Radial mixing and the transition between the thick and thin Galactic discs

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ABSTRACT
The analysis of the kinematics of solar neighbourhood stars shows that the low and high metallicity tails of the thin disc are populated by objects which orbital properties suggest an origin in the outer and inner galactic disc, respectively. Signatures of radial migration are identified in various recent samples, and are shown to be responsible for the high metallicity dispersion in the age-metallicity distribution. Most importantly, it is shown that the population of low metallicity wanderers of the thin disc (-0.7 < [Fe/H] < -0.3 dex) is also responsible for the apparent hiatus in metallicity with the thick disc (which terminal metallicity is about -0.2 dex). It implies that the thin disc at the solar circle has started to form stars at about this same metallicity. This is also consistent with the fact that ‘transition’ objects, which have \(\alpha\)-element abundance intermediate between that of the thick and thin discs, are found in the range [-0.4, -0.2] dex. Once the metal-poor thin disc stars are recognised for what they are - wanderers from the outer thin disc - the parenthood between the two discs can be identified on stars genuinely formed at the solar circle through an evolutionary sequence in \([\alpha/Fe]\) and [Fe/H]. Another consequence is that stars that can be considered as truly resulting of the chemical evolution at the solar circle have a metallicity restricted to about [-0.2, +0.2] dex, confirming an old idea that most chemical evolution in the Milky Way have preceded the thin disc formation.

Key words: Galaxy: abundances – (Galaxy:) solar neighbourhood – Galaxy: evolution

1 INTRODUCTION
The Galactic thick disc is, according to the local record, a population with characteristics neighbouring those of the thin disc: it is rotationally supported, with a higher internal kinematic dispersion, slightly metal-poor with an overlap in metallicity with this population. It is however possibly much older, and shows clear discontinuities with the thin disc, as visible in particular on chemical data. Several scenarios of the origin of this population have been put forward to explain these characteristics, among which the following three are often evoked: (1) the thick disc is an accreted population, (2) it is the first phase of the thin disc, heated up by an interaction episode with another galaxy (3) finally, it could be the result of multiple, early mergers of gas rich subsystems from which stars of the thick disc would have formed. This last suggestion has been made by Brook et al. (2007) from numerical simulations where they apparently succeed to produce a population with the main properties similar to those of the thick disc. In the first scenario, the properties of the thick disc are those of the accreted population. This is a difficulty, because while the range of properties found in Milky Way satellites is rather large, none of them approach those of the thick disc. It is doubtful in particular that a small entity could have produced, at an early epoch, stars with a relatively high level of \(\alpha\)-elements as observed on solar-neighbourhood thick disc objects. In the second scenario, it is not entirely clear what exactly occurs in the transition phase (which may have lasted several Gyr) between the interaction with the satellite and the beginning of the thin disc phase, and in particular to what discontinuities it may give rise. While it is uncertain what may differentiate the resulting thick disc of scenario (2) and (3), a kind of parenthood is certainly expected with the thin disc, but this is unlikely in scenario (1).

In the recent years, detailed spectroscopic data have demonstrated that the two discs are apparently distinct in their chemical properties, with two main differences. First, at a given metallicity, the \(\alpha\)-element content of the thick disc is offset by about +0.1 dex from the thin disc. Second, there is a hiatus of about 0.5 dex between the metal-rich stars of the thick disc (at [Fe/H] \(\approx\) -0.2 dex) and metal-poor stars of...
the thin disc (at \[\text{[Fe/H]} \approx -0.7 \text{ dex}\]). It has been suggested that these two sequences could be evolutionary connected, (Bensby et al. 2003; Reddy et al. 2003), the metallicity hiatus between the two populations being the consequence of a phase of low star formation, perhaps due to the exhaustion of gas, followed by a new infall episode, which would decrease the metallicity from which the new, thin disc stars, form.

However, this peculiar interpretation contradicts the observed behaviour of the age-metallicity distribution (Haywood, 2006, and Fig. 1, next section) which shows that, on average, the oldest thin disc stars have a metallicity of about -0.2 dex – not -0.7 dex. Meanwhile, thin disc stars this metal-poor are not specifically old, being found also at intermediate ages (starting at 2-3 Gyr). A different interpretation, suggested in Haywood (2006) and studied in more detail in the present paper, is that the metallicity spread of thin disc stars at [-0.3,-0.7] dex is a consequence of radial mixing, stars more metal-poor than about -0.3 dex being intruders from the outer disc. It has been proposed (Grenon, 1972) that super metal-rich (\([\text{[Fe/H]}]>0.2 \text{ dex}\)) stars found in the solar neighbourhood are objects that have migrated from the inner disc. It is suggested here that the same phenomenon explains the presence of the most metal-poor thin disc stars at the solar radius, these being wanderers from the outer thin disc. If correct, it would imply that the metallicity hiatus between the two populations would not be an effect of the local chemical evolution, but a consequence of radial mixing in the thin disc. The present study focuses on these discontinuities, showing that they are only apparent, and that a real evolutionary link between the two discs does exist. We emphasize that the present results are obtained from solar neighbourhood stars.

The present paper is organised as follows. In the section below, we start by looking at the signatures of radial mixing in samples of stars of the solar vicinity. We then analyse the transition between the thick and thin disc in the light of these results, and focus particularly on the discontinuities in \([\alpha/\text{Fe}]\) and \([\text{[Fe/H]}]\), arguing they are only apparent. We conclude with a summary of our results and a discussion on the status of the thick disc.

2 OBSERVATIONAL SIGNATURES OF RADIAL MIXING

Radial migration of stars in the galactic disc has been suggested to be an important ingredient of our understanding of the local galactic populations since the seventies (Grenon, 1972), in particular to justify the now compelling evidence of metal-rich stars in the solar neighbourhood. A variety of processes have been invoked to explain radial mixing, including the diffusion of stars on their orbits because of various irregularities in the galactic potential (quantified by Wielen (1977) and Wielen et al. (1996)), or caused by the passage of either a transient single spiral pattern (Sellwood & Binney, 2002), or multiple long lived or transient spiral patterns (Mincev & Quillen (2006), De Simone et al. (2004)).

There are two expected signatures of radial mixing on the metallicities of thin disc stars in the solar neighbourhood. Radial migration being a secular process, its effects are expected to be more or less correlated with age: the oldest stars are allowed to come from more distant regions, hence from regions where metallicity can be increasingly different from the mean metallicity of the solar neighbourhood. Therefore, if radial mixing is the prime contributor to the dispersion of metallicities at the solar circle, we expect dispersion to increase with age. However, other mechanisms can induce a similar effect. For example, infalling gas from the halo could alter the homogeneity of the ISM, while the amplitude of this effect could be a diminishing function of time, correlated with a possibly decreasing amount of gas in the halo ‘reservoir’. The second, more specific, signature of radial mixing, is due to the radial metallicity gradient: because stars born in the inner disc are more metal-rich than stars born in the outer disc, we may search for signatures of these opposite provenance in the orbital behaviour of the metal-rich and metal-poor solar neighbourhood stars.

2.1 The increasing dispersion of metallicity with age

We plot on Fig. 1ab two different samples of solar neighbourhood stars. The first one is made of 5600 stars within 75pc and shows metallicity derived through Geneva photometry as a function of B-V. The second sample contains about 3300 stars with metallicity from Strömgren photometry. This sample is used in Haywood (2006) to derived the age-metallicity distribution. However, a noticeable difference with Haywood (2006) is that we derived new ages with the method developed by Jørgensen & Lindegren (2005). The method is based on the evaluation of an age probability density function (pdf) for each star, the adopted age being determined from the mode of the pdf. All the details are given in Jørgensen & Lindegren (2005). We used the set of isochrones from Demarque et al. (2004) and the atmospheric parameters are those of Haywood (2006). The resulting age-[Fe/H] distribution has the same main characteristics as the one found in Haywood (2006).

The expected trend of increasing dispersion with age is observed on both plots (implicitly in panel (a)). The upper curve on panel (b) quantifies the increase in metallicity dispersion: starting at 0.1 dex, the dispersion increases to 0.25 dex for older ages. The widening of the metallicity distribution with increasing B-V is apparent in panel (a). The proportion of old disc stars increases from B-V=0.3 to 0.6, bringing more objects with wider metallicities, and, possibly, of more distant origin. Note that this is independent of age determination and is a robust result: the dispersion in metallicity is not uniform at all ages but increases from younger to older generation of stars. Young stars (0.35<B-V<0.45) indicate that the most metal-rich objects presently forming in the solar neighbourhood have a metallicity of about [Fe/H]=0.1-0.2 dex (the clump at B-V<0.3 is made of metallic and peculiar A and F stars, and is not considered here), while the inclusion of redder, and presumably older stars in the sample brings more metal-rich objects. If it is admitted that the metallicity of young stars is the end-point of the local chemical evolution, it is natural to suppose that the metal-rich, older stars seen at B-V>0.5 and [Fe/H]>0.2 dex are intruders of different galactic origin.

The role of radial mixing to explain the existence of metal-poor thin disc stars is usually not invoked, because
these are usually thought to stem from the local chemical evolution. However, the age-metallicity relation in panel (b) suggest another picture. The average metallicity of old thin disc stars is $[\text{Fe/H}] < -0.2$ dex, and there is no hint of a transition between two populations at ages 8-12 Gyr and $[\text{Fe/H}] = -0.7$ dex. On the contrary, stars with metallicities $-0.7 < [\text{Fe/H}] < -0.3$ dex are spread at various ages in the interval [2-3, 8-10] Gyr, which imply they are not suitable candidates for being transition objects between the two discs. Another noticeable characteristic from Fig. 1(b) is that none of these objects have age less than 2 Gyr, which means that stars at such metallicities do not originate from or are not forming anywhere at the solar neighbourhood.

Finally, the metallicity of the Sun relative to stars of the same age in the solar neighbourhood (differences of 0.15-0.2 dex have been claimed) has been invoked as evidence of radial mixing (see in particular Wielen et al. (1996)). The location of the Sun on Fig. 1(b) is indicated by its symbol, and shows that it is offset by less than 0.1 dex ($\approx 0.05$ dex) from the mean metallicity of stars at the same age, seriously weakening this argument. In the section below, we search for other signatures on local samples of stars.

### 2.2 Systematic variations of orbital parameters with metallicity

If we assume that stars in the metal-poor and metal-rich tails of the solar neighbourhood metallicity distribution are mostly contaminants passing through the solar circle as a result of radial mixing (see in particular Wielen et al. (1996)), the location of the Sun on Fig. 1(b) is indicated by its symbol, and shows that it is offset by less than 0.1 dex ($\approx 0.05$ dex) from the mean metallicity of stars at the same age, seriously weakening this argument. In the section below, we search for other signatures on local samples of stars.

#### 2.2.1 A photometric sample: Haywood (2006)

Our first sample has been used in the previous section and in Haywood (2006) to determine the age-metallicity relation. No kinematic criterion has been used to select the stars. We cross-identified our sample with the CGS catalogue of Nordström et al. (2004) to obtain the kinematic and orbital parameters $U,V,W$ and $R_p$, $R_a$ for about 3300 objects.

We assigned population membership probabilities according to the method of Mishenina et al. (2004) for all the stars in our sample. We adopted the kinematic parameters for the thin and thick discs and the Hercules stream given by these authors. The probabilities are derived assuming that the kinematic distributions of the stellar populations are Gaussians. Relative densities have been assumed to be 82% for the thin disc, 10% for the thick disc and 8% for the Hercules stream, in agreement with current estimates (see Famaey et al. (2005) for example). Each star has a calculated probability to belong to the thin disc ($P_{TND}$) the thick disc ($P_{TKD}$) or the Hercules stream ($P_H$) (the halo has been neglected: 3 stars only have $[\text{Fe/H}] < -1.5$). The detailed procedure is given in Mishenina et al. (2004) (see also Soubiran & Girard, 2005), and is not described further.

Figure 2(a) shows the radial galactocentric amplitude ($R_p$ to $R_a$) of the orbit of the stars as a function of metallicity for the entire sample (a) and the thin disc (b), this population being selected with kinematic membership probability higher than 0.7. On each plot, curves represent the mean orbital radius $R_m$ (defined as $(R_p+R_a)/2$), calculated on (overlapping) subsamples of 100 points. The whole sample (panel a) illustrates that there is a significant increase of the galactocentric radius towards lower metallicity stars (from $R_m=7.5$ kpc at $[\text{Fe/H}] = +0.25$ to 7.75 kpc at $[\text{Fe/H}] = -0.3$ dex). Below this limit, the contamination by the thick disc makes the mean galactocentric radius to decrease again.

Panel 2c shows the thin disc stars only, selected with kinematic probability higher than 70%. There is a clear visible increase of $R_m$ at lower metallicities in the thin disc, with $R_p$ and $R_a$ being similarly shifted. It illustrates that, for stars belonging to the thin disc, the orbits are shifted towards the outer disc at lower metallicities and towards the inner disc at higher metallicities, with a change in the mean $R_m$ limited to about 0.5 kpc on the metallicity interval (+0.2, -0.5) dex.

#### 2.2.2 A spectroscopic sample: Soubiran & Girard (2005)

There is a possibility that the increase in $R_m$ seen on Fig. 2(a) at $[\text{Fe/H}] < -0.4$ dex is partly due to the kinematic selection.
of disc stars, because the selection of $P_{TND} > 0.7$ eliminates stars that have a kinematics intermediate between the thin and thick discs, and the adopted level at which stars of each population should be selected is somewhat arbitrary. Another way to discriminate thin and thick disc stars is to use their distinct chemistry. In many spectroscopic studies of the solar neighbourhood, the thin and thick discs are often better separated in their chemical properties than in their kinematics. Figure 2 illustrates that $R_m$ varies as a function of metallicity even when no selection on the population is made (at $[\text{Fe/H}] > -0.3$ dex). However, we conducted an additional test to verify that the effect measured at low metallicities is not a consequence of the kinematic selection. In order to do so, we repeat the same analysis as above but on a sample for which $[\text{Mg/Fe}]$ abundance ratio is available and use it to select thin disc star. The new sample is the compilation by Soubiran & Girard (2005), which contains kinematic, orbital and chemical data for a set of 743 stars. An inconvenience is that part of the separation in abundance ratios between the thin and thick discs visible on individual samples is blurred by the combination of several data sets of different origins, but some of the information is certainly exploitable. In order to have kinematic and orbital parameters from the same source as the photometric sample, we cross-identified the compilation of Soubiran & Girard (2005) with the catalogue of Nordström et al. (2004), leaving about 600 stars with measured $[\text{Mg/Fe}]$.

Fig. 3 shows radial excursions of the stars as a function of metallicity. The separation between the two populations is made according to the limit $[\text{Mg/Fe}] = 0.2$ dex. The curves show the mean of $R_m$ calculated on subsamples of 70 stars. The behaviour of $R_m$ for the thin disc population (right curve) is similar to the one seen on the photometric sample, with the kinematic selection. There is a tendency for an increase of $R_m$ towards decreasing thin disc metallicity, confirming the possibility of the contamination of the vicinity by wanderers of the inner and outer disc.

**Figure 2.** (a) Radial amplitude (distance from $R_{min}$ to $R_{max}$) of the orbits of all the stars in the photometric sample as a function of metallicity. (b) Thin disc stars only, selected assuming a probability higher than 0.7. The curves are the mean of $R_p$, $R_m$ and $R_a$, calculated on subsamples of 100 (non-independent) objects.

**Figure 3.** The same as Figure 2 with the sample from Soubiran & Girard (2005) as described in the text. The classification between thick (left curve) and thin (right curve) discs is made according to the criterion that $[\text{Mg/Fe}] > 0.2$ dex and $[\text{Mg/Fe}] < 0.2$ dex. The curves are the mean of $R_m$ calculated on (non-independent) samples of 70 points.

### 2.2.3 The Geneva-Copenhagen Survey

We now consider a larger sample, that of Nordström et al. (2004), which provides kinematic and orbital parameters for about 12000 objects. The overall sample shows the same trends as those evidenced in the two previously studied data sets, and we don’t repeat the same analysis. However, these trends can be seen even more clearly on $(R_p, R_a)$ distributions as given by two subsamples separated in metallicities, see Fig. 4. Panel (a) gives the distribution around the central metallicity of the sample of Nordström et al., which is about -0.1 dex, and is used as a reference distribution. The difference between the two other distributions, plotted for $[\text{Fe/H}] < -0.4$ dex and $[\text{Fe/H}] > +0.1$ dex, can be seen on panel (b) and (c). The metal-poor subsample is shifted to larger apo and peri-centres, and in particular significantly
Figure 4. The distribution of stars kinematically selected as thin disc stars in the GCS catalogue, on different metallicity intervals. The diagonal line is for a mean galactocentric radius of 8 kpc. (a) Reference sample, for stars in a metallicity interval centred on the mode of the metallicity distribution (±0.05 dex) of the GCS catalogue, selected assuming $P_{TND} > 0.8$. (b) Thin disc stars ($P_{TND} > 0.8$) with $[\text{Fe/H}] < -0.4$ dex. (c) Stars with $[\text{Fe/H}] > +0.1$ dex. The Hyades stream is visible at (6.7-7.0, 8.0-8.7) kpc. In this metallicity interval, we assumed there is no contamination by the thick disc (no selection on membership probability was made).

Extended beyond 9.5 kpc. The concentration seen in the metal-rich subsample at ($R_p$, $R_a$)=(6.6-7.2,8.1-8.6) kpc is the Hyades stream. Famaey et al. (2007) argued that the Hyades stream is a group of stars coincidentally brought together from the inner disc to the solar vicinity by the effect of a spiral perturbation. This suggestion fits well within the general picture proposed here and contributes importantly to the detected effect.

The diagonal line on each plot indicates a mean orbital radius of 8 kpc. The symmetrical aspect of these plots is obvious: the metal-poor thin disc populates preferentially outer orbits, while metal-rich stars have a net tendency to occupy inner orbits. Although the differences are clear, there is a large overlap between the two distributions of panel (b) and (c). As an example, the Hyades stream supposedly has no stars below $[\text{Fe/H}] < -0.5$ dex (Famaey et al. (2005)), but probably contaminates the sample at $[\text{Fe/H}] < -0.4$ dex on Fig. 4(b). In addition, while we do expect to select stars that are preferentially on outer orbits at $[\text{Fe/H}] < -0.4$ dex, some of them must have already spread at various radius and therefore contaminate all radii. More generally, in 8 Gyr’s time, these processes may certainly give rise to a complex state of mixing among stars at a given galactocentric radius, and this is certainly reflected in Fig. 4.

2.3 Radial Migration

Could the detected trend be the consequence of a selection effect? The origin of the two first samples are very different. The first sample has not been selected upon kinematic criterion, while the second is a compilation of various spectroscopic catalogues. Moreover, while the two first samples are essentially contained in the third (CGS catalogue), they have only 154 stars in common. After having removed these objects from the two samples, the trends shown on Fig. 2k3 are unaffected, which means that the correlation is observed in two distinct samples with different origin, and in a much larger sample (12000 stars). We conclude that it can be assumed with confidence that the trend is real.

Is there any evidence of the time scale of the migration process in the present data? The age-metallicity distribution of Fig. 1b shows a dearth of stars below the line of -0.15 dex/Gyr. Combined with estimated radial metallicity gradients (which are uncertain and vary roughly between 0.04 and 0.1 dex/kpc), it means upper values for the migration rate of 1.5 to 3.7 kpc/Gyr. Given that the local mean disc metallicity is $[\text{Fe/H}]=0$, it implies that a star with $[\text{Fe/H}]=-0.4$ (or even less) could reach the solar circle being only 2-3 Gyr old. These estimates are high. Are they unrealistic? The data are sparse in the low metallicity regime, and these numbers, given as rough estimates, need to be confirm. However, interesting comparisons can be made with the few results available from dynamical modelling. Binney (2007) argued using simple arguments that the increase of radial random motion by the diffusion process described in Wielen et al. (1996) is not sufficient to explain the observed scatter in the age-metallicity distribution. The epicycle amplitude evaluated by Binney (2007) is about 1.2 kpc, which falls well short to explain the presence in the solar neighbourhood of stars with $[\text{Fe/H}]= -0.6$ or even -0.8 dex. Radial migration based on the effect of stochastic spiral waves has been studied by De Simone et al. (2004), giving similar values, limited to at
most ± 2 kpc. However, in an illustration of the mechanism described by Sellwood & Binney (2002), Lépine et al. (2003) concluded that stars could have migrated radially over 2–3 kpc in 1 Gyr or less. This value fits well with the required time scale, which of course does not imply it is the correct mechanism. In any case, the above numbers indicate that the increase of radial random motion does not appear sufficient to explain radial wandering on distances well above 2 kpc, and some extra-mechanism of the kind described by Sellwood & Binney (2002) is required.

2.4 Characterising the metal-poor tail of the thin disc

Figure 5 shows the velocity in the direction of galactic rotation relative to the Sun as a function of metallicity for objects with detailed spectroscopy from Reddy et al. (2003, 2006), Valenti & Fischer (2005), Bensby et al. (2005) and Gilli et al. (2006). Metal-poor thin disc stars are clearly visible (above the line), as a separate group running towards low metallicity, high-V velocity component.

The group of metal-poor stars identified in Fig. 4, 5 and 6 are undoubtedly thin disc objects. This is supported by the UVW velocity dispersions measured on the 572 stars of our selection: (32, 11, 21) km/s, and it is confirmed by the ages and $\alpha$-element content discussed in section 3. These stars are the signatures that radial mixing in the disc is an efficient process.

As expected, they are also responsible for the large dispersion towards low metallicity at a given age. This is testified by the Fig. 7b, where we selected stars of the thin disc with low metallicities from the photometric sample (age-metallicity distribution of panel a). Their position in the V-[Fe/H] diagram corresponds to the same location occupied by the group of metal-poor thin disc stars identified on Fig. 5 and 6.

3 THE TRANSITION BETWEEN THE THICK AND THIN DISCS

The results above have several consequences on the way we understand the metallicity distribution of thin disc stars, and the transition between the thin and the thick discs, as we now discuss.
3.1 Solving the problem of the metallicity hiatus between the two discs

We first focus on the hiatus in metallicity between the two discs. How does radial mixing of stars in the disc can help to solve this problem? In Fig. 8(a) we display [α/Fe] and [Fe/H] values from the samples of Reddy et al. (2003, 2006), Bensby et al. (2005) and Gilli et al. (2006). Black dots represent stars that have a metallicity between -0.7 and -0.3 dex, and [α/Fe] below the line, selecting metal-poor thin disc stars. The location of these objects on the Vrot vs [Fe/H] diagram in Fig. 8(b) illustrates that the metal-poor stars responsible for the hiatus in metallicity are the same group of stars studied in the previous section and which rotate faster than the Sun. In other words, if our tentative interpretation of section 2.3 is correct, they are wanderers from the outer disc. About 30% of the stars selected in panel (a) fall below the line in panel (b), which means that for a few cases, this line is too simplistic to differentiate accurately the kinematics of metal-poor thin stars from the main population. In some cases, the velocity in the direction of galactic rotation is clearly in the thick disc regime. This is not unexpected, since dynamical processes may have mixed the two groups to some extent.

Panel (c) and (d) below illustrate the location of the stars in the [α/Fe] vs [Fe/H] diagram when the selection is made on the V velocity component and metallicity. We selected stars of the metal-poor thin disc in panel (c) above the line. Panel (d) shows that this simple selection corresponds essentially to stars in the group responsible for the hiatus in metallicity. About 15% of the stars selected this way are not in the area of metal-poor thin disc stars of panel (d) and appear as transition or thick disc stars. Here again, this is not unexpected, since the selection is made simple and kinematic evolution certainly have mixed the two populations to some extent.

Fig. 8 demonstrates that the objects responsible for the hiatus in metallicity seen between the two populations probably originate from the outer disc. These objects have kinematics, metallicity and, as we show in section 3.3, age distribution incompatible with being transition objects between the thick and thin discs, which imply that the hiatus in metallicity is only apparent, and is not an effect of the local chemical evolution.

3.2 Transition stars

We may expect transition stars, if a transition phase between the two discs does exist, to reach the thin disc at a metallicity of about [-0.2,-0.3] dex, spread at various level of α-element enrichment between the two populations. Inspection of the literature shows that these objects are relatively rare. Partly, this is because adopted kinematic criteria in current studies are sometimes chosen to select stars with high probability to belong to one or the other population, in order to enhance the differences in the chemical properties of the two populations. This may bias samples against transition objects, if their kinematics is not clearly in the thin disc or thick disc group. The main reason however is probably that they are intrinsically rare. Bensby et al. (2005) found 4 (kinematically defined) transition or 'intermediate' objects (meaning with no clear thin or thick disc kinematics). Their stars have α-elements well intermediate between the thin and thick discs (see their Fig. 8). The suggestive clue here is their metallicity, which for 3 of them are within [-0.34, -0.28] (one has [Fe/H] = +0.37 dex), well above the lower bound metallicity of metal-poor thin disc stars (at -0.6,-0.8 dex) discussed here. This is well within our estimated value for the transition between the two discs. A similar indication is given by the transition stars of Fuhrmann (2004, see his Fig. 34 and 35). Finally, the clearest example is seen on Fig. 12 of Reddy et al. (2006), which shows [α/Fe] as a function of [Fe/H], reproduced here in Fig. 8. The data of Reddy et al. (2003) and (2006) suggest that, when transition or disc stars are (kinematically) selected (panel b and c on their figure), the pattern of α-elements shows two branches. The first one goes towards the metal-poor stars of the thin disc discussed previously. The other is starting at [Fe/H] = (-0.2,-0.3) dex and [α/Fe] = 0.05 dex and aims at the thick disc (α/Fe) = 0.2 dex and metallicity of [Fe/H] = (-0.4,-0.5) dex. These are robust indices suggesting that a transition phase between the two populations has occurred in a relatively narrow range of metallicity. It is possible that a particularly low level of star formation activity characterises this transition phase, although this is difficult assess, in particular because the duration of this phase is difficult to estimate.
3.3 Ages: transition and metal-poor thin disc stars

We now comment on the age of the stars in both groups (metal-poor thin disc and transition stars). The metal-poor thin disc stars are expected to have any age between a few Gyr (the time they need to approach the solar circle) and the age of the disc, while transition stars are expected to be exclusively old, that is, older than the age of the thin disc at the solar circle. Individual ages have been determined for the samples of Reddy et al. (2003, 2006), Bensby et al. (2005) and Gilli et al. (2006) using the method described by Jørgensen & Lindegren (2005), for stars with $M_v < 5.0$. Metallicities, $\alpha$-element content and effective temperatures of the stars are taken from the studies above. Absolute magnitudes are taken from the Hipparcos catalogue. We selected metal-poor stars of the thin disc imposing both criteria defined in Fig. 8c, while transition stars were chosen visually from the box in Fig. 10a. There is actually no working definition of what a transition star is. In principle, transition stars ought to be born at an intermediate epoch between the thick and thin discs, but we don’t know what measurable property would select stars as near as possible from this definition. Kinematically intermediate stars don’t fulfil this requirement with high precision. As an example, stars with asymmetric drift intermediate between the thin and thick discs in Reddy et al. (2006) have metallicity running from -0.87 to +0.37 and $[\alpha/Fe]$ from -0.05 to 0.24 dex, which means...
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Figure 9. Distribution of stars kinematically selected as thin disc stars in Reddy et al. (2006, their Fig. 12). Two branches are clearly visible, one made of metal-poor thin disc stars, the other of transition objects. Additional transition objects (as defined by kinematic criteria only) from Bensby et al. (2005) are also plotted (star symbols).

In spite of the relatively small dependence of age on metallicity, a combination of the α-element content and metallicity seems to be a much better proxy than kinematics. We therefore select, somewhat arbitrarily, transition stars as objects that are within the region delimited on Figure 10a. Panel (b) shows the position of both samples (metal-poor thin disc and transition stars) superposed to the age-[Fe/H] distribution of Fig. 1b. The age-scale is the same for all three samples (determined by the same method using the same set of isochrones).

The respective locations of thin disc metal-poor and transition stars confirm that transition stars are, in general, older than thin disc objects. The dichotomy between the two groups is apparent, and corresponds to our expectations. Metal-poor thin disc objects are spread at all ages starting from a few Gyr (> 2 Gyr) to about 10 Gyr for most stars. 67% of thin disc metal-poor stars have ages less than 8 Gyr, while another 21% have error bars which make them compatible with this limit. Transition stars are mostly older than 6 Gyr. The group of transition stars at ages near 7-8 Gyr have error bars making them compatible with being older than 8 Gyr. There is one outlier, HIP 26828, which has ([Fe/H],[α/Fe])=(-0.34, 0.16) dex and seems to be truly intermediate in terms of chemistry and kinematics. It is positioned in the overlap region in the HR diagram, and its age pdf indicates two peaks, one at 3.3 Gyr, the other at 4.5 Gyr. In any case, its age looks incompatible with the other properties, and it appears as a peculiar object in this distribution (a blue straggler?).

The age information is summarised in Fig. 11 where stars are represented in three different age intervals. If we discard thin disc metal-poor stars as not being stars born at solar galactocentric distance, the age-ranges displayed on Fig. 11 shows that the thick disc is dominated by stars being older than 12 Gyr, while the thin disc seems to be essentially younger than 8 Gyr at [Fe/H]>-0.25 dex. A different view is given on Fig. 12 which shows the same data with [α/Fe] as a function of age. The metal-poor thin disc stars (shown on Fig. 10) have been removed from the plot, in order to keep only stars that would be truly endemic of the solar neighbourhood, according to the scheme presented in previous sections. Transition stars of Fig. 10 are shown as stars symbols. In addition, we show as diamonds stars that have been selected with the conditions that [α/Fe]<0.1 dex, V space velocity component less than -40 km.s^{-1}, and total velocity greater than 80 km.s^{-1}. For all categories, there is a large spread in ages, but the mean increase of [α/Fe] as a function of age is apparent. Objects shown as diamonds are kinematically in the thick disc regime, while their [α/Fe] abundance ratio is more akin to the thin disc. According to their age, these objects are mostly old thin disc, with a majority having 8-12 Gyr. While their status is difficult to define, a possible interpretation is that these objects should perhaps be considered as transition objects between the two discs, but on the side of thin disc, while transition objects discussed in section 3 are transition objects nearer to the thick disc.
4 SUMMARY AND DISCUSSION

4.1 The thin disc

Analysis of the orbital parameters of local samples of stars shows a systematic correlation of the mean orbital radius of thin disc stars with metallicity. It is shown that stars in the metal-poor ([Fe/H]<-0.3 dex) and metal-rich ([Fe/H]>+0.2 dex) tails of the thin disc have orbital parameters significantly off the main population, suggesting an origin in the outer and inner galactic disc.

We note that local low-metallicity ([Fe/H]<-0.3 dex) thin-disc stars have properties well in agreement with stars found in the anticentre direction a few kpc from the solar neighbourhood. Carney et al. (2005) and Yong et al. (2005) find that the metallicity of thin disc stars decreases towards the outer disc to reach a constant value of [Fe/H]≈-0.6 dex 2-4 kpc beyond the solar circle. Moreover, the ratio [α/Fe]≈0.1 to 0.2 dex, as evaluated by Carney et al. (2005) on their stars is compatible with similar characteristics of the local thin disc stars at [Fe/H]<-0.5 dex (i.e. slightly above thin disc stars of solar metallicity). These values are in agreement with the metal-poor thin disc sampled locally.

An important characteristic of metal-poor thin disc objects is their distinctly higher-than-average space velocity in the direction of galactic rotation. Their location in the ([α/Fe], [Fe/H]) diagram shows that they are responsible for the hiatus in metallicity between the two discs. Three other important consequences that concern the local chemical evolution must be noted. First, when their distinct provenance is taken into account, stars of the thin disc that are truly endemic of the solar circle span a limited range in metallicity (from about -0.2 to 0.2 dex). This is confirmed by the mean evolution of the metallicity within the thin disc, which remains remarkably flat over 8-10 Gyr. Second, when sampling the age-metallicity distribution of the solar vicinity, care must be taken to select stars that were genuinely formed at the solar circle. For instance, the stars in the sample of Reddy et al. (2003) have been selected (voluntarily in this case) by the authors to best represent metal-poor thin disc. It implies that their age-metallicity distribution (their Fig. 8) is representative of the outer thin disc, and is offset, at a given age, to lower metallicities when compared to stars truly endemic of the solar galactocentric radius. Finally, in discussing the G-dwarf problem, the amount of the missing stellar material at low metallicity (compared to the closed-box model) resides entirely in the thick disc metallicity regime. The missing dwarfs have typical metallicity of 1/3 of solar, or about -0.5 dex. This is clearly outside the range of the local thin disc.

4.2 The thick disc status

If the above analysis is correct, a real evolutionary link is seen between the two disc components, and it is difficult to imagine how a stellar thick disc of purely extragalactic origin could insure such parenthood. It must be emphasised however that the status of the thick disc, and of the stars labeled as such in recent spectroscopic studies of local samples, is becoming increasingly ambiguous. The recent literature conveys the impression that this population possesses complex or even contradicting properties, either locally in the solar neighbourhood or on a global footage, when looking at in-situ data. On the one side, studies of in-situ samples have claimed the detection of structures (Gilmore, Wyse & Norris 2002, Wyse et al. 2006) although their characterisation and identification with the thick disc relics remains challenging. On the other side, star-counting studies seem to acknowledge a 'regular' thick disc, although it must be recognised these studies have failed to characterise uniquely the properties of this population on large scales (see for example Chen et al. 2001), and one may ask to what extent possible structures are responsible for this.

It is neither clear from local samples what exactly the thick disc is. Helmi et al. (2006), Arifyanto & Fuchs (2006) and Bensby et al. (2007) all find conclusive evidence for kinematical groupings in local samples in the range of metallicity and kinematics where the thick disc is likely to dominate.
These studies illustrate that stellar groups are found lagging the local standard of rest at various speed from about -125 km.s\(^{-1}\) (Arcturus stream, Navarro, Helmi & Freeman, 2004), -80 km.s\(^{-1}\) (Arifyanto & Fuchs, 2006) to -50 km.s\(^{-1}\) (Hercules stream, Bensby et al., 2007, Soubiran & Girard, 2005), and one is justified to ask: what room remains for a ‘regular’ thick disc? Since stellar streams are found lagging every 30 to 40 km/s behind the old thin disc, how do we know that stars sampled by local spectroscopic surveys are tracing a supposedly existing regular thick disc? Or do we have to assume that the local thick disc is essentially an accumulation of stellar streams?

Additional confusion comes from the fact that stars labelled ‘thick disc’ by kinematic membership probability in local spectroscopic surveys are far from the canonical characteristics of this population. Thick disc stars selected upon \([\alpha/Fe]>0.2\) dex in all samples studied here have a mean lag with respect to the Sun of about -74 km.s\(^{-1}\) (-85 in Soubiran & Girard 2005). This is to contrast with the canonical value of the asymmetric drift assumed to derive probabilities, which are -46 km.s\(^{-1}\) (Bensby et al. 2005), -48 km.s\(^{-1}\) (Reddy et al. 2003, 2005), and -51 km.s\(^{-1}\) (Soubiran & Girard, 2005). Similarly, the probability membership, when applied to the GCS catalogue, yields 324 stars with probabilities higher than 80% to belong to this population, with a mean rotational lag of -83 km s\(^{-1}\), with a metallicity distribution that seems to be highly dispersed and asymmetrical, with most of the stars concentrating in the range \([-1.0, 0.0]\) dex. Similarly, at least part of the structures identified by Helmi et al. (2006) are likely contained in the ‘thick disc’ we sampled from the catalogue of Nordström et al. (2004). In any case, these data sets reveal a population which is rather far from the canonical thick disc. The general consequence of these studies has been the increasing complexity in the descriptions of the local data, without actually achieving a clear identification of the thick disc. The overall picture seems to point toward a lumpy component, with direct connections with the thin disc, but the picture is fragmentary, and a consistent description of the Galaxy at intermediate metallicities is still lacking.

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