–Copenhagen Survey found the largest radial $[\text{Fe/H}]$ gradient in their youngest age group ($<1.5$ Gyr), and progressively
less gradient in their older age groups (see fig. 29 of Nordström et al. 2004). The Sloan Digital Sky Survey found that there is a smooth transition from the metallicity of thick to thin disc stars (Ivezić et al. 2008), which is also noted in spectroscopic studies (Norris 1987; Haywood et al. 2013; Kordopatis et al. 2013). Navarro et al. (2011) used a compilation of stellar spectra from the literature to find a separation between kinematically distinct thick and thin disc populations when selected based on their position in the [α/Fe]−[Fe/H] plane.

One of the largest surveys to date, Sloan Extension for Galactic Understanding and Exploration (SEGUE), compiled ~50 000 spectra from stars in the solar neighbourhood (Yanny et al. 2009). Bovy et al. (2012b, hereafter B12) studied a large sample of these and divided the stars into mono-abundance populations (hereafter, MAPs) each of which span a small range in both [α/Fe] and [Fe/H]. B12 studied each MAP individually to determine how the structural and kinematic disc properties evolved as a function of element abundance. B12 made maximum likelihood fits of the disc scaleheights and lengths for each MAP and found that each MAP’s structure can be described using a single scalelength that varies systematically with both [α/Fe] and [Fe/H]. The α-enhanced MAPs had taller scaleheights and shorter scalelengths than MAPs with solar abundance patterns. This difference implies that the oldest stars formed with shorter scalelengths when the disc was young. Additionally, the spatial structure of the Galactic disc can be well described by choosing MAPs of approximately solar [α/Fe] and showing how their scalelengths depend on [Fe/H]: more metal-rich MAPs have shorter scalelengths than [Fe/H]-poor ones, which reiterates the presence of a significant radial [Fe/H] gradient in the thin, young disc stellar population. Finally, the surface density contributions of the scaleheights from these populations smoothly decreases from thin to thick MAPs, which lead to the conclusion that the Milky Way is not composed of distinct thin and thick disc populations (Bovy, Rix & Hogg 2012a), a result predicted in theoretical work in which thick discs are the result of radial migration (Schonrich & Binney 2009; Loebman et al. 2011). The continuous distribution seems to imply that the thick disc populations did not originate from one significant calamitous event.

These exquisite data present a new opportunity for comparing models of thick disc formation to observations. There is a long history of studying the effects of satellite interactions on disc thickening (e.g. Kazantzidis et al. 2008, 2009; Villalobos, Kazantzidis & Helmi 2010, and references therein). Most such studies have used pure collisionless dynamic simulations and have not included star formation or chemical enrichment modelling, so have focused their comparisons on kinematics and structure, but not chemical enrichment or co-eval stellar populations. Recently, Minchev, Chiappini & Martig (2012) combined a chemical evolution model with sticky particle hydrodynamic simulations and found good agreement between the simulations and observations. Simulations that have tried to grow discs in a cosmological context have long found a messy beginning for the discs characterized by high early velocity dispersions with thick scaleheights (Brook et al. 2004, 2005) that only settle into thin configurations after evolution (Brook et al. 2006). Such cosmological hydrodynamic simulations now include star formation and self-consistent chemical evolution that allow more advanced comparisons with observations. Indeed, Brook et al. (2012a) made preliminary comparisons of a simulation similar to the one analysed here and found good general agreement with observations. Bird et al. (2013) examined the evolution of the disc in the high-resolution Eris simulation and found that it formed from the inside out and from an initial thick stellar distribution to something thinner.

In this paper, we compare a state-of-the-art disc galaxy formation simulation that resembles the Milky Way in its gross properties to the intricate chemo-dynamical patterns observed in the Galactic disc. If our simulations are realistic, we can explore the validity of the assumptions underlying the interpretation of observations like the assumption that MAPs are comprised of roughly ‘co-eval’ stars.

The simulated galaxy we study here is drawn from the Making Galaxies in a Cosmological Context (MaGICC) project, which simulates galaxies constrained to match the stellar mass–halo mass relationship defined in Moster, Naab & White (2013). The MaGICC simulations use supernova feedback and early (pre-supernova) stellar feedback to limit star formation to yield the present-day stellar mass prescribed by the abundance matching technique. The consequence of the early stellar feedback is to delay star formation in a Milky Way mass galaxy from the typical burst seen in simulations at $z = 4$ to a much flatter star formation history that peaks after two gas rich minor mergers that happen at $z = 1$ (Stinson et al. 2013). This history corresponds to a stellar mass to halo mass ratio that evolves similarly to what is found using abundance matching for high-redshift luminosity functions (Behroozi, Wechsler & Conroy 2013; Moster et al. 2013). Star formation is reduced because early stellar feedback maintains gas at 10 000 K and prevents gas from reaching the central 2 kpc of the galaxy (Stinson et al. 2013) and supernova feedback ejects the low angular momentum material that would normally create a massive bulge (Brook et al. 2012b). The resulting galaxy has a flat rotation curve and an exponential surface brightness profile with a scalelength of 4 kpc.

This early stellar feedback has a number of other impacts on galaxy formation. It drives metal-rich outflows that create gaseous haloes that match observations of O VI in the circum-galactic medium of star-forming galaxies (Stinson et al. 2012). It can also expand the inner dark matter density profile of dark matter in galaxies up to nearly $L^*$, producing dark matter density ‘cores’ (Macciò et al. 2012). Brook et al. (2012a) compared four simulated dwarf galaxies with observations and found that all simulations resulted in good matches to the observed scalelengths, luminosities and gas fractions.

In what follows, we present in Section 3 a quantitative study of the disc structure of the simulated L* galaxy, g1536 that was originally described in Stinson et al. (2013), but is briefly reviewed in Section 2 along with the physics used in the simulation. In Section 4, we show how the disc structure of the simulations compares with observations. In particular, we compare the correlations between scaleheights and lengths and chemical abundances, [α/Fe] and [Fe/H], and the mass-weighted disc scaleheight distribution.

2 METHODS

2.1 Simulations

We use g1536, a cosmological zoom simulation drawn from the McMaster Unbiased Galaxy Simulations. The simulation starts at $z = 99$ from a cosmologically motivated matter distribution based on Wilkinson Microwave Anisotropy Probe 3 (Spergel et al. 2007); see Stinson et al. (2010) for a complete description of the creation of the initial conditions. It includes metallicity-dependent gas cooling, star formation and a detailed chemical enrichment model that allows us to make a comprehensive comparison with observations of the Milky Way.

g1536 has a virial mass of $7 \times 10^{11} M_\odot$, a spin parameter of 0.017 and a last major merger at $z = 2.9$, corresponding to a stellar age of $\sim$10 Gyr. The mass of the Milky Way dark matter halo
is uncertain, with values from $7 \times 10^{11} \, M_\odot$ to $1.4 \times 10^{12} \, M_\odot$ (Klypin, Zhao & Somerville 2002; Xue et al. 2008; Bovy et al. 2012c) having been determined using a variety of means. $g_{1536}$ is on the low end of this mass range, and thus may not make a perfect comparison to the Milky Way. However, a comparison may give an idea of which physical processes are important for shaping the structure of a galaxy disc. The merger history of $g_{1536}$ is relatively quiet, which may also be the case for the Milky Way (Hammer et al. 2007). The mergers that do accrete on to the galaxy follow prograde orbits. Thus, $g_{1536}$ maintains a disc on a relatively constant spin axis orientation throughout its evolution.

The simulation uses the smoothed particle hydrodynamics code GASELNE (Wadsley, Stadel & Quinn 2004). Details of the physics used in the MaGICC project are detailed in Stinson et al. (2013). Briefly, stars are formed from gas cooler than $T_{\text{max}} = 1.5 \times 10^4 \, K$, and denser than $9.6 \, cm^{-3}$ according to the Kennicutt (1998) Schmidt law as described in Stinson et al. (2006) with a star formation efficiency parameter, $c_\star = 0.1$. The star formation density threshold is then set to the maximum density at which gravitational instabilities can be resolved, $\frac{2M_{\text{gas}}}{\pi c^2}(n_h > 9.3 \, cm^{-3})$, where $M_{\text{gas}} = 2.2 \times 10^9 \, M_\odot$ and $\epsilon$ is the gravitational softening (310 pc).

The star particles are $5 \times 10^9 \, M_\odot$, massive enough to represent an entire stellar population consisting of stars with masses given by the Chabrier (2003) initial mass function. 20 per cent of these have masses greater than $8 \, M_\odot$ and explode as Type II supernovae from 3.5 until 35 Myr after the star forms, based on the Padova stellar lifetimes (Alongi et al. 1993; Bressan et al. 1993). Each supernova inputs $E_{\text{SN}} = 10^{51} \, ergs$ of purely thermal energy into the surrounding gas. This energy would be radiated away before it had any dynamical impact because of the high density of the star-forming gas (Katz 1992). Thus, the supernova feedback relies on temporarily disabling cooling based on the sub-grid approximation of a blastwave as described in Stinson et al. (2006).

The stars also chemically enrich the interstellar medium (ISM) during their evolution through the explosions of SNII and SNIa. SNII chemical enrichment is based on linear fits as a function of star mass for the Woosley & Weaver (1995) model of solar metallicity SNII explosions of stars more massive than $8 \, M_\odot$. These models are only based on a single (solar) metallicity. Linear fits do not suffer from the unrealistic oxygen enrichment that some of the power-law fits do (Gibson 2002). The oxygen fit used is

$$Y_{\text{OX}} = 0.21 \, M_\star - 2 \, M_\odot$$

(1)

and the iron fit is

$$Y_{\text{Fe}} = 0.003 \, M_\star$$

(2)

SNIIa commence enriching the ISM after SNII stop exploding, 40 Myr after the formation of the stellar population, and proceed with nearly constant enrichment for the lifetime of $0.8 \, M_\odot$ stars, 12 Gyr. The SNIa enrichment follows the Nomoto, Thielemann & Yokoi (1984) W7 model from Thielemann, Nomoto & Yokoi (1986), where each SNIa produces $0.74 \, M_\odot$ of iron and $0.143 \, M_\odot$ oxygen.

The supernovae feedback does not start until 3.5 Myr after the first massive star forms. However, nearby molecular clouds show evidence of being blown apart before any SNIa have exploded. Pellegrini et al. (2007) emphasized the energy input from stellar winds and UV radiation pressure in M17 prior to any SNIa explosions and Lopez et al. (2011) found similar energy input into 30 Doradus. Thus, in the time period before supernovae start exploding, we distribute 10 per cent of the luminosity produced in the stellar population (equivalent to the UV luminosity) to the surrounding gas without disabling the cooling. Most of the energy is immediately radiated away, but Stinson et al. (2013) shows that this early stellar feedback has a significant effect on the star formation history of a Milky Way mass galaxy and places the halo on the Moster et al. (2013) stellar mass–halo mass relationship at $z = 0$.

### 2.2 Stellar sub-populations

Throughout the paper, we divide star particles into sub-populations using either their abundance or their age. We refer to these sub-populations as either a MAP or a co-eval population, respectively. These are defined as follows

(i) **MAP:** each population is taken from a section of the [O/Fe]–[Fe/H] plane, with $\Delta[O/Fe] = 0.05$ and $\Delta[Fe/H] = 0.1$.

(ii) **Co-eval:** stars all formed at the same time. The simulation is divided into 50 co-eval populations with equal numbers of star particles. Each population contains 11 410 stars and has a characteristic age-spread of $\sim 250$ Myr.

### 2.3 Fitting the structure of sub-population discs

For comparison with observations, disc structural parameters (scale-length and height) are fit throughout this paper using a maximum likelihood method. Specifically, we fit the number density of simulated star particles following B12, who fit a number density of G dwarf stars. The radial density profile is modelled with an exponential function while the vertical density distribution uses a $\text{sech}^2(z)$ function to capture the flattening of the vertical density distribution near the disc mid-plane. The likelihood for finding a simulated particle at radius $R_{xy,i}$ and height $|z_i|$ is

$$\ln(L) = \sum_{i=1}^{N} \left[ -\frac{R_{xy,i}}{r_{\text{exp}}} + \ln \left( \text{sech}^2 \left( \frac{|z_i|}{h_z} \right) \right) \right]$$

$$- \ln(4\pi r_{\text{exp}} h_z (-e^{-\frac{z_{\text{max}}}{h_z}} (r_{\text{exp}} + r_{\text{max}})))$$

$$+ e^{-\frac{z_{\text{min}}}{h_z}} (r_{\text{exp}} + r_{\text{min}})$$

$$\left( \frac{\tanh \left( \frac{z_{\text{max}}}{h_z} \right) - \tanh \left( \frac{z_{\text{min}}}{h_z} \right) }{h_z} \right),$$

(3)

where $h_z$ and $R_{\text{exp}}$ are the disc structural parameters to be fit in the annulus from $r_{\text{min}} = 6 \, kpc$ to $r_{\text{max}} = 10 \, kpc$ in radius and $z_{\text{min}} = 0$ to $z_{\text{max}} = 3 \, kpc$ in height. This likelihood function is turned into a minimization problem by taking its negative. Initial best-fitting parameters are found using Powell’s method for minimization (Powell 1964; Press et al. 2007). These parameters are used as initial conditions for an ensemble Monte Carlo–Markov Chain (MCMC) sampler (Foreman-Mackey et al. 2013). The MCMC program samples the posterior distribution. The median of the distribution is used as the best-fitting value because it provides better fits than the results from Powell’s method. The quoted errors are the interval that contains 68 per cent of the posterior distribution for the given parameter.

The profiles for a selection of example MAPs are presented in Fig. 1. It shows the great variation of profiles apparent in the various MAPs, differences that will be described in Section 4.1. The models provide a good description of the data.

### 3 QUALITATIVE STRUCTURAL EVOLUTION

To give a brief introduction to the analysis that follows, we begin with images of the stellar populations that comprise our simulated.
The density profiles for a selection of simulated MAPs. This selection is composed of three columns each two plots across. The left-hand plot of the pair is the vertical fit that uses the $\text{sech}^2(z)$ function while the right-hand column shows the corresponding exponential radial scalelength fit. The dashed green lines represent the best fit. The vertical error bars on the points are the Poisson errors. The top row includes fits from two different [O/Fe] values. The first pair is for $[\text{O/Fe}] = 0.2–0.25$, which shows typical profiles of the $\alpha$-enhanced stellar population. The second two pairs have $[\text{O/Fe}] = 0.1–0.15$ and show some variation in scalelength, but to a lesser degree than the bottom two rows. The plots in the bottom two rows contain a selection of fits with constant [O/Fe] and increasing [Fe/H] from left to right. The bottom row is $[\text{O/Fe}] = 0–0.05$, the middle row is $[\text{O/Fe}] = 0.05–0.1$. These [O/Fe] values are selected because of the large variation in scalelength as a function of [Fe/H] as shown in Fig. 4. In several cases, the stellar density is nearly flat as a function of radius. In these cases, the quoted scalelengths are taken from the bottom 1 per cent of the posterior distribution so represent an extreme lower limit of the scalelength. The left-hand panels show where the stars formed, while panel (b) shows where those same stars are at $z = 0$. These images give a qualitative sense that the oldest stars formed with a short scalelength and tall scaleheight, while the youngest stars have a long scalelength disc with a short scaleheight. A comparison with the right-hand panels shows that the co-eval populations have not evolved significantly in their structure other than some slight thickening. Thus, it is possible to look at the structural properties of present-day stellar populations and make inferences about where those stars formed. In Section 4, we examine the structural parameters of MAPs. Fig. 3 shows the $z = 0$ stellar structure for a sample of MAPs. The selection includes representatives from the three main MAP families we find in our quantitative analysis in Section 4: old-thick disc, intermediate and young thin. The upper-left panel represents the old-thick population that has a tall scaleheight, short length and enhanced [O/Fe]. The right two panels in the upper row represent the intermediate population that arises from a significant transition in the evolution of the stellar disc. In this population, the stars with the tallest scaleheights also have the longest scalelengths. The bottom two rows represent the young-thin population. All of these populations have as thin a disc as can be resolved in the simulation. The scalelengths, however, vary greatly as a function of [Fe/H], creating a significant [Fe/H] gradient that is apparent in the youngest, solar [O/Fe] abundance populations.

4 RESULTS

With the procedure in place for fitting the scaleheight and scalelength of sub-samples of stars in the simulations at $z = 0$, we can now compare the MAPs between the observed Galactic disc and the simulations. We further study how the structure of the MAPs compares to co-eval populations in Section 4.4.

4.1 Simulated MAP Structure

Fig. 4 shows how the disc scaleheight (left) and length (right) vary as a function of [Fe/H] and [O/Fe] for different MAPs in the simulation. There are smooth changes in both the scaleheight and scalelength as a function of abundance. The tallest scaleheights exist in the [Fe/H]-poorest and most oxygen-enhanced populations. The scaleheight
A thick disc from stellar feedback

Figure 2. Projections of the stellar density for stars grouped into nine different age bins. The left-hand panel shows the location of the stars when they formed. The right-hand panel shows the present-day \((z = 0)\) distribution of the various MAPs. In both cases, there is a trend from round (large scaleheight, short scalelength) to flattened (small scaleheight, long scalelength) distributions, when going from old to young sub-populations: (a) where stars formed, (b) where stars are at \(z = 0\) (co-eval populations).

Figure 3. Edge-on stellar surface densities for a selection of mono-abundance stellar populations (MAPs).

shrink as the [Fe/H] enrichment increases and the oxygen enhancement decreases, reaching a minimum of \(~200\) pc.

Regarding the scalelengths in the right-hand panel, the oxygen-enhanced stellar populations all have comparable scalelengths around 2 kpc. In less oxygen-enhanced populations, the scalelength generally grows. However, the [Fe/H]-enriched stellar populations at solar [O/Fe] have scalelengths that are shorter, \(r_{\text{exp}} \sim 1\) kpc, than the oxygen-enhanced populations.

The [Fe/H]-enriched populations represent the most recent star formation, occurring near the galactic centre. There is a limited radius inside which the ISM has been sufficiently enriched to produce such stars. Outside this radius, star formation is also ongoing, but with a scalelength much larger than fits on the colour bar scale. The change in scalelength is separated by a variation of only 0.2 dex in [Fe/H].

The \(\alpha\)-enhanced populations show much less variation in their scalelengths, staying around 2 kpc. They show only moderate variation in their scaleheights, which gradually decrease with higher [Fe/H] and lower [O/Fe]. These are the stars that make up the thick disc of g1536. Liu & van de Ven (2012) found that in the Milky Way, stars with \(\alpha\)-enhanced abundances share many kinematic properties.

Fig. 5 illustrates an important qualitative difference between the simulation and the Galactic disc: the simulated disc is \(~50\) per cent thicker than the Milky Way. The extra thickness is correlated with the \(~50\) per cent greater velocity dispersion in the simulation \((\sigma_z \sim 60\) km s\(^{-1}\) in solar neighbourhood for the oldest, thickest population, \(\sigma_z \sim 30\) km s\(^{-1}\) for a 4 Gyr old population). The variation in each may be due to either a difference in mass between g1536 and the Milky Way or stellar feedback that is too strong. As mentioned
Figure 4. Dependence of the scaleheight (left) and length (right) as a function of [Fe/H] and [O/Fe] for different simulated mono-abundance stellar populations. Stars are divided into abundance populations with $\Delta [O/Fe] = 0.05$ and $\Delta [Fe/H] = 0.1$. These are the same fits as Fig. 8 only projected into the abundance plane: (a) scaleheight, (b) scalelength.

Figure 5. Present-epoch scaleheight versus scalelength for various MAPs in the simulations. The stars are split into MAPs, 0.05 wide in [O/Fe] and 0.1 in [Fe/H]. The simulated points are coloured by [O/Fe], the observed points are all grey. In many cases, the errors are smaller than the symbol size. The simulated MAPs show some trends. The scaleheight decreases with [O/Fe], while the scalelength remains around a constant value of 2 kpc. Below a scaleheight of 600 pc, the scalelengths are longer.

Before, g1536 is at the low end of the Milky Way total mass estimates and has less stellar mass than the Milky Way disc. Less mass would make the disc potential shallower and thus the disc thicker at a given velocity dispersion.

Switching focus to the MAPs with low (solar) [O/Fe], Figs 4 and 5 show that they all have scaleheights $< 500$ pc and a wide range of scalelengths from 1 kpc to large values. Fig. 1 shows that the low [Fe/H] bins have the longest scalelengths, such that the fraction of stars with such low [Fe/H] values increases further out in the disc. Fig. 1 shows that the stellar density profiles are nearly flat as a function of radius for these populations. As [Fe/H] increases, the scalelength becomes dramatically shorter. Such a scale trend with [Fe/H] is also clear in Fig. 5 of B12 and points to a metallicity gradient present in recently formed stars.

Our simulation predicts the existence of a compact metal-rich stellar population with short scaleheight and scalelength. It is plausible that this population did not show up in the analysis of B12 because the SDSS G-dwarf data sets do not include stars within 300 pc of the disc mid-plane or sightlines towards the Galactic Centre.

There are also intermediate (0.1–0.15) [O/Fe] stellar populations that show a direct correlation between scaleheight and scalelength. Fig. 4 shows that this is again related to the metallicity gradient of the disc. The most enriched MAP ([Fe/H] $\sim 0$) in this [O/Fe] range has the shortest scalelength and height of these populations. At progressively lower [Fe/H] abundances, the scaleheight and scale-length both become longer. This correlation is also apparent in Fig. 5 from B12, although only in the observed MAPs where fits are poor. We will examine this intermediate population further in the stellar populations summary, Section 4.6.

4.2 Radial abundance gradients

To make the [Fe/H] radial gradient clearer and identify the best way to search for its signature in observations, Fig. 6 shows the [Fe/H] gradient in populations divided using either age or [O/Fe]. As expected from Figs 4 and 5, there is a strong radial metallicity gradient.
4.3 Comparing abundances and ages

In the simulation, we can examine the age distribution of the stars within each MAP. The left-hand panel of Fig. 7 shows the mean age for all the MAPs. It shows that the $[\text{O/Fe}] = 0.1–0.15$ MAPs formed between 5 and 7.5 Gyr ago. In this range of $[\text{O/Fe}]$ values, the stars that formed the longest ago have the longest scalelength and height. This is an indication that the disc did not strictly form from the inside out. This intermediate $[\text{O/Fe}]$ population seems to indicate that there is a transition epoch as the disc shifts from a short, thick distribution to a long, thin distribution.

The right-hand panel of Fig. 7 shows, however, that most stars within each MAP did form at similar times, with a typical age spread of less than 1 Gyr. This implies that $[\text{O/Fe}]$ and $[\text{Fe/H}]$ jointly are a good proxy for co-eval populations across much of the $[\text{O/Fe}]$–$[\text{Fe/H}]$ abundance plane.

The MAP with $0.05 < [\text{O/Fe}] < 0.1$ and $-0.3 < [\text{Fe/H}] < -0.2$ has an exceptionally large dispersion, containing contributions from stars with a range of 6 Gyr. We overplotted the mean $[\text{O/Fe}]$ and $[\text{Fe/H}]$ values for stars split into age bins. These points show that the normal enrichment pattern makes an excursion towards higher $\alpha$-enrichment about 7 Gyr from the end of the simulation. A look at the star formation history of this galaxy in fig. 9 of Stinson et al. (2013) shows that this is the time at which the galaxy undergoes an increase in star formation. An examination of the evolution of the galaxy\(^1\) shows that there are two prograde minor mergers in rapid succession during this epoch. This increase in star formation causes stars to form with higher $[\text{O/Fe}]$ and then continue on a parallel abundance trajectory. No $[\alpha/\text{Fe}]$ excursion has yet been observed in the Milky Way.

4.4 Structure of the co-eval Populations

We repeat our analysis of the evolution of structural parameters, but using co-eval population rather than MAPs. Fig. 8 shows the scaleheight, $h_z$, as a function of scalelength, $r_{\text{exp}}$, for 50 different co-evol populations between $r_{\text{min}} = 6$ kpc and $r_{\text{max}} = 10$ kpc. The structural evolution of the co-evol populations is smoother and more gradual than for the MAPs. The oldest stars are in a thick distribution.

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\(^1\) http://www.mpia.de/~stinson/magicc/movies/c.1td.05rp.1/far.mp4
with a scalelength of 2 kpc. The younger populations have progressively shorter scaleheights and longer scalelengths. For these young stars, the disc scalelength begins to increase while the scaleheight becomes more constant.

Compared to the MAPs in Fig. 5, the wide range of scalelengths for the recently formed, solar [O/Fe] MAPs disappear. Instead, the scalelengths of the youngest population are 4–6 kpc, an average of the wide range in the MAPs. Fig. 6 shows that the [Fe/H] gradient is still quite strong in the youngest population, even stronger than for the MAPs since the MAPs mix populations of different ages. What is apparent from a comparison of the structure of the co-eval and MAPs is that the structure of MAPs is a mixture of disc evolution and enrichment. The enrichment is not uniform. Fig. 9 shows the fits of the disc scaleheight and scalelength of stars in an annulus 6 to 10 kpc from the galactic centre, comparable to the plots in Fig. 1. These sample fits show the gradual transition from a thick disc with a short scalelength to a thin disc with a long scalelength.

4.5 The mass-weighted scaleheight distribution

We can calculate how much different sub-populations contribute to the local surface density at the solar circle. For each co-eval population, we calculate its integrated surface density using its scaleheight and scalelength in the density equation:

\[ \rho(R, z) = \rho_0 e^{-R/R_\exp \sech^2 \left( \frac{|z|}{2h_z} \right)} \]

integrated over \(|z|\) from 0 to 3 kpc:

\[ \Sigma_{\rho} = 2 \rho_0 e^{-R/R_\exp} \int_{0 \text{kpc}}^{3 \text{kpc}} \sech^2 \left( \frac{|z|}{2h_z} \right) \text{dz}. \]

We then plot this surface density as a function of the characteristic scaleheight of each co-eval population, which roughly maps to metallicity and abundance (Fig. 7). Fig. 10 shows that there is a nearly flat distribution of the surface density contributed by populations with large scaleheights up to 800 pc. There is then an absence of surface density contributed by populations with scaleheights between 800 and 1200 pc, but then a distinct component with scaleheights from 1.2 to 1.5 kpc, which corresponds to the old, thick disc formed in the simulation. These scaleheights are far greater than any so far observed in the Milky Way and may be due to the low mass of g1536 or the overheating from the stellar feedback. The absence of populations with scaleheights around 1 kpc illustrates how the simulation transitions suddenly from its thick disc forming phase to thin disc. The data from the Milky Way does not show any such sudden transition.

4.6 Summary of populations

Based on the comparison of our simulations with observations, we identified three distinct stellar populations. The simulation shows clear indications of the evolution from one population to the next as the disc evolves and the signature of these transitions are also apparent in the observed MAPs.

4.6.1 Old thick disc

The MAPs with [O/Fe] > 0.15 all have constant scalelengths of ~2 kpc in both the simulated galaxy and the Milky Way. These MAPs also have the tallest scaleheights, though they shrink by a factor of 2 as the disc evolves. The MAPs are all older than 8 Gyr and over the 5 Gyr of their evolution, their [Fe/H] increases from ~1 to ~0.5 in both the simulated galaxy and the Milky Way. The shrinking scaleheight is steady as [Fe/H] becomes more enriched...
in the Milky Way. While the shrinking scaleheight is not so clear as a function of [Fe/H] in the simulated galaxy, it is apparent as a function of age in Fig. 8.

4.6.2 Intermediate population

There is a general evolution of scaleheight as an inverse function of scalelength. There is one series of MAPs that does not follow this trend, but instead scaleheight directly follows scalelength. These MAPs all have [O/Fe] = 0.1–0.15 in the simulations and 0.25 in the observations. However, this trend does not show up at all in Fig. 8, which displays scaleheight as a function of scalelength for co-eval populations. It shows a strictly inversely proportional evolution. Fig. 7 shows that the reason these MAPs show the odd trend is because they include the widest range of ages. These MAPs are filled with stars ∼6 Gyr old that formed when the abundance evolved to a more [Fe/H]-enriched track. This abundance evolution happens due a suddenly increased star formation rate. These populations are much more massive in the simulation than in the Milky Way.

4.6.3 Young thin disc

At the lowest [O/Fe] enhancements, the discs in both g1536 and the Milky Way are their thinnest. For g1536, these populations have [O/Fe] < 0.1 and [Fe/H] > −0.5, while in the Milky Way, they have [O/Fe] < 0.2 and [Fe/H] > −0.7. The scaleheights of these populations range from 500 down to 200 pc in the Milky Way and from 700 down to 300 pc in g1536 with the lower [O/Fe] enhanced populations have the thinnest discs. The scalelengths vary greatly for these MAPs from 2 to >5 kpc in the Milky Way and from 1 to >10 kpc in g1536. In both cases, these scalelengths vary directly as a function of [Fe/H]. All these MAPs are <3 Gyr old in the simulation, so the wide variation in [Fe/H] represents the metallicity gradient evident in the young thin disc.

4.6.4 Differences between simulation and Milky Way

The simulated galaxy has scaleheights that are twice those observed in the Milky Way. The simulation also shows evidence for a sudden event that makes the disc much thinner over a short period of time. It leaves an absence of stars that have a scaleheight of 1 kpc in the distribution of scaleheights. The Milky Way plot made from MAPs shows no similar absence, so it appears that the MW more smoothly evolved from thick to thin disc formation.

5 CONCLUSIONS

We make a detailed comparison between the stellar structure of a disc formed in a cosmological simulation and recent observations of the chemical and kinematic structure of the Galactic disc. In particular, we compare the systematic variations of disc scaleheight and scalelengths between simulations and observations. At a qualitative level, we find a striking similarity.

Our disc structural analysis is based on both age and chemical enrichment. The oldest stellar populations have short scalelengths and tall scaleheights. When the disc is decomposed according to metal abundance as in observations, the thickest populations that have the short scalelength are those that are α-enhanced. It is clear in the simulations that these are the oldest populations. The young stellar populations that have solar α-enhancement have the shortest scaleheights. Since we have divided our populations in [O/Fe] and [Fe/H] simultaneously, we can see that these young populations have a wide range of scaleheights that is strongly dependent on [Fe/H]. This illustrates how much chemical enrichment varies at different locations in the disc. In particular, the centre of the galaxy is the most metal ([Fe/H]) enriched while the outskirts of the disc follow a lower [Fe/H] path to solar [O/Fe].

The correspondence between the Milky Way and the MagICC simulation add support to scenarios where thick discs form kinematically hot. In future work, we will show how the morphology of the MagICC galaxy evolves, but since it is a relatively low-mass galaxy, it does not have large clumps of star formation at high redshift. Rather, the stellar feedback heats the galactic gas early in its evolution so that it does not settle into any sort of thin disc until z ∼ 1. The remaining presence of this thickened stellar component is what compares best with the thick disc observed in the Milky Way. As the galaxy increases in mass the gas settles down and forms a thin disc.

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REFERENCES

Alongi M., Bertelli G., Bressan A., Chiosi C., Fagotto F., Greggio L., Nasi E., 1993, A&A, 97, 851
Behroozi P. S., Wechsler R. H., Conroy C., 2013, ApJ, 770, 57
Bensby T., Feltzing S., Lundström I., 2008, A&A, 480, 1057
Bensby T., Feltzing S., Gudel M., 2010, A&A, 520, 138
Bird J. C., Kazantzidis S., Weinberg D. H., Guedes J., Callegari S., Mayer J., 2012, ApJ, 751, 131
Bovy J., Rix H.-W., Hogg D. W., 2012a, ApJ, 751, 131
Bovy J., Rix H.-W., Liu C., Hogg D. W., Beers T. C., Lee Y. S., 2012b, ApJ, 753, 148 (B12)
Bovy J. et al., 2012c, ApJ, 759, 131
Bressan A., Fagotto F., Bertelli G., Chiosi C., 1993, A&AS, 97, 851
Brook C. B., Stinson G., Gibson B. K., Quinlan G. D., Wadsley J., Quinn T., 2010, MNRAS, 408, 812
Brook C. B., Stinson G., Gibson B. K., Wadsley J., Quinn T., 2012b, MNRAS, 424, 1275
Burstein D., 1979, ApJ, 234, 829
Chabrier G., 2003, PASP, 115, 763
Chiba M., Beers T. C., 2000, ApJ, 542, L91
Chib M., Beers T. C., 2000, ApJ, 119, 2843
Chollet S., 2003, A&A, 399, 1145
Chojnowski M., 2009, MNRAS, 398, 1145
Chojnowski M., 2010, MNRAS, 403, 1711
Chojnowski M., 2011, ApJ, 737, 8
Chojnowski M., 2012, MNRAS, 428, 3121
Chojnowski M., 2013, MNRAS, 428, 129
Chojnowski M. et al., 2013, preprint (arXiv:1305.4663)
Ivezic Z., et al., 2008, ApJ, 684, 287
Jurić M. et al., 2008, ApJ, 673, 864
Katz N., 1992, ApJ, 391, 502
Kazantzidis S., Bullock J. S., Zentner A. R., Kravtsov A. V., Moustakas L. A., 2008, ApJ, 688, 254
Kazantzidis S., Zentner A. R., Kravtsov A. V., Bullock J. S., Debattista V. P., 2009, ApJ, 700, 1896
Kennicutt R. C., 1998, ApJ, 498, 541
Klypin A., Zhao H., Somerville R. S., 2002, ApJ, 573, 597
Kordopatis G. et al., 2013, A&A, 555, 12
Liu C., van de Ven G., 2012, MNRAS, 425, 2144
Loebman S. R., Roškar R., Debattista V. P., Ivezic Z., Quinn T. R., Wadsley J., 2011, ApJ, 737, 8
Lopez L. A., Krumholz M. R., Bolatto A. D., Prochaska J. X., Ramirez-Ruiz E., 2011, ApJ, 731, 91
Macciò A. V., Stinson G., Brook C. B., Wadsley J., Couchman H. M. P., Shen S., Gibson B. K., Quinn T., 2012, ApJ, 744, L9
Majewski S. R., 1999, ARA&A, 31, 575
Minchev I., Chiappini C., Martig M., 2012, preprint (arXiv:1208.1506)
Moore B. P., Naab T., White S. D. M., 2013, MNRAS, 428, 3121
Navarro J. F., Abadi M. G., Venn K. A., Freeman K. C., Anguliano B., 2011, MNRAS, 412, 1203
Nomoto K., Thielemann F.-K., Yokoi K., 1984, ApJ, 286, 644
Norris J., 1987, ApJ, 314, L39
Pellegrini E. W. et al., 2007, ApJ, 658, 1119
Powell M. J. D., 1964, Comput. J., 7, 155
Press W. H., Teukolsky S. A., Vetterling W. T., Flannery B. P., 2007, Numerical Recipes: The Art of Scientific Computing, 3rd edn. Cambridge Univ. Press, Cambridge
Prochaska J. X., Naumov S. O., Carney B. W., McWilliam A., Wolfe A. M., 2000, AJ, 120, 2513
Reddy B. E., Lambert D. L., Allende Prieto C., 2006, MNRAS, 367, 1329
Ruchti G. R. et al., 2010, ApJ, 721, L92
Schönrich R., Binney J., 2009, MNRAS, 399, 1145
Seth A. C., Dalcanton J. J., de Jong R. S., 2005, AJ, 130, 1574
Spergel D. N. et al., 2007, ApJS, 170, 377
Stinson G., Seth A., Katz N., Wadsley J., Governato F., Quinn T., 2006, MNRAS, 373, 1074
Stinson G. S., Bailin J., Couchman H., Wadsley J., Shen S., Nickerson S., Brook C., Quinn T., 2010, MNRAS, 408, 812
Stinson G. S. et al., 2012, MNRAS, p. 3506
Stinson G. S., Brook C., Macciò A. V., Wadsley J., Quinlan G. D., Couchman H. M. P., 2013, MNRAS, 428, 129
Thielemann F.-K., Nomoto K., Yokoi K., 1986, A&A, 158, 17
van der Kruit P. C., Searle L., 1982, A&A, 110, 61
Villalobos A., Kazantzidis S., Helmi A., 2010, ApJ, 718, 314
Wadsley J., Stadel J., Quinn T., 2004, New Astron., 9, 137
Woosley S. E., Weaver T. A., 1995, ApJS, 101, 181
Wyse R. F. G., Gilmore G., Norris J. E., Wilkinson M. I., Kleyna J. T., Koch A., Evans N. W., Grebel E. K., 2006, ApJ, 639, L13
Xue X. et al., 2008, ApJ, 684, 1414
Yanny B. et al., 2009, AJ, 137, 4377
Yoachim P., Dalcanton J. J., 2006, AJ, 131, 226

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