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The Effects of Radial Migration on the Vertical Structure of Galactic Discs

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ABSTRACT

We present evidence that isolated growing discs, subject to internal spiral perturbations, thicken due to both heating and radial migration. We show this by demonstrating that the thickness and vertical velocity dispersions of coeval stars depend on their age as well as the change in their radii. While the disc thickens due to internal processes, we find that this induces only a minor amount of flaring. We further demonstrate the consequences of such thickening on the structural properties of stellar populations and find that they qualitatively agree with recent studies of the Milky Way disc.

Other mechanisms for creating a thickened disc component involve either heating the disc through bombardment (e.g. Quinn, Hernquist & Fullagar 1993), forming a thickened disc from the remnants of a gas-rich last major merger (Brook et al. 2004) or accreting an extra-planar stellar component (Abadi et al. 2003). All three of these mechanisms are a result of the cosmological environment and consequently the thick disc is often considered to be an indicator of the MW’s cosmic history. On the other hand, a thickened component built up by migration has little to do with cosmological evolution but depends largely on internal disc dynamics. If migration can influence the properties of the thicker stellar component then it can muddle the signatures of cosmologically-relevant events that undoubtedly marked the early stages of the MW’s disc formation. The formation of the thick disc through heating by clump instabilities is in principle also an in-situ formation mechanism (Bournaud, Elmegreen & Martínez 2009), but it still relies on the cosmological environment for the rapid gas accretion.

Sales et al. (2009) proposed using the eccentricity distribution of thick-disc stars to distinguish between thick disc formation mechanisms. Consequently, several groups sought to apply the Sales et al. (2009) eccentricity test to observational data. Dierickx et al. (2010), Casetti-Dinescu et al. (2011), and Wilson et al. (2011), all reached a general conclusion that the eccentricity distribution is mostly inconsistent with the accretion scenario, but broadly consistent with the other three (the gas-rich merger scenario being the most favorable). The eccentricity distribution is not alone enough to break the degeneracies among the models, but such constraints become stronger once metallicities and abundances are also considered. Liu & van de Ven (2012) showed that low eccentricity stars from a SEGUE survey sample follow a continuous distribution in the [Fe/H]-[\(\alpha/Fe] plane while the high eccentricity stars seem disconnected in this plane.

The separation in the [\(\alpha/Fe] vs. [Fe/H] plane of thick-and thin-disc selected stars lends strong support to the
idea that the two discs are formed as separate structures (Bensby, Feltzing & Lundström 2003). In such a formation scenario, the variation of structural parameters in [alpha/Fe] vs. [Fe/H] for two distinct populations would be expected to be abrupt even for an unbiased sample of stars. However, recently Bovy et al. (2012b) found that such a strong dichotomy does not exist for a selection function-corrected sample of SEGUE stars. Bovy et al. (2012b) find a smooth distribution of structural trends when stars are separated into mono-abundance populations with alpha-rich, metal-poor large scale height populations having a short scale-length, while metal-rich stars have low scale-heights and long scale-lengths. (a similar result was found for the high-α SEGUE population by Cheng et al. 2012). These findings are consistent with Bensby et al. (2011), who also found a short scale-length for targeted thick-disc stars using entirely different data. These recent results contrast strongly with the usual view that the thick disc has a larger scale height and a longer scale length, as is obtained, for example, by fitting the stellar density with a two-component model (Juric et al. 2008).

The stars in individual abundance bins are also vertically isothermal (Bovy et al. 2012a), strengthening the argument that they are single populations. Both of these properties seem to favour strong internal evolution for the MW disc, because if a disc builds up entirely from internal processes, a distinct second component that dominates away from the plane does not readily form. It is, however, also possible to recover many of these trends in the cosmological context if the disc initially forms hot and thick, subsequently forming increasingly thinner populations as its self gravity gradually increases (Bird et al. 2013; Stinson et al. 2013).

However, even if stars form in a thicker component early in the history of the disc, they do not become immune to disc perturbations. N-body simulations have shown that stars in the thick disc were also able to migrate to and from the galactic center (Solway, Sellwood & Schönrich 2012). The same study showed that migrating stars on average (but not individually) conserve their vertical action, rather than their vertical energy. Recently, Schönrich & Binney (2012) studied the co-dependence of vertical and horizontal motions analytically. They found that the vertical motion significantly affects the detailed in-plane velocity distributions. Following Binney (2010), the coupling between the two components of motion was achieved through the assumption of vertical action invariance. This assumption has been shown to be a reasonable approximation by more rigorous torus modeling (Binney & McMillan 2011).

While the above analytic studies have focused on the co-dependence of oscillations about the guiding centre and the vertical motion, in this Paper we explore the implications of radial migration (i.e. the change in the guiding centres) for the vertical distribution. Under action conservation in a radially-increasing disc potential, any change in radius will lead to a modification of the vertical motion. However, while stars oscillate in radius by up to ~1 – 2 kpc they might migrate radially by many kpc and we can therefore expect that migration would have a larger effect on their vertical motion.

However, Minchev et al. (2012a) argue that vertical action conservation prevents the stars from thickening as they migrate outwards. They support this claim with results from isolated N-body/SPH simulations of the GalMer database (Chilingarian et al. 2010) as well as sticky-particle semi-cosmological simulations (Martig et al. 2012). Their conclusion disagrees sharply with the findings of Schönrich & Binney (2009b), who assumed energy conservation rather than action conservation when modeling the vertical distribution in their analytic models. However, it also disagrees with Loebman et al. (2011) who used high-resolution N-body/SPH simulations and found that the migrated population formed a thicker component that was shown to be broadly consistent with MW thick-disc trends in both chemistry and kinematics.

In Roškar et al. (2012a), we focused on the details of the radial migration mechanism in a suite of N-body/SPH simulations. We found evidence that the largest migrations were taking place at the corotation resonance (CR) of dominant spirals, confirming the mechanism proposed by Sellwood & Binney (2002). In this paper, we elucidate the connection between radial migration and vertical disc structure using the fiducial simulation of Roškar et al. (2012a).

To gain insight into the physical nature of the processes involved, we compare the simulation data with expectations based on the simplified analytic models of Schönrich & Binney (2012). The paper is organized as follows: our methods are presented in Section 2; the basic results are presented in Section 3; we compare the results to a simple analytic model for disc thickening in Section 4; we discuss the consequences of such thickening on the trends in structural properties of stellar populations in Section 5.

2 SIMULATIONS

We analyze the same N-body/SPH simulation that we used in Loebman et al. (2011). This simulation is a re-run of the fiducial simulation analyzed in Roškar et al. (2008a,b; Roškar et al. 2012) using metal diffusion, but is otherwise identical in every respect. The initial conditions consist of two NFW (Navarro, Frenk & White 1997) halos, one of dark matter with a mass of $10^{12} M_\odot$ and the other of gas in hydrostatic equilibrium with a mass of $10^1 M_\odot$, both sampled with $10^6$ particles. The gas also rotates with $\lambda = 0.039$ and $j \propto R$, where $j$ is the specific angular momentum and $R$ is the cylindrical radius. We use the code GASOLINE (Wadsley, Stadel & Quinn 2004) to perform the computation. Once the simulation begins, the gas cools and collapses into a disc that forms stars according to a standard prescription (Stinson et al. 2006) with a density threshold of 0.1 amu/cc and a temperature cutoff of $1.5 \times 10^4$ K. Star particles provide “feedback” to the gas by injecting it with energy and polluting it with supernova ejecta. The simulations are evolved completely in isolation and no cosmological context is included. By the end of the simulation, the disc is populated by more than $2 \times 10^6$ star particles. The softening we use for the baryonic component is 50 pc. The reader is referred to Roškar et al. (2008b) and Roškar et al. (2012) for further details on the simulations. The simulations were analyzed with the aid of the PYTHON-based analysis package PYNBODY (Pontzen et al. 2013) and IPython (Pérez & Granger 2007).

Our simulation code includes prescriptions for the generation of metals in supernova type Ia and II explosions as well as in AGB stars. SN II yields are taken from (Raiteri, Villata & Navarro 1996), SN Ia yields from Thielemann, Nomoto & Yokoi (1986), and the mass returned to the ISM via stellar winds follows Weidemann (1987). We can therefore follow the abundances of α elements relative to Fe (Oxygen is used as the α element proxy). Due to uncertainties in metal yields, the absolute values of [O/Fe] do not match with observations, but relative trends are nevertheless informative. For details on the metal enrichment implementation see Stinson et al. (2006). As in Loebman et al. (2011), in this paper we use the code google.com/p/pynbody/
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3 RESULTS

The simulation yields a disc that is kinematically similar to that of the Milky Way. In Fig. 1 we show the age-velocity dispersion relation for stars that are found in the “solar neighborhood” at the end of the simulation. We define solar neighborhood as a disc region between 7.5-8.5 kpc and within 200 pc from the plane. The disc scale length in our model is ~ 2.5 kpc, so this is a reasonable approximation to the region of the MW disc where analogous relations have been observed.

The age-velocity relation from the Geneva-Copenhagen survey (Holmberg, Nordström & Andersen 2009) shows similar power-law dependencies and values, though in our case the oldest stars are hotter by ~ 10%. The vertical velocity dispersion shows a shallow dependence for the young stars, similar to that shown for the GCS sample (Seabroke & Gilmore 2007). Part of the increased dispersion for the old stars may be due to the fact that our simulation yields a slightly more massive disc (the circular velocity $v_c \sim 250$ km/s). Fitting power-laws to the relations in Fig. 1 we obtain power-law indices of 0.24, 0.26, 0.25, and 0.15 for $\sigma_{\text{tot}}$, $\sigma_R$, $\sigma_\phi$, and $\sigma_z$ respectively. These indices are lower than those observed in the MW, indicating that an additional source of heating may be needed. On the other hand, the fact that the heating indices are not too high also means that the amplitudes of non-axisymmetric structure forming in the disc are not unreasonably high. A related issue is that the youngest stars are not quite as kinematically cool as the observations due to the dispersion floor in the gas component, which also contributes to higher overall velocity dispersions. We discuss this last point further in Sect. 4.

3.1 Thickening and vertical velocity dispersion due to migration and heating

Because radially migrating stars feel a smaller restoring force towards the midplane as they move outward, the amplitude of their vertical oscillations increases. However, at the same time, heating processes due to the recurring spiral structure also heat the stars, regardless of whether they have migrated or not, providing another source of increased vertical motion. Comparison between Figs. 3 and 5 in Loebman et al. (2011) shows this implicitly. Their Fig. 3 shows that when significant migration is present, the stars dominating the distribution away from the plane have migrated from the interior of the disc. By contrast, in the model with less migration shown in their Fig. 5, the populations away from the plane are there mostly because of heating (i.e. they are old) rather than migration (they formed in-situ).

In Fig. 6 we show the relative dependence of stellar population thickness on radial migration and heating. As a measure of thickness, we use the model-independent $z_{\text{rms}} \equiv \sqrt{\Delta z}$, where $\Delta z$ is the change in thickness since birth, as a function of age and distance $R$. This is the change in thickness, as a function of age and $R \equiv R_{\text{form}} - R_{\text{now}}$, for a given range of formation radii. The distributions shown in each of the panels are made by selecting particles in a particular range of formation radii (indicated at the top of each panel). We bin the particles in this space on a grid – each bin then corresponds to a roughly coeval population (born at approximately the same radius, of the same age, and migrated by the same amount). The contours show the mass density of particles.

If all the changes to the thickness of each population were due to heating, we would expect age to be the determining factor in setting the $z_{\text{rms}}$. As a result, the 2D gradient in $\Delta z_{\text{rms}}$ would be predominantly in the vertical direction. Conversely, if all the changes in thickness were due to radial migration, the gradient would be horizontal.

The gradients in all of the panels of Fig. 6 are diagonal, with $\Delta z_{\text{rms}}$ increasing in the direction of older ages and larger $R$, implying that radial migration as well as heating contribute substantially to the vertical thickness of the stellar populations. This is true for all ages and all $R$. For positive $\Delta R$, $\Delta z_{\text{rms}}$ is a monotonic function of $\Delta R$, stars migrating inward decrease their $z_{\text{rms}}$ so long as they stay away from the central bulge region. Those stars that migrate to the very centre of the disc increase their $z_{\text{rms}}$, presumably due to rapid heating that occurs there due to the presence of multiple inner Lindblad resonances and a weak oval that develops in the centre from time to time. The high velocity dispersions for these stars indicate that this may indeed be the case (see Fig. 3 discussed below). The oldest stars in the interior of the disc (upper-left corners of the top two panels) are on eccentric orbits and therefore not as affected by disc perturbations but their $z_{\text{rms}}$ decreases due to adiabatic contraction. Our main finding from Fig. 6 is that 1) at any given age, thickness is a monotonic function of $\Delta R$, and 2) at any $\Delta R$ thickness is a monotonic function of age.

We find a very similar kind of co-dependence for $\sigma_z$, the vertical velocity dispersion, shown in Fig. 7. The velocity dispersions of the stars migrating outward are lower than the dispersions of those migrating inwards. This is to be expected because the stars are moving to a region of a shallower midplane potential and because stars in the inner disc heat very efficiently (due to inner Lindblad resonances or non-axisymmetric structure). Nevertheless, the dispersion clearly depends on both parameters, age as well as distance migrated since birth, consistent with Fig. 5.

In Figs. 2 and 3 we have shown that the thickness and vertical velocity dispersion of coeval stellar populations depend on the magnitude of migration as well as their age. In other words, at a fixed present-day radius, the velocity dispersion and thickness of a population depends on its birth location and its time of formation. However, we have also shown that $\sigma_z$ of stars actually decreases as they migrate outward, so can these stars entering the solar neighborhood from the inner disc then still masquerade as the thick disc? From Fig. 7 we can see that the old (> 8 Gyr) stars that have mi-

Figure 1. Age-velocity dispersion plot for stars with $7.5 < R$ [kpc] < 8.5 and $|z| < 200$ [pc] after 10 Gyr of evolution.
Figure 2. Mean change in thickness as a function of age and $\Delta R$ plotted in four different bins of formation radii. Contours show the particle mass density and are logarithmically spaced from $10$ to $10^4$ particles per bin. Colours correspond to the change in thickness, defined as the root-mean-square of the vertical displacement from the midplane, $z_{\text{rms}} = \sqrt{\bar{z}^2}$. Increase in thickness is a function of both, age and $\Delta R$, i.e. stars undergo heating but their vertical distribution is also affected by the effective change in potential as they migrate inwards or outwards in the disc. Note that the $x$-axis range is different in each panel.

Migrated outward by several kpc have vertical velocity dispersions of 40-50 km/s. These stars comprise the $\alpha$-old population that in the MW has very similar velocity dispersions (Liu & van de Ven 2012; Bovy et al. 2012a); note that for the purposes of defining the thick disc, the “characteristic” $\sigma_z$ is taken to be $\sim 35$ km/s (Bensby, Feltzing & Lundström 2003), a criterion met by this migrated population. Even if the populations “cool” as they migrate outwards, their present-day properties can remain consistent with a thickened, $\alpha$-rich population. Note that in our models only 5 Gyr old and certainly the only ones that are thickened enough to represent the thick disc are even older and have migrated substantially. The in-situ young stars have $\sigma_z < 20$ km/s, making up the “thin” disc.

Minchev et al. (2012a) similarly found that velocity dispersions decrease as stars migrate outwards. They interpreted the decrease in $\sigma_z$ as an indication that radial migration cannot contribute to a thickened population. However, because the stars migrating from the inner to outer disc begin with a relatively high velocity dispersion, they still end up somewhat kinematically hotter relative to the in-situ population when they arrive to the outer disc. Furthermore, as Fig. 2 clearly shows, the outward-migrating populations thicken vertically as well. We find therefore that it is indeed possible to form a thickened and kinematically hotter component with the aid of radial migration. Our results therefore appear qualitatively similar to those of Minchev et al. (2012a), although we arrive at different conclusions. We speculate further that possible discrepancies between our findings and those of Minchev et al. (2012a) may arise in part due to the rapid heating apparent in their simulations due to a violent initial instability. At later times, the phenomenon driving the disc trends in their models (the same simula-
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Figure 3. Same as Fig. 2 except here the colours correspond to $\sigma_z$, the vertical velocity dispersion at the end of the simulation. The old stars that the “solar neighborhood” (i.e. $\sim 8$ kpc) from the interior of the disc have $\sigma_z \sim 40 - 50$ km/s in broad agreement with thick disc values in the MW.

3.2 Disc flaring

An important consideration for any model that deals with the thickening of the stellar disc is the change in scale height with radius, i.e. disc flaring. While substructure bombardment is particularly efficient at thickening discs, it may also cause rather drastic flaring to occur (Kazantzidis et al. 2009). Such flaring is not typically seen in extragalactic observations of edge-on discs (de Grijs & van der Kruit 1996).

While, radial migration has also previously been associated with dramatic flaring (Minchev et al. 2012a), we show in Fig. 3 that this is not necessarily the case. In the top panel, we show the vertical profiles of the disc at several different radii, all normalized to their values at 1 kpc from the plane to more easily compare the profiles furthest from the plane. The vertical distribution clearly becomes more extended in the outer parts of the disc, but the flaring is rather minor.

In the bottom panel, we quantify the flare by showing the values of maximum-likelihood estimates (MLE) for the scale height of the thicker component of a double sech$^2$ distribution as a function of radius. We use MLE instead of a least-squares fit to the binned...
MLE gives consistently good results. To find the MLE parameters, we maximize the log-likelihood function

$$\ell(h_1, h_2, f) = \sum_{i=0}^{N} \ln [\rho(z_i|h_1, h_2, f)] - \ln(p_0),$$

with

$$\rho(z)/\rho_0 = (1 - f) \, \text{sech}^2(z/2h_1) + f \, \text{sech}^2(z/2h_2)$$

where $\rho$ is the volume density, $N$ is the total number of particles in the bin, $z_i$ is the vertical position of the $i$-th particle, $h_1$ and $h_2$ are the thin and thick disc scale heights, $f$ is the thick disc fraction, and $\rho_0$ is the midplane density. To estimate the parameters, we select particles found in 1 kpc radial bins centred on each point shown in Fig. 4 and up to 4 kpc from the midplane. Following Bovy et al. (2012b), the likelihood function $\ell$ is maximized using an MCMC sampler (Foreman-Mackey et al. 2012), yielding parameter estimates and uncertainties, represented by the error bars in Fig. 4.

The increase in scale height is only 50% across approximately 10 kpc (corresponding to 4 disc scale lengths). The thick disc fraction is $\sim 12 - 20\%$ in the main disc region (4-10 kpc) and rises to $\sim 40\%$ in the outer disc. Interior to 10 kpc, the scale height is essentially constant. Note that most studies fitting the vertical density of the Milky Way disc (e.g. Gilmore & Reid 1983, Jurić et al. 2008, Bovy et al. 2012b) use an exponential fitting function and that the scale heights between the two functional forms are not strictly comparable. We find that fitting our simulated particle distribution with an exponential model yields scale heights larger by up to $\sim 30\%$, making them only slightly smaller than similar thick disc scale height measurements in the MW. However, we use the sech$^2$ because it gives a better fit to our model.

4 DISC THICKENING DUE TO CONSERVATION OF VERTICAL ACTION

Here we consider the simplified 1D problem with a star oscillating above and below the plane of a thin disc. This is similar to the model described by Minchev et al. (2012a), who use it to show that the vertical velocity dispersion is expected to decrease as stars migrate outward if the vertical action is conserved. We show that this same model leads to the conclusion that the stellar vertical distribution must thicken. In this simple case, the vertical frequency is

$$\nu \propto \sqrt{\rho(R)},$$  

(1)

where $\rho(R) = \rho_0 e^{-R/R_d}$ is the midplane density of the disc at radius $R$, $\rho_0$ is the density at the disc centre, and $R_d$ is the disc scale length. The vertical action can be approximated by $L_z = E_z/\nu$, where $E_z$ is the vertical energy. For a population of stars we assume that $E_z \sim \sigma_z^2$. If we assume that the vertical action $L_z$ is conserved (Solway, Sellwood & Schönrich 2012), then

$$\sigma_z^2/\nu \propto e^{-R/2R_d},$$  

(2)

as shown previously by Minchev et al. (2012a).

The vertical density distribution of an isothermal population is given by (Spitzer 1942)

$$\rho(z) = \rho_{z=0} \, \text{sech}^2(z/2h_z),$$  

(3)

with the vertical scale-height

$$h_z = \frac{2\sigma_z^2}{\pi G \Sigma(R)}$$  

(4)

Plugging Eq. 2 into Eq. 1 and assuming that the disc surface density $\Sigma \propto e^{-R/R_d}$, one finds that $h_z \propto e^{R/2R_d}$, i.e. the scale height increases with positive changes in radius. Combining the approximation for change in $\sigma_z$ for a migrating population with Eq. 4 yields a simple expression relating the change in radius $\Delta R$ and $R_d$ to the ratio of initial and final scale heights, $h_{z,f}/h_{z,i}$:

$$h_{z,f}/h_{z,i} = \exp \left( \frac{\Delta R}{2R_d} \right).$$  

(5)

This simple derivation of Eq. 5 ignores the presence of other disc components; such an isothermal population is just one of many that make up the disc. In particular, the addition of mass (by gas accretion and star formation) in the midplane would adiabatically compress the migrated population, which has previously been shown to alleviate some of the thickening effects of infalling substructures (Villalobos, Kazantzidis & Helmi 2010, Moster et al. 2010). Furthermore, even in a disc not subject to outside perturbations, $\sigma_z$ will also increase with time due to heating from disc structure thereby further boosting the scale height, an additional effect that we discuss below.

Eq. 5 is an approximation to the more general expression de-
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We have shown above that the thickness of a coeval population is an exponential function of its migration in the disc. It is interesting to pose a similar question for stars that share the same angular momentum today but that may have originated in different parts of the disc, i.e. are not to be considered a coeval population. As in Fig. 2 in the leftmost panel of Fig. 6, we show the ratio \( z_{\text{rms}}/z_{\text{rms},g} \) for stars with \( 5 < R_{\text{final}} [\text{kpc}] < 5.5 \) vs. \( \Delta R_g \). We see similar exponential trends at all values of \( j_z/j_c \), as before.

Since the most circular (red line) population is the least affected by heating, we can once again use it as a proxy for the overall effect of radial migration on population thickness. Across the range of \( \Delta R_g \), we find that migration can lead to an thickness increase by a factor of 2.5 (we cannot eliminate all heating so thickness increases by 50% simply by virtue of these stars spending 5 Gyr in the disc). Again, taking the range from blue to red as the effect of heating, we see that heating contributes another factor of \(< 1.5 \). Based on this and Fig. 5, we conclude that migration thickens stellar populations by about the same proportion as the internal heating processes, for parts of the disc outside the bulge.

In our simulations, the gas cooling function does not include metal line or molecular cooling, limiting the temperature of the gas to \( > 10^4 \) K. As a result, the gas velocity dispersion is largely set by the minimum temperature and consequently the gas scale height increases as a function of radius. Due to this gas flaring, the populations at each \( \Delta R_g \) in Fig. 6 are actually born with different thicknesses, as shown in the middle panel. The variation across the range of 5-6 Gyr old stars that end up at the specified angular momentum is a factor \( \sim 2 - 3 \). Hence, while it is inevitable that individual populations change their vertical distribution as they migrate (Fig. 2), these changes are partially offset by the flaring of stars at birth (middle panel of Fig. 6). As a result, at a fixed final angular momentum (i.e. \( R_g \)) there is little variation of thickness with \( \Delta R_g \).

However, the molecular and atomic gas components in the MW show little variation in thickness out to \( \sim 10 \) kpc (Brunthaler et al. 1988; Wouterloot et al. 1998; Narayan & Jog 2002). We may therefore expect that in the MW the flaring would not mask the thickening resulting from radial migration. Evidence for similarly constant scale heights as a function of radius has also recently been found with resolved-star studies of edge-on nearby discs (R. de Jong & D. Streich, private communication).

We checked the results of this section against a higher-resolution version of our simulation that uses four times as many particles (simulation R4 from Roškar et al. 2012) and found no significant differences, so we consider the dynamical results to be numerically robust. However, assessing the significance of the gas disc flaring and the subsequent radial dependence of the scale height of young stars is a much more difficult problem. It depends sensitively on the details of the gas physics on scales that are an order of magnitude smaller than what we (or any other similar state-of-the-art simulations at present) are able to adequately resolve.

5 CONSEQUENCES FOR LOCAL ABUNDANCE TRENDS

The consequence of the thickening described above on the observed properties of stellar populations is that their structural properties vary considerably with metallicity and abundance. This has been pointed out by Bovy et al. 2012b, who found that when they sliced the SEGUE G-dwarf sample into “mono-abundance” bins, the structural parameters varied smoothly from short and thick at the metal-poor \( \alpha \)-rich end, to long and thin at the metal-rich \( \alpha \)-
The ratio of $z_{\text{rms}}$ (thickness now) to $z_{i,\text{rms}}$ (thickness at formation) of 5-6 Gyr old stars that were formed within the indicated radial range, plotted against the change in guiding radius $\Delta R_g = \Delta j_z/V_c$ from their birth to the present, where $\Delta j_z$ is the change in angular momentum and $V_c$ is the circular velocity. The colours of the solid lines correspond to different ranges in the orbital circularity parameter $j_z/j_c(E)$. The overplotted red dashed lines are exponential fits, indicating that the changes in thickness satisfy the expectations from adiabatic invariance of the vertical action (see text). The other coloured dashed lines show the relation from Eq. [27] of Schönrich & Binney (2012) for the kinematically coldest population, overplotted for different values of $\alpha$ and assuming a scale length of 2.5 kpc.

The change in population thickness as a function of $\Delta R_g$, the change in guiding radius since birth, defined as $R_g = j_z/V_c$ (same as in Figure 5) for particles with $R_g$ in the indicated range. The left panel shows the ratio of $z_{\text{rms}}/z_{i,\text{rms}}$, predicted by Eq. 5 to follow an exponential. The centre and right panels show $z_{\text{rms}}$ at time of formation and at the present time respectively. Stars used in this figure are 5-6 Gyr old.

To obtain the structural parameters, we parametrize the stellar distribution as
$$\rho(R, z) \propto f(R) f(z),$$
where the radial and vertical density functions are
$$f(R) = \exp \left( -\frac{R}{h_R} \right),$$
and
$$f(z) = \text{sech}^2 \left( \frac{z}{2h_z} \right),$$
respectively. We fit these functions to the simulated particle density distribution for the maximum likelihood values of $h_R$ and $h_z$ using a procedure similar to the one described in Sect. 3.2. We use stars within a range of $4 < R < 9$ kpc and $|z| < 3$ kpc to obtain the fits. By requiring at least 100 particles per each plotted cell, we obtain $1\sigma$ uncertainties that are everywhere less than 10%. As in Sect. 3.2, we experimented also with an exponential function for the vertical distribution, and found that we can obtain smaller errors using the sech$^2$ form. If we fit the vertical distributions of stellar populations in our model with a single exponential, we obtain scale heights that are somewhat higher than those shown in Fig. 7, similar to what we found in Sect. 3.2.

The locus of “saturated” scale-lengths in Figure 7 below $[O/\text{Fe}] \sim -0.05$ are all young stars. Their scale-lengths are long because they are forming out of the cold gas which is also very extended. A similar saturation is seen in Bovy et al. (2012b). In our model, the sub-solar part of this locus originates in the outer disc, and Bovy et al. (2012b) similarly find that the mean radii for these stars are beyond the solar neighborhood. These are young, 0-2 Gyr old stars that formed in the outer disc and scattered into the solar neighborhood (see also Haywood 2008). They did not migrate via the corotation mechanism, because their tangential velocities exceed the circular velocity by $\sim 20$ km/s. Therefore, they heated and although one would naively expect their negative $\Delta R$ to lead to a thinner scale height, their scale heights are slightly higher than
the local young population by virtue of this heating. We can identify this population in the lower right panel of Fig. 2 as the 2 Gyr-old stars that migrate inward by ∼ 1 – 2 kpc and find that their scale height h_z ∼ 0.3 kpc.

An interesting discrepancy with the Bovy et al. (2012b) distribution is seen at the extreme metal-rich, α-poor corner ([O/Fe] < −0.1 and [Fe/H] > 0.1). We find that those stars have a short scale-length much like the older, more α-rich population. In Bovy et al. (2012b) no such population exists. In our model, these stars are dominated by intermediate age populations, mostly around ∼ 3 Gyr and 5 – 6 Gyr old. The majority (75%) of these stars came from inside 3 kpc, i.e. from the same part of the disc as some of the oldest stars in the solar neighborhood. These are the prototypical “extreme” migrants that were able to migrate far because they never heated considerably. However, their overall velocity dispersion is ∼ 5 – 10 km/s lower than other stars of similar age and because of the lower heating they remain thinner than the average population of the same age. Note that to increase particle numbers for more realistic simulations, we extended the selection in Fig. 2 to include stars to kpc, this population still exists when we restrict the sample to 7-9 kpc. We speculate that should such stars exist in the MW, they may be absent from the SEGUE sample due to their thin distribution and low numbers. However, should they be observed in future surveys, they would be an indication of significant radial mixing in the MW disc. An enticing connection to such a migrated population may be the newly-discovered metal-rich, high-α stars (Adibekyan et al. 2011, 2013; Gazzano et al. 2013) whose chemical properties suggest that they formed in the Galactic interior, but they are kinematically akin to thin disc stars.

If the local abundance and metallicity distributions are affected by stars migrating from the inner disc, one would expect to find corresponding populations in the present-day bulge. The thickest parts of the local thickened disc have low [Fe/H] and high α abundance, which may correspond qualitatively to a bulge population ‘C’ identified by Ness et al. (2012). The timing of the migration is difficult to predict, though in general stars can migrate more easily before they heat considerably. On the other hand the bulge region seems to host stars of all abundances, metallicities, and ages (Bensby et al. 2013), limiting the constraints one could impose on the models. In contrast to the local disc, however, the inner Galaxy does show a strong age-metallicity relation. Therefore, if the thickened population at the Sun’s position is old and metal-poor, it could be broadly consistent with being migrated from the inner disc/bulge. Determining whether migration should be considered critical for the evolution of the Milky Way will be determined in part by upcoming chemical tagging surveys such as HERMES (Bland-Hawthorn, Krumholz & Freeman 2010).

6 CONCLUSIONS

We have demonstrated that an outward migrating population of stars in a galactic disc always thickens. At the same time, the vertical velocity dispersion of such a population decreases, but we find that despite this decrease the old stellar populations arriving from the interior at the solar neighborhood match the kinematics of the MW thick disc. Further, we find that radial migration and internal heating thicken coeval stellar populations by comparable amounts. The thickening due to radial migration alone is well-approximated by a simple analytic treatment that assumes a conservation of vertical action. Importantly, we find that while radial migration does cause an increase in scale height with radius, the flaring that results is minor. If radial migration can contribute to a thickened component of a galactic disc then it has important consequences in the broader context of disc galaxy formation since most other mechanisms proposed to form a thick disc component involve the cosmological environment.

Our simulation recovers the qualitative structural stellar population trends observed in the MW SEGUE data. In particular, we find a similar dependence of scale height and scale length on oxygen abundance and metallicity to those found in Bovy et al. (2012b). However, our model produces a thick disc that is somewhat too thin compared to the MW. This is to be expected, since the disc we considered in this work is built up entirely from internal mechanisms in the absence of a cosmological environment. Additional perturbations in a more realistic setting would thicken the disc further.

Finally, we identify an interesting sub-population in the low-[O/Fe] high-[Fe/H] corner of the abundance plane (Fig. 7), which appears to be absent from the Bovy et al. (2012b) distribution, perhaps due to the lack of low-latitude coverage in the SEGUE data. These stars are the prototypical extreme-migrants having migrated from ∼ 3 kpc in a few Gyr.

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Figure 7. The distribution of stars in the [O/Fe] vs. [Fe/H] plane, coloured by scale length $h_r$ on the left and scale height $h_z$ on the right. The logarithmically-spaced contours indicate mass density from 10^{-10} to 10^{-4} particles per bin. The stars lie between $4 < R [\text{kpc}] < 9$ and $|z| < 3 [\text{kpc}]$. 

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