Through thick and thin: kinematic and chemical components in the solar neighbourhood

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ABSTRACT

We search for chemically distinct stellar components in the solar neighbourhood using a compilation of published data. Extending earlier work, we show that 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 traditional thin and thick disc components of the Milky Way. The group akin to the thin disc is traced by stars with [Fe/H] > -0.7 and [α/Fe] < 0.2. The thick disc-like group overlaps the thin disc in [Fe/H] but has higher abundances of α elements and Eu. Stars in the range $-1.5 <$ [Fe/H] < -0.7 with low [α/Fe] ratios, however, seem to belong to a separate, dynamically cold, non-rotating component that we associate with tidal debris. The kinematically hot stellar halo dominates the sample for [Fe/H] < -1.5. 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. With such definition, the kinematics of *thin disc* stars is found to be independent of metallicity: their average rotation speed remains roughly constant in the range $-0.7 <$ [Fe/H] $< +0.4$, a result that argues against radial migration having played a substantial role in the evolution of the thin disc. The velocity dispersion of the thin disc is also independent of [Fe/H], implying that the familiar increase in velocity dispersion with decreasing metallicity is the result of the increasing prevalence of the thick disc 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 would enable us to scrutinize these trends critically in order to understand which result from accretion events and which result from secular changes in the properties of the Galaxy.

Key words: Galaxy: abundances – Galaxy: evolution – Galaxy: formation – Galaxy: kinematics and dynamics – galaxies: formation – galaxies: structure.

1 INTRODUCTION

The discovery that the vertical distribution of stars in the solar cylinder is best approximated by two exponential laws suggested the presence of two components of different scaleheights and ushered in the concept of the Galactic thick disc (Gilmore & Reid 1983). The concept of separate 'thin' and 'thick' disc 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. Since there is no a priori reason why the vertical structure of galaxy discs cannot be more complex than a single exponential, confirming the identity of the thick disc as a component truly distinct from the thin disc requires additional evidence.

In that regard, the finding that thick disc stars are substantially older and more highly enriched in α elements than their thin disc counterparts supports the two-component nature of the Galactic disc (Gilmore & Wyse 1985; Gratton et al. 1996; Fuhrmann 1998; Prochaska et al. 2000; Bensby, Feltzing & Lundström 2003; Reddy, Lambert & Allende Prieto 2006; Bensby et al. 2007; Fuhrmann 2008). The thin and thick discs have metallicity distributions that overlap in [Fe/H] but that differ, *at given* [Fe/H], in their kinematics,

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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 (see e.g. Chiappini, Matteucci & Gratton 1997; Reddy et al. 2006). 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.

The price to pay is one of increased model complexity. Did accretion events supply mostly gas or stars to the disc? Were stars in the thick disc brought into the Galaxy during the event or is the thick disc the stirred-up remnant of an early thin disc? How many accretion events took place? What were the masses of the accreted dwarfs? When did these events take place? Accretion models provide only rudimentary answers to these key questions and, as a result, there is little consensus in the community regarding the origin of the thick disc.

This state of affairs has been highlighted by a number of recent papers, which argue that the chemo-dynamical evidence for accretion events is weak and that all relevant data can be explained by reconsidering the importance of radial migration of both gas and stars during the evolution of the disc (Haywood 2008; Roškar et al. 2008; Schönrich & Binney 2009a). Inspiration for this work came from the realization by Sellwood & Binney (2002) that inhomogeneities in the disc do not just perturb disc stars diffusively, easing them gradually into more and more eccentric orbits, but can also transport, resonantly, stars across the disc without increasing their eccentricity. Stars on nearly circular orbits in the solar neighbourhood could therefore have formed at different radii in the Galactic disc. The properties of local thin disc stars may thus reflect large-scale gradients in the Galaxy rather than different conditions in the solar neighbourhood at the time of their formation. Using a simple but plausible model that includes radial migration, Schönrich & Binney (2009b) demonstrate that most available data for the thin and thick discs can be accommodated without invoking a violent accretion event at all.

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 disc) in the solar neighbourhood. In migration-based scenarios the metal-poor tail of the local thin disc 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 (Schönrich & Binney 2009b). 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 disc.

Such correlations have been difficult to study because of the widespread practice of assigning stars to the thick or thin disc 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. After all, chemistry is a relatively stable property of a star that relates it to the conditions at the time/place of its birth, whereas its distance to the centre, vertical height or spatial velocity are far less durable features.

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 focus on spectroscopic samples where abundance of individual elements, such as Fe, Mg, Ti and Ca, are also available. We use these data to apportion stars to separate components on the basis of chemistry alone, and use their kinematics to place constraints on their possible origins.

2 DATA SET

We have used the compilation of Venn et al. (2004), which includes abundance data for solar neighbourhood stars with good spatial motions, supplemented by data in the more recent papers of Reddy et al. (2006), Bensby et al. (2005) and Nissen & Schuster (2010). This is a heterogeneous compilation of data from many different sources. We have gone carefully through this compilation in order to remove repeated stars and to bring all velocities to a consistent reference frame, taking into account the fact that some papers use either right- or left-handed *UVW* frames. The sample spans a wide range in metallicity ($-4 <$ [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 shall use these two subsamples in what follows. As in Venn et al. (2004), the spatial velocities assume that the Sun moves in a Galactic reference frame with $(U, V, W) = (9, 232, 7)$ km s^{-1} and that the local standard of rest (LSR) has $V_{\mathrm{LSR}} = 220$ km s^{-1}.

3 RESULTS

Fig. 1 shows, as a function of the iron content, [Fe/H], an index measuring the average abundance of the α elements Mg, Ti and Ca, plus the *r*-process element Eu for all stars in our sample. The index is constructed by simply averaging the Mg, Ti, Ca and Eu abundances. As usual, all quantities are shown in log$_{10}$ units normalized to solar values. Like the α elements, Eu is thought to form mainly in massive stars, and it therefore may be combined with the α elements to define an index that gauges the importance of massive-star nucleosynthesis in a given stellar component.

3.1 A chemical definition of the thin disc

Fig. 1 suggests that stars with measured Fe, α and Eu abundances separate into two 'families', one with high [Fe/H] and low [(α + Eu)/Fe] (shown in red) and the other with lower [Fe/H] and high [(α + Eu)/Fe] (green). This separation is confirmed in the top panel of Fig. 2, which is identical to Fig. 1 but for the index normalized to Fe. The [(α + Eu)/Fe] histogram, which should be relatively free from selection biases, hints strongly at the presence of two distinct components. This separation highlights the well-known α enhancement of thick disc stars relative to the thin disc, 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 [(α + Eu)/Fe] $= 0.2$, the value that roughly marks the 'valley' in the histogram.
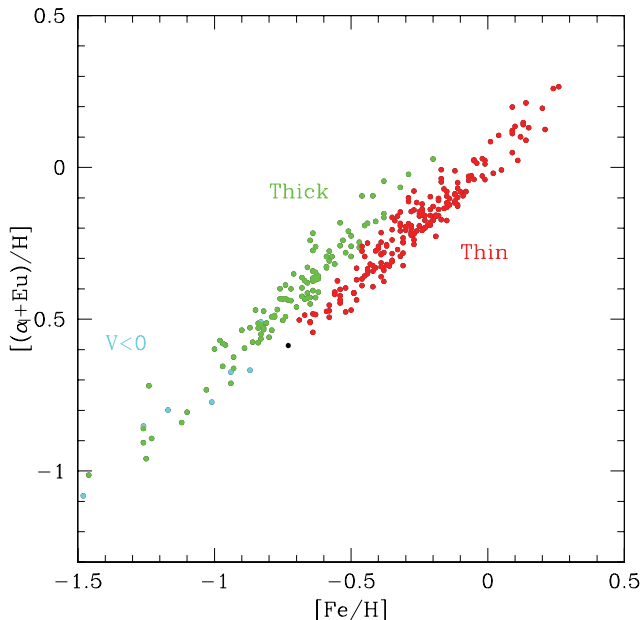
Figure 1. Iron abundance versus an index constructed by averaging the abundance of the α elements (Mg, Ti and Ca) plus the *r*-process element Eu. Note the presence of two well-defined 'families' of stars each spanning a wide range in [Fe/H]. Stars in the family plotted in red (i.e. those with [α/Fe] < 0.2; see Fig. 2) are those traditionally assigned to the thin disc. Those in green are α-enhanced stars ([α/Fe] > 0.2) usually associated with the thick disc. Counterrotating stars unlikely to belong to either the thin or thick discs are shown in cyan.

Guided by this, we have chosen arbitrary but plausible boundaries to define the two components in Fig. 1 and the top panel of Fig. 2, which we colour in green and red, respectively. The simple criteria, (i) [Fe/H] > −0.7 and (ii) [(α + Eu)/Fe] < 0.2, distinguish 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 disc as usually conceived. The minimum [Fe/H] boundary is suggested by the fact that the most metal-rich counterrotating star in the sample (certainly not a member of the thin disc) has [Fe/H] $\sim$ −0.7.

The distinction between components blurs when including stars for which Eu abundances are not available (see bottom panel of Fig. 2), but the sample more than doubles. In order to take advantage of this larger sample, we *define the thin disc* by the same criteria as above, namely

(i) [Fe/H] > −0.7 and
(ii) [α/Fe] < 0.2.

We emphasize that the above criteria are purely chemical. This differs from the traditional practice of selecting thin disc stars by their kinematics and might therefore include stars not expected in kinematic definitions of the 'thin disc'. We shall hereafter call them 'thin disc stars', but this caveat should be kept in mind when comparing our results with other work on the topic.

Both panels of Fig. 2 show the wide range in [Fe/H] spanned by thin disc 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 time-scale is long compared with the
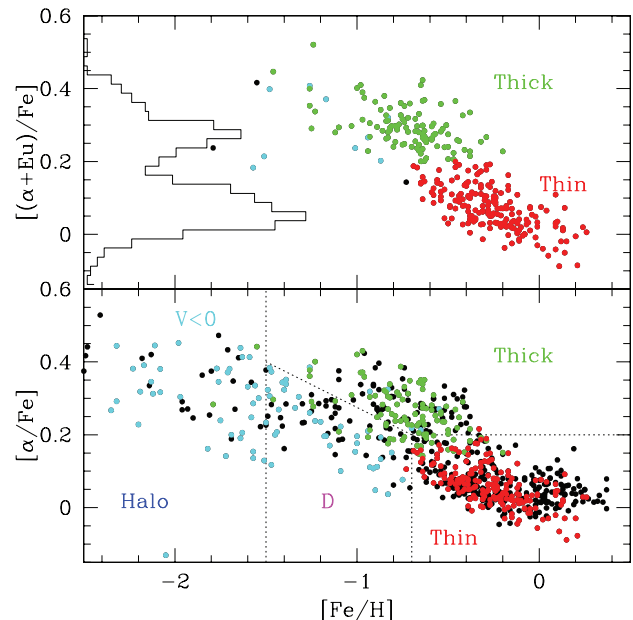
Figure 2. Top panel: same as Fig. 1, but for the α + Eu index normalized to Fe. The presence of the two families of stars hinted at in Fig. 1 is confirmed by the [(α + Eu)/Fe] histogram. We identify the bottom sequence, shown in red, with the thin disc, and the top sequence, in green, with the thick disc. The conditions used to define the thin disc are (i) [Fe/H] > −0.7 and (ii) [(α + Eu)/Fe] < 0.2. Stars in the region defined by [Fe/H] > −1.5 and [(α + Eu)/Fe] > 0.2 are those traditionally associated with the thick disc. Note that this condition allows in some counterrotating stars ($V < 0$, shown in cyan) unlikely to be true members of the thick disc; the remainder are shown in black. Bottom panel: same as top panel but for the index without Eu. Stars with available Eu are shown here using the same red and green colours as in the top panel. Stars in cyan are counterrotating ($V < 0$) stars, unlikely to belong to either the thin or thick discs. Note that counterrotating stars in the range −1.5 < [Fe/H] < −0.7 have lower [α/Fe] values than those of the thick disc. These stars appear to belong to a component ('D') separate from the thin and thick disc or the traditional stellar halo, which we link to tidal debris. See text for further details.

lifetime of stars that end their lives as supernovae Type Ia (SNIa). These supernovae return mostly Fe and little α to the ISM, and therefore the ratio [α/Fe] of successive generations of stars declines steadily as [Fe/H] increases.

In this interpretation, the formation of the metal-poor tail of the thin disc precedes that of the metal-rich one since [Fe/H] is assumed to march roughly monotonically with time. One difficulty with this interpretation is that the wide range in metallicity spanned by the thin disc (−0.7 < [Fe/H] < +0.4; see top panel of Fig. 2) 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 disc stars. One must note here that stellar ages are notoriously difficult to estimate, and that the strength of the predicted correlation depends on assumptions about infall and star formation efficiency that are difficult to pin down accurately. Despite these caveats, a number of authors have concluded that the lack of a strong age–metallicity relation signals the need to consider a different mechanism to explain the properties of the thin disc (see e.g. Haywood 2008, and references therein).
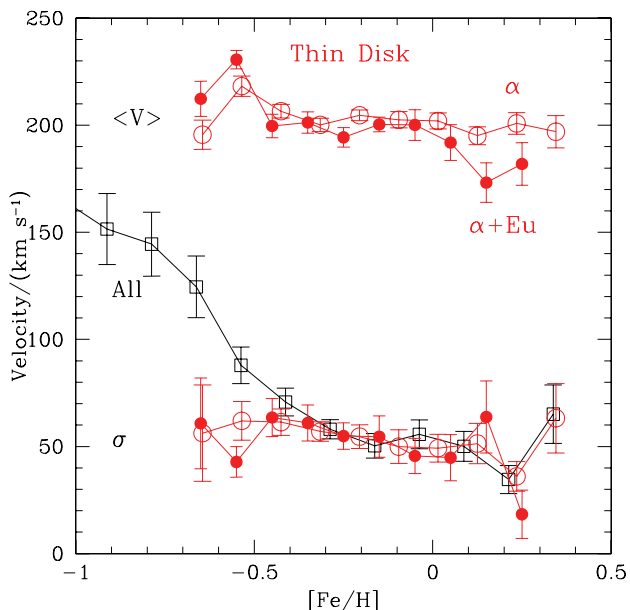
These difficulties are circumvented in a second, different interpretation of the properties of the local thin disc. As shown by Schönrich & Binney (2009b), radial migration can populate the vicinity of the Sun with 'thin disc' stars that formed either inside or outside the

solar circle. The properties of local thin disc stars might not trace the chemical history of the solar neighbourhood, but rather reflect the spread in birth radii of such stars. Given the metallicity gradient in the Galaxy, this could explain naturally the wide range in metallicity of thin-disc stars found today in the solar neighbourhood. The same modelling predicts that, once a steady state is reached, additional enrichment at different radii would be balanced by the infall of fresh metal-poor gas from the intergalactic medium. Because of higher densities, star formation progresses nearer the centre more intensely relative to the amount of available gas, leading to lower metallicities and higher [α/Fe] ratios with increasing Galactocentric birth radius. These gradients are today reflected locally in the observed correlation between [Fe/H] and [α/Fe].

One disadvantage of this scenario is that it requires a steeper metallicity gradient in the ISM than is usually accepted (see Maciel, Quireza & Costa 2007, and references therein), as well as careful balancing of the time-scales 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. Another potential challenge may arise from the fact that at least some metal-rich stars in the inner Galaxy seem to be α-enriched (Meléndez et al. 2008) whereas those in the solar neighbourhood are not.

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 disc*. Reading off from fig. 4 in Schönrich & Binney (2009b), the mean rotation speed is expected to change from roughly 250 to 160 km s^{-1} as the metallicity in the thin disc increases from [Fe/H] = −0.7 to +0.5.

As shown in Fig. 3, this prediction finds some support in the data. Filled circles here refer to the α + Eu data shown in the top panel of

Fig. 2 whereas open symbols correspond to the much larger sample of stars without Eu data (bottom panel of Fig. 2). The mean rotation speed of the thin disc (defined by the above conditions) decreases somewhat with [Fe/H] in the α + Eu data set but the trend is weaker than expected from Schönrich & Binney (2009b) and the error bars are large.

Furthermore, when the larger sample without Eu is considered (open circles) the mean rotation speed is actually *independent* of metallicity. It appears as if the mean rotation speed, as well as the velocity dispersion, remains roughly constant over the whole range in [Fe/H] spanned by the thin disc. The constant velocity dispersion of the thin disc should be contrasted with the familiar increase in σ with decreasing [Fe/H] (Strömgren 1987); this is shown by the open squares in Fig. 3 which corresponds to *all* stars in our compilation.

The kinematic invariance of the thin disc with metallicity is a somewhat surprising result for either of the two scenarios advanced above. The absence of a ⟨V⟩– [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. 3 disfavour such gradual heating; if present, the heating mechanism must operate promptly and saturate quickly, as has been suggested in the past (Strömgren 1987; Freeman 1991; Quillen & Garnett 2000; Soubiran et al. 2008). Inefficient heating would actually be easier to reconcile with theoretical models, which have struggled to explain the rapid increase in velocity dispersion with age inferred from earlier observations (see e.g. Wielen 1977; Lacey 1984; Jenkins & Binney 1990; Aumer & Binney 2009).
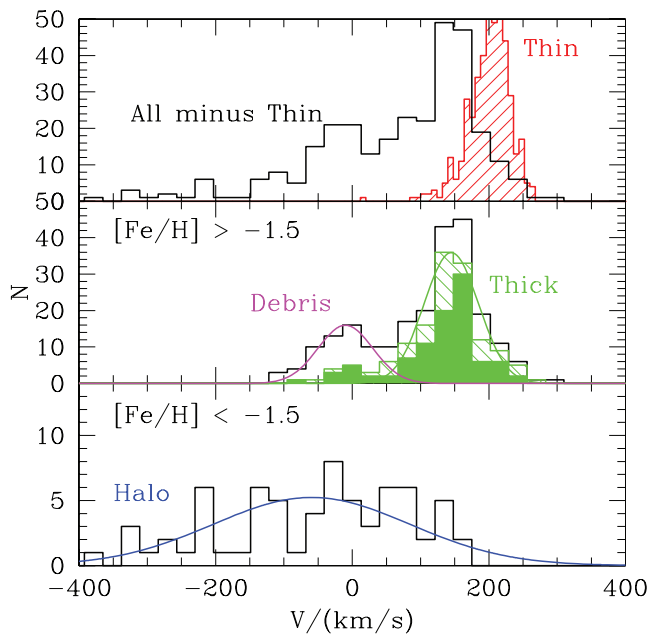
3.2 A chemical definition of the thick disc

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 disc at low metallicity. Indeed, as mentioned in Section 1, it is generally agreed that the thick disc is metal-poor; lags the thin disc in rotation speed and has a higher velocity dispersion. This is shown in the top panel of Fig. 4, where we compare the distribution of the rotation speed (V component) of all stars in our sample with that of the thin disc.

The V distribution of stars *not* in the thin disc is complex, and hints at the presence of distinct dynamical components. It shows two well-defined peaks, one at $V \sim 160$ km s^{-1} and another at $V \sim 0$ km s^{-1}, 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 disc. 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 panel of Fig. 4). 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^{-1} (shown in the bottom panel with a blue curve).

Interestingly, the V distribution of non-thin-disc stars with [Fe/H] > −1.5 (middle panel of Fig. 4) shows even more clearly the double-peak structure noted above. The peak at $V \sim 160$ km s^{-1} is well traced by the stars identified with the thick disc in the α + Eu panel of Fig. 2, shown by the solid-shaded histogram in the middle panel of Fig. 4.

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 the

Figure 3. Mean rotation velocity and velocity dispersion as a function of [Fe/H] for stars identified as belonging to the thin disc component in Fig. 2. Filled circles correspond to stars with measured Eu abundances (top panel of Fig. 2); open circles to all stars in the region labelled 'Thin' in the bottom panel of Fig. 2. Error bars indicate 1σ bootstrap error estimates. Note that although they span more than a decade in [Fe/H], *the average rotation velocity and velocity dispersion of thin disc stars are roughly independent of metallicity*. The open squares show the σ –[Fe/H] correlation for all stars in our sample and illustrate the familiar increase of the total velocity dispersion (σ) with decreasing [Fe/H].

Figure 4. Top panel: the open histogram shows the distribution of the rotation velocity (V component) for all stars in the sample. (Units are number of stars per bin.) The shaded histogram corresponds to those in the thin disc, as defined in the bottom panel of Fig. 2. The remainder are shown by the open histogram. Bottom panel: V-distribution of stars in the metal-poor tail, i.e. [Fe/H] < −1.5. This illustrates the velocity distribution of the slowly rotating, dynamically hot stellar halo. The blue curve illustrates the best-fitting Gaussian, with $\langle V \rangle = -60$ km s^{-1} and $\sigma_V = 144$ km s^{-1}. Middle panel: V distribution of stars with [Fe/H] > −1.5 but *excluding* the thin disc. The distribution is strongly non-Gaussian, and shows two well-defined peaks; one at $V \sim 0$ km s^{-1} and another at $V \sim 160$ km s^{-1}. The latter is well traced by stars in the 'thick disc' component identified in the top panel of Fig. 2 (with Eu; filled green histogram). Including stars without Eu measurements but of comparable [α/Fe] ratios (the 'Thick' region in the bottom panel of Fig. 2) results in the shaded green histogram. Note that stars near the $V \sim 0$ peak are almost exclusively those in the debris ('D') region of Fig. 2. They define a non-rotating, dynamically cold component distinct from either the thick disc or the stellar halo. Both the debris and thick disc components are relatively cold dynamically; the V-distribution can be well approximated by the sum of two Gaussians with similar velocity dispersion, of the order of ~40 km s^{-1} (see green and magenta solid curves).

bottom panel of Fig. 2. The V distribution of these stars is well approximated by a Gaussian with $\langle V \rangle = 145$ km s^{-1} and $\sigma_V = 40$ km s^{-1} that accounts for nearly all stars with $V > 100$ km s^{-1}.

The association between the thick disc and 'high-α' stars is reinforced by inspecting the location of counterrotating stars in Fig. 2 (shown in cyan). These stars, which clearly do not belong to a rotationally supported structure like the thick (or thin) disc, are evenly distributed among stars with [Fe/H] < −1.5 but shun the 'high-α' region in the range −1.5 < [Fe/H] < −0.7. Of the 38 counterrotating stars in our sample with −1.5 < [Fe/H] < −0.7, only three lie above the dotted line that delineates the 'Thick' region in the bottom panel of Fig. 2.

It is tempting therefore to adopt a purely chemical definition of the thick disc in terms of [Fe/H] and [α/Fe]:

(i) [Fe/H] > −1.5;
(ii) [α/Fe] > 0.2 − ([Fe/H] + 0.7)/4 for −1.5 < [Fe/H] < −0.7;
(iii) [α/Fe] > 0.2 for [Fe/H] > −0.7.

If our analysis is correct, then the thick disc emerges as a chemically and kinematically coherent component that spans a wide range in metallicity (−1.5 < [Fe/H] < −0.3) and contains mainly stars highly enriched in α elements. Stars in this component have $(\langle U \rangle, \langle V \rangle, \langle W \rangle) = (10, 133, -2)$ km s^{-1}, and $(\sigma_U, \sigma_V, \sigma_W) = (95, 61, 61)$ km s^{-1}.

The average V lags below the ~160 km s^{-1} peak because the chemical definition allows in a few stars with discrepant velocities (some with negative V) more closely associated with the $V \sim 0$ peak than with a rotationally supported structure like a thick disc. This suggests that the chemical definition of the thick disc proposed above is not perfect, and that it includes spurious stars belonging to a different, non-rotating component. We turn our attention to that component next.

3.3 Tidal debris in the stellar halo

The last feature of note in the top and middle panels of Fig. 4 is the peak centred at $V \sim 0$. These are stars with no net sense of rotation around the Galaxy and with a surprisingly low velocity dispersion. (The Gaussian fit to the low-V tail shown in magenta in the middle panel of Fig. 4 has a dispersion of just 40 km s^{-1}.) Their vertical (W) velocity distribution (computed for stars with $V < 50$ km s^{-1} to better isolate the peak[1]) is also indistinguishable from that of the thick disc component discussed above, with $\langle W \rangle \sim 0$ km s^{-1} and $\sigma_W \sim 72$ km s^{-1}. On the other hand, their U velocity dispersion is large (~180 km s^{-1}). Further, the U distribution (not shown) is rather flat, with hints of two, symmetric peaks, one at $U \sim -250$ km s^{-1} and another at $U \sim +250$ km s^{-1}.

As discussed by Meza et al. (2005), this is 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. 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 apocentre with large, positive U or coming from their apocentre, with symmetric $-U$.

This suggests that most non-thin-disc stars with [Fe/H] > −1.5 and low, but still enhanced relative to solar, [α/Fe] (previously thought to belong to the classical halo) belong to this new component. Guided by Nissen & Schuster (2010), we inspect the Na and Ni content of such stars for supporting evidence of this conclusion. This is shown in Fig. 5, where we show [Na/Fe] versus [Ni/Fe] for all stars in our sample with [Fe/H] < −0.7. Blue squares correspond to the very metal-poor stars in our sample ([Fe/H] < −1.5); green open circles are stars in the α-rich 'Thick' region of Fig. 2 and magenta filled circles denote stars in the α-poor 'debris' ('D') region of Fig. 2. The three groups separate clearly in the Na–Ni plane, supporting our claim that the 'debris' component is truly distinct from the thick disc and from the metal-poor 'classical' halo.

Using the same [Fe/H] and [α/Fe] parameters as above, we can characterize 'debris' stars in the [α/Fe] versus [Fe/H] plane (region labelled 'D' in Fig. 2) by

(i) −1.5 < [Fe/H] < −0.7 and
(ii) [α/Fe] < 0.2 − ([Fe/H] + 0.7)/4.

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[1] Lifting this restriction has only a small impact on the dispersion; $\sigma_W \sim 90$ km s^{-1} for *all* stars in the 'D' region of Fig. 2.
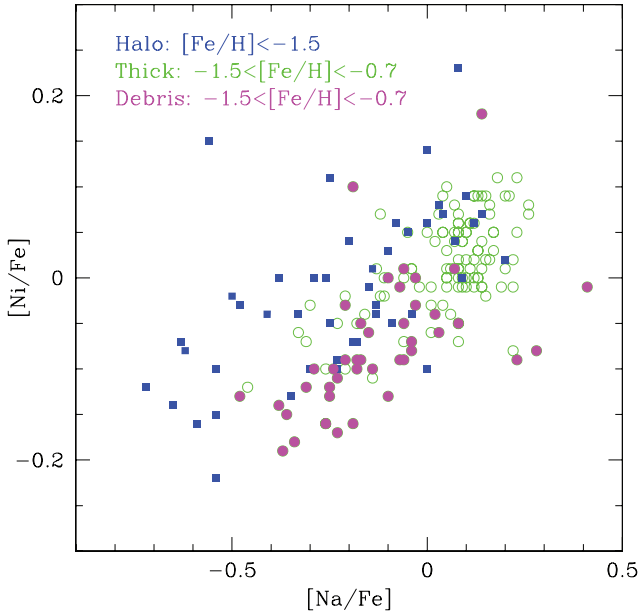
Figure 5. [Na/Fe] versus [Ni/Fe] correlation for all stars in our sample with [Fe/H] < −0.7. Blue squares correspond to [Fe/H] < −1.5 'classical halo' stars; green open circles to α-rich 'thick disc' stars with −1.5 < [Fe/H] < −0.7 and magenta filled circles to stars in the 'debris' ('D') region of Fig. 2. Note how these three components separate neatly in the Na versus Ni plane and, in particular, the tight scatter around the mean trend of 'debris' stars. This strengthens our conclusion that they correspond to three components of distinct origin.

Our conclusion agrees with that of Nissen & Schuster (2010), who studied a large spectroscopic sample of 'halo' stars and argued, in agreement with our analysis, that most metal-rich 'α-poor' halo stars are indeed tidal debris from disrupted dwarfs. Our debris population is reminiscent of the population identified by Morrison et al. (2009).

4 SUMMARY AND DISCUSSION

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 disc in the $[(\alpha + Eu)/Fe]$ versus [Fe/H] plane is particularly straightforward, and suggests that the kinematics of the thin disc is invariant with metallicity. This is an intriguing result unexpected in migration-based scenarios for the chemo-dynamical evolution of the thin disc. It implies that the familiar increase in velocity dispersion with decreasing metallicity (Strömgren 1987) is the result of the increased prevalence of the thick disc at lower metallicities, rather than of the sustained operation of a dynamical heating mechanism. If confirmed, the kinematic invariance of the thin disc with metallicity will place strong constraints on the formation of the Galactic disc and on the role of accretion events, in situ formation and/or migration.

The 'thick disc' can also be charted in the [α/Fe] versus [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 $V \sim 160$ km s^{-1}. 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 disc. If that were possible, questions such as whether the thick disc 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 disc stars were either accreted or simply stirred.

A substantial fraction of stars in the range −1.5 < [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 (see e.g. Venn et al. 2004; Tolstoy, Hill & Tosi 2009): the low-[Fe/H], α-poor region should be a good hunting ground for the remnants of accretion events.

The V-distribution associated with the stream or 'debris' seems to peak at slightly negative V (~ -10 km s^{-1}). This implies that most stars in the stream have angular momenta similar to that of the globular cluster ωCen (Dinescu et al. 1999). It is therefore tempting to associate these stars with the parent galaxy of this massive cluster, long suspected to be the survivor of the disruption of a dwarf galaxy in the Galactic potential (Freeman 1993). Supporting evidence comes from ωCen's low vertical velocity, as well as from the overlap in metallicity between ωCen and stars in the putative stream (see Meza et al. 2005; Nissen & Schuster 2010, for a full discussion).

Although the orbital parameters of the stream might suggest a link with the globular cluster ωCen, we caution that evidence of a true relation between those stars and ωCen is circumstantial at best. For example, the metallicity distribution in ωCen peaks at [Fe/H] = −1.7 (Smith 2004) and have distinct elemental abundances (Norris & Da Costa 1995; Johnson & Pilachowski 2010), so it might be useful to seek evidence for a stream in stars of similar metallicity and peculiar abundance ratios when larger samples become available (see e.g. Wylie-de Boer, Freeman & Williams 2010, for some progress in this direction).

One corollary of this finding is that very few stars with [Fe/H] > −1.5 in our sample seem to belong to the classical, dynamically hot stellar halo. Recent work has suggested that halo stars in this 'metal-rich' tail might actually belong to a distinct 'inner halo' component (see e.g. Carollo et al. 2007, and references therein). The connection between this and the stream we advocate above is, however, unclear, not least because the 'inner halo' component is reported to co-rotate with the Sun, whereas our putative stream counterrotates slowly around the Galaxy.

The 'inner halo' identification typically relies mainly on estimates of [Fe/H] and lacks information on the abundance of individual elements. On the other hand, our sample is relatively small in comparison and has potentially a number of selection biases. Thus, the possibility that our stream constitutes a small subset of the inner halo remains.

It might be possible to test these ideas by examining other abundance ratios, such as the neutron-capture elements [Ba/Y] or [Ba/Eu]. This is because these elements are contributed in different amounts by AGB stars that undergo slow neutron capture nucleosynthesis during the thermal pulsing stages and by massive stars that undergo rapid neutron capture nucleosynthesis during supernova explosion. Indeed, variations in those ratios have already been seen in individual stars of dwarf galaxies (see fig. 14 in Tolstoy et al. 2009).

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. The planned HERMES survey[2] should be a major first step in this regard. This undoubtedly ambitious endeavour would allow us to dissect chemically and kinematically the solar neighbourhood and to learn the true provenance of the many stellar families that today call this small place of the Galaxy home.

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[2] www.aao.gov.au/AAO/HERMES