Mem. S.A.It. Suppl. Vol. 25, 11

Memorie della
Supplementi

The structure and formation of the Milky Way disks*

M. Haywood

GEPI, Observatoire de Paris, CNRS, Université Paris Diderot, 5 place Jules Janssen, 92190, Meudon France

Abstract. I go through the recent literature about the Milky Way thin and thick disks and show that, in spite of some recent claims, radial migration is not necessary to make the Galaxy look as it is, and that - at least in the case of the Milky Way - the inside-out process is still only a paradigm. Outlines of a scenario that has been worked out in details in Haywood et al. (2013) and which reconciles recent results from large scale surveys and local data are given.

Key words. Stars: abundances – Stars: kinematics and dynamics – Galaxy: solar neighborhood – Galaxy: disk – Galaxy: evolution

1. Introduction

A stellar population is commonly defined as an ensemble of stars that share some common observable properties (Baade 1944). Ideally, a useful definition would allow us to link these observable quantities to properties that we think uniquely define the conditions of the formation of the population. Ultimately, such an approach would help us in finding out how the formation of individual stellar populations relates to the evolution of galaxies. In practice, however, such goal seems to have remained largely out of touch and there is no simple way to define unambiguously a single population of stars. An example of this failure is epitomized by the recent discussion about the existence of a thick disk as a separate population in its own right (e.g. Bovy et al. 2012). Structural parameters may give us a hint of the existence of such a population in the Milky Way (Gilmore & Reid 1983), but no clue as to its origin or to its link to the other populations. Kinematics is also often used to segregate thin and thick disk stars (e.g. Soubiran et al. 2003; Bensby et al. 2003), but have currently offered few insights beyond simple classification. Finally, chemical characteristics have been proposed as a way to parametrize the properties of various stellar populations in the Milky Way (scale height, scale length, kinematics, etc. see Bovy et al. 2012), or for setting limits on the characteristics of the thin and thick disks (see Navarro et al, 2011), but defined in an arbitrary way, and with no direct evidence that these definitions correspond to the properties of the interstellar medium (ISM) at a particular epoch. Up to now, no clear picture has emerged as to where to put boundaries or even if boundaries exist between the thick and thin disk population (Norris 1987; Bovy et al. 2012).

Send offprint requests to: M. Haywood

* This work and many of the ideas presented here were developed in collaboration with P. Di Matteo, D. Katz, A. Gomez (GEPI, Observatoire de Paris, France) and M. Lehnert (IAP, France).

Perhaps a more insightful approach would reverse this proposition: identify the markers that trace best the conditions of formation of stars at a given epoch, then define the population accordingly. In doing so, we may have to recognise that what we have, in the last 30 years, taken the tree for the forest by identifying a scale height component, an ellipsoïd, or a level of alpha enrichment as the defining characteristics of a population. Here we give a simple outline of what this approach could be (see Haywood (2013) et al. for a detailed account), while reviewing our present knowledge of the Milky Way disks, evocating various questions such as: is the presence of a step in metallicity at about 10 kpc and the termination of the alpha-rich population at about the same radius (Cheng et al. 2012a) mere coincidence or is there something more about it ? Why is the content of alpha-elements higher in the outer disk ? If radial mixing has been as important as advocated in some recent papers, why is the outer disk not dominated by stars with [Fe/H]>0 ? No radial but a vertical gradient has been found in the thick disk: what does it imply ? Does the combination of an old thick disk with a short scale length + a younger thin disk with a longer scale length makes an inside-out formation scenario ?

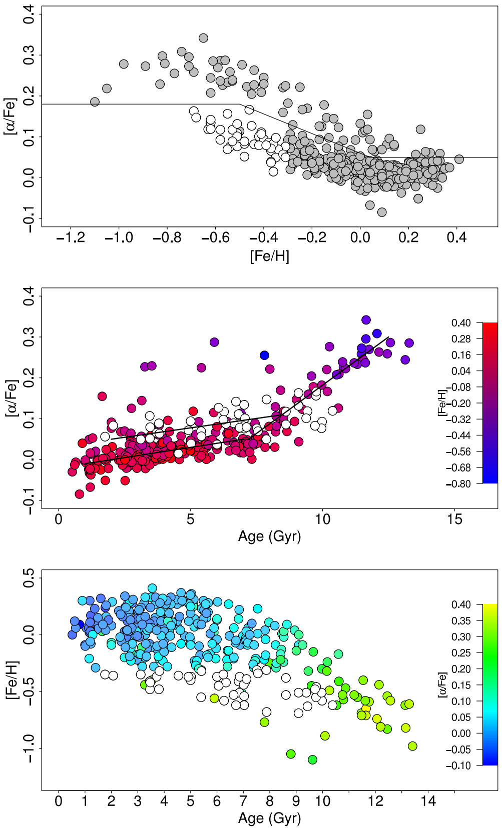

Fig. 1. Top panel: the [Fe/H]-[α/Fe] distribution of stars in Adibekyan et al. (2012), for stars which could be dated. Low metallicity thin disk stars are plotted as empty circles. Middle Panel: the age-[α/Fe] relation as obtained in Haywood et al. (2013) from these same objects. The color scale codes the metallicity of the stars. The branch at age > 8 Gyr is identified as the thick disk phase, and the thin disk below this limit. Metal-poor thin disk stars draw a sequence parallel to thin disk objects. Bottom panel: Age-metallicity relation for the same stars. Color scale codes the [α/Fe] content of stars. Note how well the alpha-element content is correlated with age. Once metal-poor thin disk stars are identified at ages >8 Gyr, the thick disk age-metallicity relation is conspicuous (colored points at age >8 Gyr).

2. Redefining the thin and thick disks

Fig. 1 (top panel) shows [α/Fe] *vs* [Fe/H] for a sample of F and G dwarfs from Adibekyan et al. (2012) for which good ages could be derived (see Haywood et al. 2013). The distribution of [α/Fe] *vs* age (middle panel) shows that the rate at which the alpha enhancement declines has a clear break at ~8 Gyr. That rate is a factor of 5 higher for stars older than ~8 Gyr. Thin disk stars with [Fe/H]<-0.3 (white circles) make a sequence parallel to the main thin disk sequence. It is worth noting that the oldest metal-poor thin disk stars are as old as the youngest thick disk objects, at 8-10 Gyr.

Fig. 1 (bottom panel) shows the age-metallicity relation for the same sample. The color scale shows the neat variation of [α/Fe] as a function of age. On this plot, the old metal-poor thin disk stars are shown as white dots. These stars are probable wanderers from the outer disk (Haywood 2008). Once they are identified in the age-metallicity distribution, the correlation between age and metallicity for thick disk stars (coloured points between 8 and

13 Gyr) becomes much clearer, and is, in fact, very tight. The increase in metallicity in the thick disk phase (~0.15 dex Gyr^{-1}) is much steeper than in the thin disk (0.025 dex Gyr^{-1}), also implying a decrease by a factor of 5–6 in the production of iron after 8 Gyr. We define the thick and the thin (inner) disk stellar populations on the basis of these two plots, as two populations having radically different regimes of iron enrichment, with a clear break at ~ 8 Gyr. Metal-poor thin disk stars, identified by white circles on all three plots, with a probable origin in the outer disk (Haywood 2008), have followed a different evolutionary path, starting to form at a significantly more distant epoch than local thin disk objects.

The vertical velocity dispersion along the thin disk sequence (points below the line in Fig. 1, top panel) increases from about 9±1.5 km s^{-1} for alpha-young stars ([α/Fe]<0.0) to 35±6 km s^{-1} at [α/Fe]~0.15, while in the thick disk sequence, the dispersion varies from 22±3.7 km s^{-1} (at [α/Fe]~0.1) to 50±8.3 km s^{-1} (at [α/Fe]~0.3) – see Haywood et al. (2013) for details. It is interesting to note that it is the group of old, metal-poor thin disk stars that is responsible for the higher dispersion of 35 km s^{-1} in the thin disk sequence. When these objects are discarded by selecting thin disk sequence stars with [Fe/H]>-0.3 dex (-0.4 dex), the vertical dispersion rises to only 22 km s^{-1} (27 km s^{-1}).

It is interesting to note that the so-called age-σ_W relation, which has been investigated intensely in the hope of measuring a saturation value or a step that would indicate a transition from the thick to the thin disk, mixes stars of different provenance and which for a given age, have different vertical dispersions. Stars in the (inner) thin disk population with ages of ~8 Gyr have similar dispersion as thick disk objects with ages of ~9-10 Gyr, probably due to the same process of vertical heating. Paradoxically, stars of the metal-poor (outer) thin disk, also being 9-10 Gyr old, have a dispersion higher than that of the thick disk of the same age. Therefore, we should not be surprised that samples comprising different amount of metal-poor thin disk, "young" thick disk, would produce different overall σ_W at a given age, being a mix of stars of different populations with different vertical energies. We emphasize that discussing an age-σ_W relation is meaningful only if the contributions of the different components are properly disentangled.

3. Disk structure and formation

The fact that the age-metallicity-alpha relation in the thick disk is so well defined has many implications. Given that the sample discussed here must contain stars born in different places and different radii implies that the ISM from which the thick disk formed was homogeneous. This is confirmed by the lack of radial gradient measured on the SEGUE data (Cheng et al. 2012b). If the thick disk had formed with a gradient that was subsequently erased (by radial migration for example), we should detect it through significant dispersion in the age-metallicity relation. Moreover, if the ISM was well mixed during the whole thick disk phase, with chemical evolution giving rise to a monotonic enrichment up to values of metallicity and [α/Fe] found in the thin disk 8 Gyr ago, it is reasonable to suppose that the thick disk has set the initial conditions of the inner thin disk formation.

Evidences from vertical velocity dispersion imply that the "thick disk" population is not only thick, it has a thin component, with σ_W varying from about 50km.s^{-1} to 25 km.s^{-1}. This is not in contradiction with the results of Bovy et al. (2012): lower resolution spectroscopic [α/Fe] index, used as a proxy for age, will easily smear out the differences between the thin disk and "thin" thick disk, giving the impression of a continuum between the two populations. Note that an age-metallicity correlation in the thick disk, together with an age-σ_W relation is expected to give a vertical gradient: older and metal weaker stars will reach higher distances from the galactic plane. Hence the thick disk has a vertical (see Katz et al. 2011 and references therein), but no radial metallicity gradient (Cheng et al. 2012b).

Since the oldest metal-poor thin disk stars were formed at the same epoch as the youngest thick disk objects (8-10 Gyr), and since they have different metallicities and angular momentum, they must originate from a different region of the disk. Our suggestion (Haywood et al. 2013) is that the outer thin disk started to form stars while the formation of the thick disk was still going on in the inner parts. The similar amount of α element abundance found in the outer thin disk objects and the younger thick disk suggest the outer regions may have been contaminated by gas expelled from the then forming thick disk, diluted with more pristine accreted material.

The specific status of metal-poor thin disk stars is not spelled out in the study of Bovy et al. (2012), where they seem to be outliers to the scale height - scale length anticorrelation of their Fig. 5, and possibly generate the point that can be seen at (4.3 kpc, 440pc). Metal-poor thin disk stars don't fit into their scheme because they are resulting from the evolution of a different structure, namely the outer disk. Moreover, we emphasize that the outer thin disk is not specifically young, contrary to some expectations (Bovy et al. 2012, Roškar et al. 2012), as testified by their local representatives.

From these results, a scenario can be established (Haywood et al. 2013), whereby thick disk stars start forming in a turbulent ISM at $\sim$ 13 Gyr, giving rise to a thick stellar structure. The gaseous disk cools and stars continue to form in progressively thinner layers, a process that continues for several Gyr. Because of the violent, starbursting regime of the first gigayears, enriched gas from the thick disk is expelled to the outer regions where it dilutes with the incoming, more pristine gas from the galactic halo. At $\sim$10 Gyr, stars are able to form from this mixture in the outer (>10 kpc) disk. At about 8 Gyr, the regime of star formation changes to become more quiescent in the inner (< 10 kpc) disk, starting the formation of the thin disk.

4. Implications: radial migration

Since the suggestion by Sellwood & Binney (2002) that migration could play a significant role in redistributing stars in disks, there has been several studies suggesting that migration is necessary to explain patterns observed at the solar neighbourhood (Haywood 2008, Schönrich & Binney 2009ab, Loebman et al. 2011).

It has been suggested that the mean metallicity of solar neighborhood stars is dominated by objects that have migrated from the inner disk. This argument has been proposed in particular to explain how the mean metallicity at the solar radius had already reached [Fe/H]$\sim$-0.1 dex 8-10 Gyr ago. However, our results show that the thick disk stars set the chemical initial conditions for the formation of the thin disk, so there is no necessity to invoke the action of radial migration to explain the metallicity of the old thin disk, by bringing stars with [Fe/H]$\sim$–0.1 dex at the solar neighborhood. Moreover, the fact that the outer disk is dominated by stars with a metallicity significantly lower than that of the youngest thick disk means that no inner disk stars (either thin disk or thick disk) have migrated to the outer disk to significant proportion in the last 10 Gyr.

In case of a more limited migration, just the tails of the solar neighborhood metallicity distribution (at [Fe/H]<-0.2 dex and [Fe/H]>+0.2 dex) could be populated by stars that come from other radii. Which mechanism (churning/blurring) is more likely to have produced such contamination? These contaminating stars have metallicities similar to stars found at 2-3 kpc from the Sun, and which have a mean metallicity of +0.2 dex at just 2 kpc towards the galactic center (Hill et al. 2012), and -0.3 dex at 10 kpc (Bensby et al. 2011). Simple estimates of radial excursions due to epicycle oscillations give of the order of 1-2 kpc at the solar galactocentric radii, which put stars of the inner or outer disk within reach of the solar vicinity. These stars are found in limited amount in the solar neighborhood (a few percent), and certainly does not requires large amount of radial migration across the solar circle. If only the tails require pollution by objects born outside the solar circle, then probably epicycle oscillation could bring a few percent of stars that dominate the disk at just 2 kpc from the solar radius. We consider that blurring (which we know to occur in disks) would be sufficient to explain these tails. Orbital parameters of metal-poor thin disk stars support this conclusion.

Our conclusion is, therefore, that no evidence of radial migration in the sense of churning is necessary to explain the characteristics of the sample studied here.

5. Implications: inside-out disk formation

An interesting consequence of the proposed scenario concerns the so-called inside-out paradigm that has been proposed for the formation of disks (Larson 1976, and e.g. Brooks et al. 2012), and which received support from the analysis of Bovy et al. (2012). How much of that picture is due to the superposition of two components that have different scale length and age, and how much to the effect of a real inside-out process?

Combining our results with those of Bovy et al. (2012), one can see that the formation of the thick disk, which lasted 4-5 Gyr (Fig. 1), did not produce any significant increase in scale length – the scale length remains < 2kpc down to [α/Fe]$\sim$ 0.25, which, in their α abundance scale, is the passage to a thin disk regime (see their Fig. 5). At the same time, the thick disk scale height decreased by a factor of 2 to 3, which it well in agreement with the decrease in σ_W mentionned above. Moreover, a tight age-metallicity relation combined with an inside-out scenario, should produce a radial metallicity, or [α/Fe], gradient in the thick disk, as mentionned in Haywood et al.(2013). This is not observed (Cheng et al. 2012b).

Within the (inner) thin disk itself, whose formation lasted 8 Gyr, one can hardly see any trend of an inside-out process in the Fig. 5 of Bovy et al. (2012) (their blue and cyan points in the upper panel of Fig. 5, or orange and red points in the lower panel): Several points with the lowest [α/Fe] (<0.05 dex), and high metallicities, which ought to be young and to have long scale length in the scheme of Bovy et al., have indeed scale length as short as 2.1 or 2.8 kpc, while some others, at the limit between the thick and thin disk in terms of [α/Fe], have scale length greater than 4 kpc.

It is clearly the combination of the two structures that gives Bovy et al. the impetus to favor an inside-out process, but this is much less supported once one look more into the details of the age structure of each population.

6. Conclusions

Present and future data are/will be of sufficient quality that we will soon have to revise our working definition of stellar populations, an approach outlined here by linking the gross characteristics of the stellar disks of the Milky Way to properties that reflect the ISM in which they were formed at an identifiable epoch. In doing so however, we pulled the old labelling of "thin" and "thick" disks further away from their original meaning. In our new definition, the thick disk is not only thick, it has a thin component, it is not only older than, but also coeval with the (outer) thin disk. The "thin" outer disk, as sampled in the solar vicinity, shows vertical velocities more akin to a conventional "thick" disk. We emphazise that the way we apprehend the thin/thick disk problem is not reducible to a question of continuity/discontinuity between components as defined by a series of scale heights and scale lengths. Even though we show that there is direct filiation between the inner thin disk and the thick disk, we maintain a distinction between the two, due to the evidence of different regimes in the ISM at these epochs, not to the evidence of structural discontinuity.

Acknowledgements. The author warmly thanks the organisers, P. Di Matteo and C. Jog for their invitation at EWASS 2012. The author acknowledges the support of the French Agence Nationale de la Recherche (ANR) under contract ANR-10-BLAN-0508 (Galhis project).

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