EPJ Web of Conferences **19**, 01010 (2012)
DOI: 10.1051/epjconf/20121901010
© Owned by the authors, published by EDP Sciences, 2012

Kinematic and chemical components in the solar neighbourhood

J.F. Navarro[a]

Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada V8P 5C2

Abstract. Abundance data on solar neighbourhood stars suggest the presence of chemically-distinct stellar components in the solar neighbourhood. When the abundances of Fe, α elements, and the r-process element Eu are considered together, stars separate neatly into two groups that delineate the thin and thick disk components of the Milky Way. The group akin to the thin disk is traced by stars of relatively high Fe content and low [α/Fe] ratios. The thick disk-like group overlaps the thin disk in [Fe/H] but has higher abundances of α elements and Eu. Fe-poor stars with low [α/Fe] ratios, however, seem to belong to a separate, dynamically-cold, non-rotating component likely associated with debris from past accretion events. The kinematically-hot stellar halo dominates the sample at the metal-poor end. These results suggest that it may be possible to define the main dynamical components of the solar neighbourhood using *only* their chemistry, an approach with a number of interesting consequences. For example, the average rotation speed and velocity dispersion of *thin disk* stars is roughly independent of metallicity, a result unexpected in most current theories of thin-disk formation. In this scenario, the familiar increase in the velocity dispersion of disk stars with decreasing metallicity is the result of the increasing prevalence of the thick disk at lower metallicities, rather than of the sustained operation of a dynamical heating mechanism. The substantial overlap in [Fe/H] and, likely, stellar age, of the various components might affect other reported trends in the properties of stars in the solar neighbourhood. A purely chemical characterization of these components allows the use of their kinematics to assess their origin, an powerful approach denied to traditional ways of apportioning stars to the various Galactic components.

1. INTRODUCTION

The vertical distribution of stars in the solar cylinder is poorly approximated by a single exponential law, a result that led to the view that two components of different scaleheights make up the Galactic disk [1]. Since there is no *a priori* reason why the vertical structure of galaxy disks cannot be more complex than a single exponential, the concept of separate "thin" and "thick" disk components in the Milky Way, however, is useful insofar as they refer to different types of stars; i.e., distinct in ways other than kinematics or spatial distribution.

The finding that thick disk stars are substantially older and more highly enriched in α elements than their thin disk counterparts supports the two-component nature of the Galactic disk [2]. The thin and thick disks have metallicity distributions that overlap in [Fe/H] but that differ, *at given* [Fe/H], in their kinematics, age, and α content. This dichotomy in properties at fixed metallicity requires adjustments to traditional models of chemical evolution, which have invoked violent accretion events, as well as episodic hiatus in star formation, to explain the data [3]. Such events may reset selectively the heavy-element abundance of the ISM, disrupting the monotonic trends with [Fe/H] expected in simple models of chemical evolution and enabling better fits to the data.

Accretion models are not the only ones able to explain the data. Indeed, a few recent papers argue that the chemo-dynamical evidence for accretion events is weak and that all relevant data can be explained

---

[a] e-mail: `jfn@uvic.ca`

This is an Open Access article distributed under the terms of the Creative Commons Attribution-Noncommercial License 3.0, which permits unrestricted use, distribution, and reproduction in any noncommercial medium, provided the original work is properly cited.

Article available at http://www.epj-conferences.org or http://dx.doi.org/10.1051/epjconf/20121901010

by reconsidering the importance of radial migration of both gas and stars during the evolution of the disk [4, 5]. Inspiration for this work came from the realization that inhomogeneities in the disk can transport, resonantly, stars across the disk without increasing their eccentricity [6]. Stars on nearly circular orbits in the solar neighbourhood could therefore have formed at different radii in the Galactic disk. Simple but plausible modesl that includes radial migration are indeed able to accommodate most available data for the thin and thick disks without invoking a accretion event at all [5].

Deciding between migration or accretion scenarios requires identifying patterns in stellar properties that point to the presence of truly distinct stellar component and assessing whether their properties are the result of secular evolution or accretion events. In general, secular evolution mechanisms such as radial migration should lead to increased mixing, blurring the boundaries between components and leaving dynamical and chemical imprints different from those predicted by accretion scenarios.

Take, as an example, the wide range in metallicity spanned by stars on nearly-circular orbits (the thin disk) in the solar neighbourhood. In migration-based scenarios the metal-poor tail of the local thin disk is populated by stars that formed further out in the Galaxy, while the opposite holds for stars in the metal-rich tail. Stars at these two extremes were born with very different angular momenta, and this difference would be preserved in local samples even after their orbits have migrated to the solar neighbourhood Therefore very metal-rich (poor) stars would be found in the solar neighbourhood at relatively low (high) rotation velocities. A relatively clean prediction of migration models is, then, the presence of a negative correlation between mean rotation speed and metallicity for stars in the thin disk.

Such correlations have been difficult to study because of the widespread practice of assigning stars to the thick or thin disk according to their kinematics. Although this may be an expeditious procedure, it imposes an obvious bias that precludes searching for correlations of the kind alluded to in the preceding paragraph. It would be much more useful to devise a *purely chemical* characterization of the various components in the Galaxy.

We explore these ideas here using a compilation of data for stars in the solar neighbourhood with good estimates of their spatial motions and reliable measurements of their heavy-element abundances. We have used the compilation of [8], supplemented by data in the more recent papers of [3], [9] and [10]. The sample spans a wide range in metallicity ($-4 < [\mathrm{Fe/H}] < +0.5$), and there are reliable abundance measurements of [Fe/H] and of the α elements Mg, Ti, and Ca, for 743 stars. Abundance measurements of the r-process element Eu are also available for 306 of those stars. We use these data to identify separate components on the basis of chemistry alone, and use their kinematics to place constraints on their possible origins. A full account of this work is presented in [7].

2. RESULTS

The top-left panel of Fig. 1 suggests that stars with measured Fe, α and Eu abundances separate into two "families", one with high [Fe/H] and low $[(\alpha + \mathrm{Eu})/\mathrm{Fe}]$ and the other with lower [Fe/H] and high $[(\alpha + \mathrm{Eu})/\mathrm{Fe}]$. This separation highlights the well-known α enhancement of thick disk stars relative to the thin disk, accentuated by the addition of Eu to the α index. The data suggest that a plausible boundary between the two families may be drawn at $[(\alpha + \mathrm{Eu})/\mathrm{Fe}] = 0.2$.

Guided by this, we have chosen arbitrary but plausible boundaries to define the two components: (i) $[\mathrm{Fe/H}] > -0.7$, and (ii) $[(\alpha + \mathrm{Eu})/\mathrm{Fe}] < 0.2$, distinguishes well one of the two families of stars. This family (coloured red) contains the Sun (which would be at the origin of the plot) and contains mostly stars associated with the thin disk as usually conceived.

The distinction between components blurs when including stars for which Eu abundances are not available (see bottom panel of Fig. 1), but the sample more than doubles. In order to take advantage of this larger sample, we *define the thin disk* by the same criteria as above, namely

- (i) $[\mathrm{Fe/H}] > -0.7$; and
- (ii) $[\alpha/\mathrm{Fe}] < 0.2$.

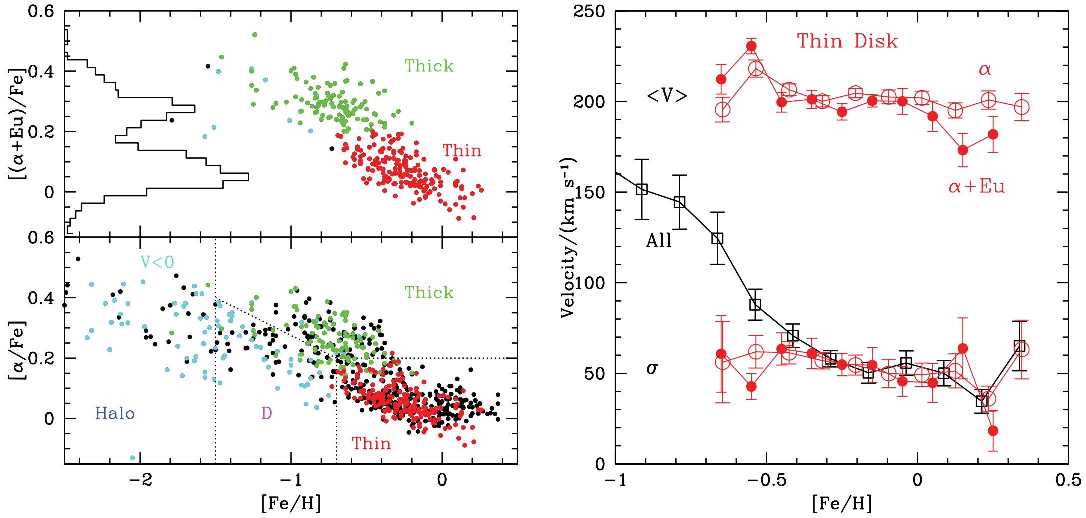

Figure 1. *Left:* α and α + Eu enhancement of stars in our sample versus iron abundance, both referred to solar values. *Right:* Mean velocity and velocity dispersion of stars in the thin disk (circles) as a function of iron abundance. Solid circles refer to stars with α + Eu measurements, open circles to those with α measurements alone.

We emphasize that the criteria above are purely chemical. This differs from the traditional practice of selecting thin disk stars by their kinematics and might therefore include stars not expected in kinematic definitions of the "thin disk".

The data in Fig. 1 show the wide range in [Fe/H] spanned by thin disk stars, as well as the strong correlation between the abundance ratio and metallicity in this population; [α/Fe] and [(α + Eu)/Fe] decrease slightly but steadily with increasing [Fe/H]. This trend suggests two possible interpretations. In standard chemical evolution models it is reminiscent of a self-enriched population whose star formation timescale is long compared with the lifetime of stars that end their lives as supernovae type Ia (SNIa). One difficulty with this interpretation is that the wide range in metallicity spanned by the thin disk ($-0.7 <$ [Fe/H] $< +0.4$; see top panel of Fig. 1) requires a protracted star formation history and implies a strong correlation between age and metallicity. This seems at odds with the relatively weak age-[Fe/H] relation observed for thin disk stars [4].

These difficulties are circumvented in a second, different interpretation of the properties of the local thin disk. As shown by [5], radial migration can populate the vicinity of the Sun with "thin disk" stars that formed either inside or outside the Solar circle. The properties of local thin disk stars might not trace the chemical history of the solar neighbourhood, but rather reflect the spread in birth radii of such stars. One disadvantage of this scenario is that it requires a steeper metallicity gradient in the ISM than is usually accepted, as well as careful balancing of the timescales of star formation, radial migration, and gas infall at different radii in order to explain the observed slope of the [α/Fe]-[Fe/H] correlation.

One potential test of the migration scenario was discussed in the Introduction, and concerns the prediction of a negative correlation between metallicity and rotation speed *in the thin disk*. We explore this in the right-hand panel of Fig. 1: there is indeed a weak negative correlation when considering the α + Eu data, although the trend is weaker than expected from migration models. Note that the correlation actually goes away when considering the larger sample without Eu (open circles) so, if there is indeed a correlation it is quite weak. A more recent analysis of SDSS data [11] confirms this finding.

Note as well that the velocity dispersion remains roughly constant over the whole range in [Fe/H] spanned by the thin disk. This should be contrasted with the familiar increase in σ with decreasing [Fe/H] [13], which is shown by the open squares in Fig. 1, computed using *all* stars in our compilation.

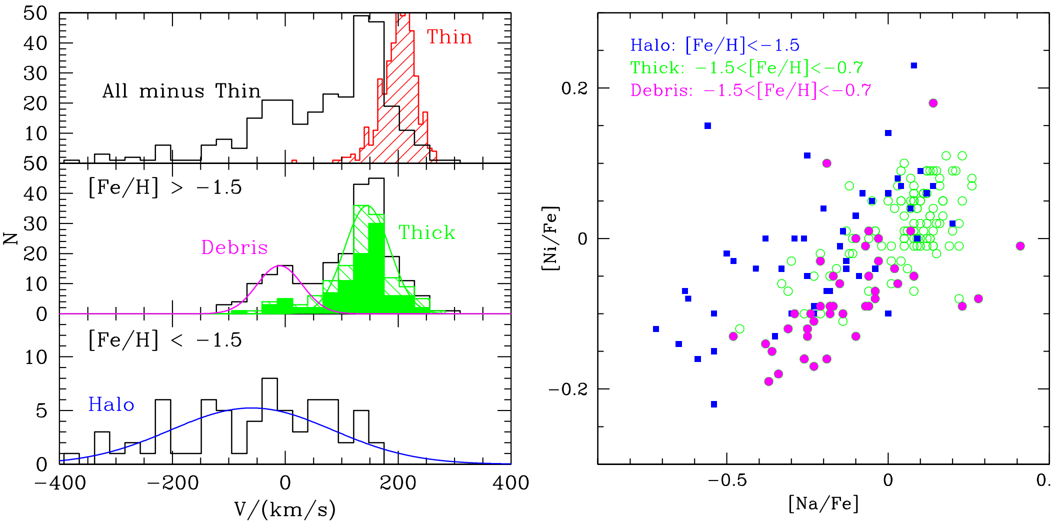

Figure 2. *Left:* Distribution of rotation velocity for stas in the samples identified in Fig. 1. *Right:* [Ni/Fe] vs [Na/Fe] correlation for all stars in our sample *not* in the thin disk.

The kinematic invariance of the thin disk with metallicity is a somewhat surprising result for either of the two scenarios advanced above. The absence of a strong $\langle V\rangle$-[Fe/H] correlation disfavours the migration scenario; on the other hand, *in-situ* self-enrichment scenarios would predict the velocity dispersion to rise with decreasing [Fe/H] since metal-poor stars would be, on average, older, and therefore exposed for longer to gravitational heating by inhomogeneities in the Galactic potential. The data in Fig. 1 disfavours such gradual heating; if present, the heating mechanism must operate promptly and saturate quickly.

If our interpretation is correct, then the increase in velocity dispersion with decreasing metallicity for stars in the vicinity of the Sun must result from the increased prevalence of the thick disk at low metallicity. This is shown in the top-left panel of Fig. 2, where we compare the distribution of the rotation speed (V component) of all stars in our sample with that of the thin disk.

The V distribution of stars *not* in the thin disk is complex, and hints at the presence of distinct dynamical components. It shows two well defined peaks, one at V $\sim$ 160 km/s and another at $V \sim$ 0 km/s, as well as a tail of fast counterrotating stars at highly-negative values of V. The first peak corresponds to a rotationally-supported structure: the traditional thick disk. Stars belonging to this rotating component seem to disappear from our sample when only metal-poor stars with [Fe/H] < -1.5 are considered (bottom-left panel of Fig. 2). The latter trace the classical, kinematically-hot, metal-poor stellar halo: the V distribution is consistent with a gaussian with velocity dispersion $\sigma_V \sim 144$ km/s (shown in the bottom panel with a blue curve).

Interestingly, the V distribution of non-thin-disk stars with [Fe/H] > -1.5 (middle panel of Fig. 2) shows even more clearly the double-peak structure noted above. The peak at V $\sim$ 160 km/s is well traced by the stars identified with the thick disk in the α + Eu panel of Fig. 1, shown by the solid-shaded histogram in the middle panel of Fig. 2.

Indeed, the peak is traced almost exclusively by stars with high values of [α/Fe]. This is shown by the shaded green histogram, which corresponds to all stars in the region labelled “Thick” in Fig. 1. The V distribution of these stars is well approximated by a gaussian with $\langle V\rangle = 145$ km/s and $\sigma_V = 40$ km/s that accounts for nearly all stars with $V > 100$ km/s.

The association between the thick disk and “high-α” stars is reinforced by inspecting the location of counterrotating stars in Fig. 1 (shown in cyan). These stars, which clearly do not belong to a rotationally-supported structure like the thick (or thin) disk, are evenly distributed among stars with $[\mathrm{Fe/H}] < -1.5$ but shun the "high-α" region in the range $-1.5 < [\mathrm{Fe/H}] < -0.7$. Of the 38 counterrotating stars in our sample with $-1.5 < [\mathrm{Fe/H}] < -0.7$, only 3 lie above the dotted line that delineates the "Thick" region in the bottom panel of Fig. 1.

It is tempting therefore to adopt a purely chemical definition of the thick disk in terms of [Fe/H] and $[\alpha/\mathrm{Fe}]$:

- (i) $[\mathrm{Fe/H}] > -1.5$;
- (ii) $[\alpha/\mathrm{Fe}] > 0.2 - ([\mathrm{Fe/H}] + 0.7)/4$ for $-1.5 < [\mathrm{Fe/H}] < -0.7$;
- (iii) $[\alpha/\mathrm{Fe}] > 0.2$ for $[\mathrm{Fe/H}] > -0.7$.

If our analysis is correct, then the thick disk emerges as a chemically and kinematically coherent component that spans a wide range in metallicity ($-1.5 < [\mathrm{Fe/H}] < -0.3$) and contains mainly stars highly enriched in α elements.

Note that the chemical definition of the thick disk is not perfect, since it includes some spurious stars with negative V which likely belong to a separate component. This may be seen in Fig. 2 as the peak centered at $V \sim 0$. These are stars with no net sense of rotation around the Galaxy and with a surprisingly low velocity dispersion $\sim 40\,\mathrm{km/s}$. (The W dispersion has a similar value.) On the other hand, their U velocity dispersion is large (~ 180 km/s). Further, the U distribution (not shown) is rather flat, with hints of two, symmetric peaks, one at $U \sim -250\,\mathrm{km/s}$ and another at $U \sim +250\,\mathrm{km/s}$.

This is actually the kinematic structure expected for a tidal stream originating in a dwarf galaxy whose orbital plane at the time of disruption was coincident with the plane of the Galaxy [12]. The low V and W velocity dispersions are easily explained in this scenario, since such stream would be, locally, kinematically cold and confined to the orbital plane. The double-peaked U distribution also arises naturally in this scenario if stream stars have apocentric radii outside the solar circle and pericentric radii inside the solar circle. Stream stars in the solar neighbourhood are therefore either going to their apocenter with large, positive U or coming from their apocenter, with symmetric $-$U.

This suggests that most non-thin-disk stars with $[\mathrm{Fe/H}] > -1.5$ and low, but still enhanced relative to solar, $[\alpha/\mathrm{Fe}]$ (previously thought to belong to the classical halo) belong to this new component. We inspect the Na and Ni content of such stars for supporting evidence of this conclusion. This is shown in te right-hand side of Fig. 2, where we show [Na/Fe] vs [Ni/Fe] for all stars in our sample with $[\mathrm{Fe/H}] < -0.7$ [10]. Blue squares correspond to the very metal poor stars in our sample ($[\mathrm{Fe/H}] < -1.5$); green open circles are stars in the α-rich "Thick" region of Fig. 1, and magenta filled circles denote stars in the α-poor "debris" ("D") region of Fig. 1. The three groups separate clearly in the Na-Ni plane, supporting our claim that the "debris" component is truly distinct from the thick disk and from the metal-poor "classical" halo.

Using the same [Fe/H] and $[\alpha/\mathrm{Fe}]$ parameters as above, we can characterize "debris" stars in the $[\alpha/\mathrm{Fe}]$ vs [Fe/H] plane (region labelled "D" in Fig. 1) by

- (i) $-1.5 < [\mathrm{Fe/H}] < -0.7$; and
- (ii) $[\alpha/\mathrm{Fe}] < 0.2 - ([\mathrm{Fe/H}] + 0.7)/4$.

We conclude that most metal-rich "α-poor" halo stars are indeed tidal debris from disrupted dwarfs [10].

3. SUMMARY

The preceding analysis suggests that apportioning the various components of the Galaxy according to purely chemical criteria is both possible and fruitful. The definition of the thin disk in the $[(\alpha + \mathrm{Eu})/\mathrm{Fe}]$ vs [Fe/H] plane is particularly straightforward, and suggests that the kinematics of the thin disk is invariant with metallicity. This is an intriguing result unexpected in migration-based scenarios for the chemo-dynamical evolution of the thin disk. It implies that the familiar increase in velocity dispersion with decreasing metallicity is the result of the increased prevalence of the thick disk at lower metallicities, rather than of the sustained operation of a dynamical heating mechanism. If confirmed, the kinematic invariance of the thin disk with metallicity will place strong constraints on the formation of the Galactic disk and on the role of accretion events, in situ formation, and/or migration.

The "thick disk" can also be charted in the [α/Fe] vs [Fe/H] plane. As reported in earlier work, it seems to contain mainly stars highly enriched in α elements. It shows as a separate dynamical component in rotation speed, with the bulk of its stars rotating at $V \sim 160\,\mathrm{km/s}$. A simple criterion in α content isolates most of these stars, although a few outliers with nearly zero, or negative, V velocities are also included. The latter might very well be contaminants from a different population that a crude boundary in the α-Fe plane is unable to weed out.

The inclusion of additional heavy elements in the defining criteria might enable a cleaner characterization of the thick disk. If that were possible, questions such as whether the thick disk shows evidence of self-enrichment, or whether correlations between metal content and velocity dispersion are present, could be addressed. This would allow us to distinguish between migration and accretion models and, among the latter, between those where the bulk of thick disk stars were either accreted or simply stirred.

A substantial fraction of stars in the range $-1.5 < [\mathrm{Fe/H}] < -0.7$ seem to belong to a dynamically-cold, non-rotating component with properties consistent with those of a tidal stream. These are mainly stars of low-α content, comparable in that regard to individual stars in many of the satellite companions of the Milky Way: the low-[Fe/H], α-poor region should be a good hunting ground for the remnants of accretion events.

Overall, our success in dividing and assigning stars of the solar neighbourhood to families of distinct chemistry and kinematics seems to favour models where accretion events have played a significant role in the formation of the Galaxy rather than models, such as those based on migration, where secular evolutionary mechanisms rule. We hasten to add, however, that the criteria to separate components proposed here are imperfect, and that our conclusions are based on small and heterogeneous samples. These samples likely conceal a number of biases which can only be revealed and lifted by a concerted effort to survey a large, volume-limited, kinematically-unbiased sample of stars with the high-resolution spectra needed to measure the abundance of individual heavy elements.

References

[1] Gilmore, G., & Reid, N. 1983, MNRAS, 202, 1025
[2] Bensby, T., Zenn, A. R., Oey, M. S., & Feltzing, S. 2007, ApJ, 663, L13
[3] Reddy, B. E., Lambert, D. L., & Allende Prieto, C. 2006, MNRAS, 367, 1329
[4] Haywood, M. 2008, MNRAS, 388, 1175
[5] Schönrich, R., & Binney, J. 2009, MNRAS, 396, 203
[6] Sellwood, J. A., & Binney, J. J. 2002, MNRAS, 336, 785
[7] Navarro, J. F., Abadi, M. G., Venn, K. A., Freeman, K. C., & Anguiano, B. 2011, MNRAS, 412, 1203
[8] Venn, K. A., Irwin, M., Shetrone, M. D., et al. 2004, AJ, 128, 1177
[9] Bensby, T., Feltzing, S., Lundström, I., & Ilyin, I. 2005, A&A, 433, 185
[10] Nissen, P. E., & Schuster, W. J. 2010, A&A, 511, L10
[11] Lee, Y. S., Beers, T. C., An, D., et al. 2011, ApJ, 738, 187
[12] Meza, A., Navarro, J. F., Abadi, M. G., & Steinmetz, M. 2005, MNRAS, 359, 93
[13] Strömgren, B. 1987, The Galaxy, 229