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The role of radial migration in shaping the stellar populations of spiral galaxies

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Abstract. Over the past several years, the radial migration of stars in galactic disks has been recognized as an important mechanism in the evolution of stellar population properties. I review some of its implication and discuss new developments regarding the influence of migrated stellar populations on the vertical structure of disks.

Key words. galactic dynamics; Galactic structure

1. Introduction

Stars in spiral galaxies form out of gas condensing in rotationally-supported disks. Gas is distributed in a thin layer and because it can radiate away excess orbital energy, its orbits are mostly circular. As a result, young stars have low velocity dispersions but as they age they are heated by a variety of mechanisms, such as scattering off giant molecular clouds (GMCs), interactions with disk overdensities like spiral arms, or by infalling substructures. Observations of stars in the local solar neighborhood show that such heating proceeds as a power law with time and that the velocity dispersion of the oldest disk stars is $\sim$ 50 km/s (Holmberg et al. 2009). In turn, this limits their radial epicyclic motion to $<$ 2 kpc, which is significantly less than their mean galactocentric distance. Since this is the amplitude of radial oscillation for the *oldest* stars, one may therefore conclude that most stars remain fairly close to their home radii throughout their orbits and indeed throughout their lives.

However, in the presence of a mechanism that can alter the angular momentum of individual stars, the mean orbital radii must also change. Redistribution of angular momentum occurs in disks during bar formation (Hohl 1971), at spiral resonances or during interactions with infalling satellites (Quillen et al. 2009; Bird et al. 2012). Typically, the mechanisms that redistribute angular momentum also inject stars with excess orbital energy, increasing the velocity dispersion. The velocity dispersion constraints from the solar neighborhood therefore restrict the overall effect of these processes.

Wielen et al. (1996) postulated that the Sun itself must have come from a different part of the galaxy due to its high metallicity when compared to other similar stars in the solar neighborhood and the local ISM, which was likely sub-solar $\sim$ 5 Gyr ago. Some radial mixing of stars also seems to be required on the basis of other solar neighborhood indicators, such as the age-metallicity relation

(AMR). If stars found in the solar neighborhood today remained near their birth radii for the entirety of their lives, we should observe a strong age-metallicity relation such as those frequently produced by 1-dimensional chemical evolution models (e.g. Boissier & Prantzos 1999). Althogh earlier measurements (Edvardsson et al. 1993) hinted at an existence of an AMR, more recent data from the Geneva-Copenhagen survey data show that the relation is very weak at best (Holmberg et al. 2009). The data also show a very large scatter at all ages, which cannot easily be explained away with measurement errors. This implies that stars from different birth locations have mixed into the local stellar populations throughout the history of the disk.

A mechanism that readily mixes stars throughout the disk *without* excessive heating was proposed by Sellwood & Binney (2002). If a star encounters a corotation resonance of a transient spiral, it may surf along the spiral inward or outward and do so in a way that preseves the ratio of orbital angular momentum and energy. Spiral transience is crucial for the mechanism to work because otherwise the stars simply get trapped at the corotation resonance. Such radial mixing is qualitatively different from other mechanisms for angular momentum exchange because it is not by itself a source of heating and is therefore not self-limiting and it does not imprint an obvious kinematic signature. The lack of heating implies that even stars that today appear on mostly circular orbits (such as the Sun!) may have come from a different part of the Galaxy. Radial migration by transient spirals can be very efficient and transport stars across many kiloparsecs in short amounts of time if they happen to encounter successive spiral waves (Roškar et al. 2012b). While the spirals found in some simulations (e.g. Roškar et al. 2012b) are patterns with discrete pattern speeds, other simulations seem to support spiral structure whose pattern speed matches the circular velocity at all radii (Wada et al. 2011; Grand et al. 2012; Baba et al. 2013). This means that the spiral is everywhere co-rotating and the entire disk is susceptible to efficient redistribution.

2. Impact of radial migration on disk stellar populations

In galactic archaeology, stars that are found in a given region of a disk today are assumed to share a common history. On the basis of this assumption, one may try to reproduce the stellar population demographics from a model and in this way reconstruct the star formation history for a given part of a disk (see, for example, Dolphin 2002; Gogarten et al. 2010). In the Milky Way, the most detailed data exists for a small volume around the Sun, but the stellar demographics are interpreted in a similar way (Boissier & Prantzos 1999; Chiappini et al. 2001). However, as described above, such modelling leads to a prediction of a strong AMR, which is not observed.

We study the phenomenon of radial migration using N-body Smooth Particle Hydrodynamic (SPH) simulations. The simulations are initialized as spherical NFW halos (Navarro et al. 1997) consisting of dark matter and gas. The latter is in hydrostatic equilibrium with the halo potential, and we impart upon it a spin corresponding to the spin parameter $\lambda = 0.039$ (Bullock et al. 2001). Each component is initially sampled by 1-million particles. The simulation is evolved with the N-body/SPH code Gasoline (Wadsley et al. 2004). The simulations include prescriptions for enrichment by supernova Ia and II ejecta, as well as from AGB stars (Stinson et al. 2006), essentially making them crude chemical evolution models with full dynamics. See Roškar et al. 2008b,a; Roškar et al. 2012b for additional details about the models.

Figure 1 illustrates some of the basic results of radial migration for the solar neighborhood from our fiducial simulation. All panels concern stars that at the end of the simulation are found in the solar neighborhood, defined as a region from 7-9 kpc. From the left panel, which shows the formation radii of these solar neighborhood stars, it is clear that the entire disk is represented in this local stellar population mix. The consequence for the AMR shown in the middle panel is clear: the AMR using stars from the whole disk (diamonds) is much flatter than the in-situ AMR (squares). The metallicity distribution function (MDF), shown in the right panel, is similarly diversified. If only the in-situ stars are considered, a fairly narrow range of metallicities is possible, but including stars arriving at the solar neighborhood from other parts of the disk increases the metallicity range considerably.

3. Polluting the thick disk with migrated stars

The vertical structure of the Milky Way disk can be fit with two exponential components dubbed the thin and thick disks (Gilmore & Reid 1983). Selecting solar neighborhood stars kinematically in order to separate ones that likely belong to each component yields samples that are also well-separated in their abundance patterns, with the thick disk stars having higher α-element abundance ratios. (Bensby et al. 2003). This separation implies that "the Disk" is in fact composed of two disks, each with its own enrichment and formation history. A geometric decomposition of the disk into two such components yields a thick and thin disks with long and short scale lengths respectively (Jurić et al. 2008). However, recent studies deriving scale-lengths from high-α sub-populations indicate that the scale-length of these canonical thick disk stars is instead very short Bensby et al. (2011); Cheng et al. (2012); Bovy et al. (2012). These authors find a thick disk scale length of $\sim$ 2 kpc, whereas Jurić et al. (2008) derived a scale length of $\sim$ 3.6 kpc. Furthermore, while the thick and thin disk stars tend to separate well in abundance space, there is no clear dichotomy in their structural properties when stars with the same chemistry are treated as individual populations. Instead, scale-lenghts and scale-heights tend to vary smoothly in the abundance-metallicity plane (Bovy et al. 2012). These structural properties favor a scenario where the thickened component is built up gradually, rather than in a single violent event. Two plausible mechanisms for such gradual build-up may be continued interactions with substructure (e.g. Kazantzidis et al. 2008) or due to progressive thinning of the star-forming component (Bird et al. 2013; Stinson et al. 2013). Note that Liu & van de Ven (2012) identified a high-eccentricity component in the SEGUE data that is on the extreme end of α-enrichment and may be an indication of a low-mass component with a truly distinct origin.

Recently, however, several works raised the possibility that some fraction of the thick disk may be composed of stars that were formed in the same way as the thin disk, but later migrated to their present locations. In analytic chemical evolution models that allowed for the radial migration of stars, Schönrich & Binney (2009) showed that under certain assumptions the migrated population could reproduce many of the chemical and kinematic properties observed in the thick disk. Using the same simulations described in Section 2 above, Loebman et al. (2011) showed that in their models an old, thickened component at the solar neighborhood is comprised mostly of stars that came from the interior of the disk. Although the disk in their simulations forms in isolation only through quiescent accretion of gas, migration gives rise to a characteristic two-component vertical profile.

On the other hand, doubts have been raised whether migrated stars could contribute to the thicker and hotter component in significant numbers, since an outward-migrating population should also decrease its velocity dispersion (Minchev et al. 2012). Whether or not migrated stars can thicken, Solway et al. (2012) showed that stars already in the thickened component may migrate subsequently with only slightly lower migration rates than the stars in the thin disk. Thus, even the thick disk seems to not be immune from the radial mixing process, even if it is formed in a different way than the thin disk.

The argument for stellar populations "cooling" as they migrate outwards comes from action conservation (Minchev et al. 2012), but the same action conservation inevitably also leads to their thickening (Schönrich & Binney 2012; Roškar et al. 2012a). In fact, if the vertical action is approximately conserved, *any* change in radius during the orbit will also lead to a change in the vertical oscillation amplitude

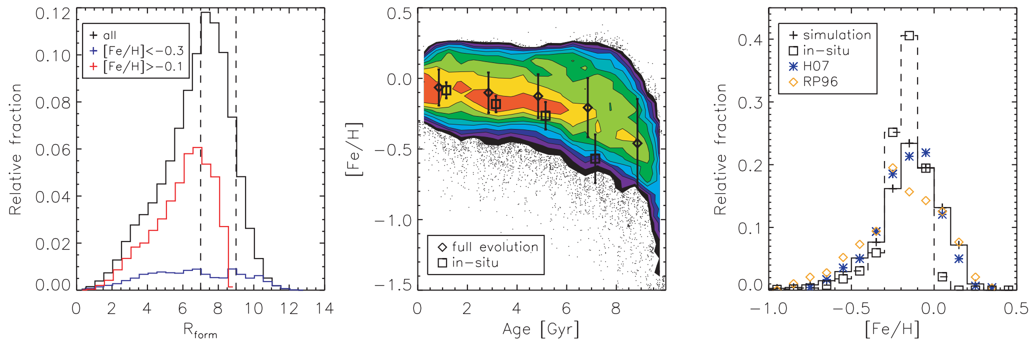

Fig. 1. Solar neighborhood stellar population properties. All panels are generated using stars that are found between $7 < R$ [kpc] < 9 at the end of the simulation (marked by vertical dashed lines in the left panel). **Left:** Distribution of formation radii; **Center:** Age-metallicity relation; **Right:** Metallicity distribution function.

(see also Sect. 3.6.2 in Binney & Tremaine 2008).

In Figure 2, we show the dependence of thickness measured as the root-mean-square of the z position (top panels) and velocity dispersion (bottom panels) on age (y-axis) and change in radius (x-axis). Each panel is constructed for stars that form in a given range of R (shown at the top of each panel). Each square represents a co-eval population of stars that on-average had a common history. Those stars did not need to remain together at all times, they simply started their lives in a similar place and are found again in a similar location at the end of the simulation. The simulation used is the same as in Loebman et al. (2011).

Moving across any of the panels horizontally at a fixed age gives the effect of migration on the given quantity, and moving vertically at a fixed ΔR shows the effect of heating. In the top two panels, it is clear that for $\Delta R > 0$, the stars tend to thicken. If they migrate significantly inwards, they begin to encounter inner-disk structure that can rapidly heat them and therefore we see also an increase in thickness for $\Delta R < 0$. At each fixed ΔR, it is also evident that stars heat, since Δz_{rms} increases with age everywhere. Therefore both processes, heating as well as migration, contribute to the thickening of a population. For example, a 6 Gyr old population in the top left panel thickens by heating by ~ 200 pc (at $\Delta R \sim 0$). However, the population of the same age that formed in the same part of the disk but ended up 4 kpc further out in the disk has thickened by 500 pc. (Roškar et al. 2012a) show that migration and heating cause roughly equal amounts of thickening in these simulations. For the kinematically coldest populations, they also showed that the amount of thickening agrees well with theoretical expecations, which assume conservation of vertical action from Schönrich & Binney (2012).

We can see similar trends in the bottom panels showing σ_z, the z-component of velocity dispersion. The trends are diagonal, indicating that both migration and heating contribute to the evolution of the velocity dispersion. σ_z also decreases with increasing ΔR, in agreement with Minchev et al. (2012). Note, however, that although the dispersion decreases with increasing ΔR, stars from the inner disk still end up in a kinematically hotter component when they reach the solar neighborhood at ~ 8 kpc. The thick disk of the MW is *defined* to have $\sigma_z \sim 35$ km/s (Bensby et al. 2003), which agrees well with the final velocity dispersion of these stars in the simulation. Therefore, even though they cool somewhat, they could still disguise as a thick disk population both structuraly and kinematicaly.

4. Conclusions

Migration of stars due to a mechanism that obfuscates their provenance by not leaving an obvious kinematic imprint has substantial implications for Galactic archaeology studies. In re-

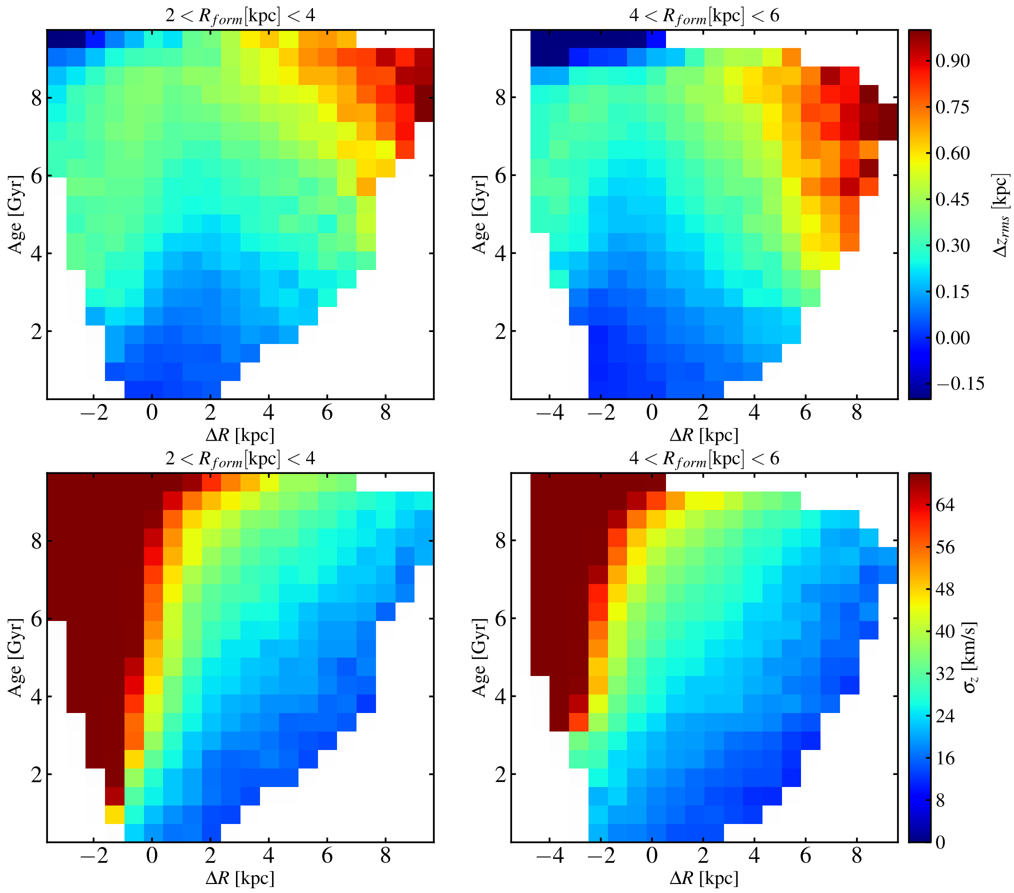

Fig. 2. The dependence of stellar population thickness (top panels) and vertical velocity dispersion (bottom panels) on age and change in radius ΔR. The quantities are computed for particles forming in the radial interval indicated at the top of each panel.

cent years, much attention has been devoted to this phenomenon as well as to other mechanisms that can alter the structure of disks, such as bar formation and satellite bombardment. Of particular interest is the possibility that stars which formed in the inner disk of the Milky Way may partially populate the thickened component near the solar radius. The efforts to understand such effects come at a good time, as the volume and quality of data of the Milky Way structure are increasing at a rapid pace and several much-anticipated projects such as Gaia are nearing first-light.

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