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THE THIN AND THICK GALACTIC DISKS: MIGRATION AND LINEAGE

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Abstract. Our understanding of the local constraints of the chemical evolution of the Galaxy have significantly changed in the recent years. This includes new results on the link between the two disks and on the two main constraints of galactic chemical evolution - the distribution of metallicities and the age-metallicity relation - and their new interpretation when radial migration of stars is properly taken into account. I discuss most recent advances on these three points.

It is argued that the so-called G dwarf problem cannot constrain infall because, starting with an initial metallicity of -0.2 dex, the thin disk could not have formed stars with 1/3 of solar abundance. Given this initial metal content, the problem is not to explain why there are so few metal-poor stars, but more likely to explain why there are so few metal-rich ones, for which infall could bring a correct answer. As a consequence of the conclusive link that relates the thin and thick disks, the picture that emerge is that the thick disk appears to have been the main episode of chemical enrichment in the Galaxy. The Gaia perspective is evoked.

1 Introduction

Our understanding of local constraints (within 100 pc of the Sun) of the chemical evolution of the Galaxy have significantly changed in the recent years. This is due to both new accurate spectroscopic data and from the in depth analysis of the Hipparcos catalogue and complementary data (Nordström et al., 2004), giving access to the full 3D space velocities of solar neighbourhood stars. Several recent studies (Haywood (2008), Roškar et al. (2008), Schoenrich & Binney (2008)) have pointed out the importance of analysing both kinematic and chemical data in order to interpret key features, leading to a new understanding to the main constraints of the disk galactic chemical evolution. This includes new results on the link between the two disks, and the two main constraints of galactic chemical evolution, the age-metallicity relation and the distribution of metallicities. I review most recent advances on these three subjects.

2 Linking the thick and thin disks

2.1 Radial migration & the homogeneity of chemical species in the disk

Empirical evidences that radial mixing is effective have been found in solar neighbourhood data (Haywood, 2008). The study of the metallicity and orbital characteristics of thin disk stars sampled locally shows that the low and high metallicity tails of the thin disk are populated by objects which origins are in the outer and inner disk, and brought to the solar radius by radial migration. One possible mechanism giving rise to this mixing has been identified in Sellwood & Binney (2002), and its impact on the local kinematics and chemistry has been studied thoroughly by Schoenrich & Binney (2008). Signatures of this mixing is detected on the kinematic and orbital behaviour of thin disk stars, which show systematic trends as a function of metallicity. Metal-poor stars of the thin disk have guiding centres larger than the mean of solar neighbourhood stars (Fig. 1b), corresponding to a V space velocity systematically higher than the LSR (Fig. 1a). Metal-rich stars have a symmetrical behaviour (Fig. 1c). This is best interpreted as corresponding to the inward and outward shift of stars that migrate from the outer and inner disk.

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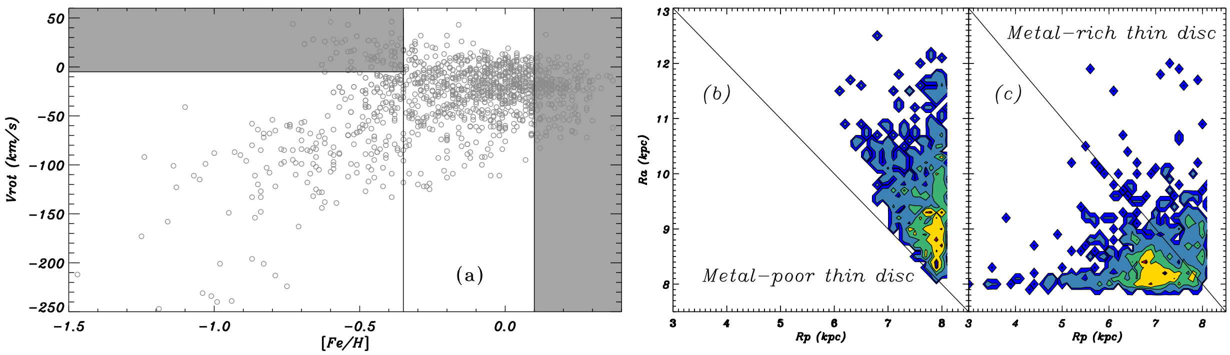

Fig. 1. (a) V_{rot}-[Fe/H] plot for a sample of stars with accurate metallicities. (b) and (c) are the density distribution in the (pericentre, apocentre) space for stars as selected by the 2 boxes of plot (a) in the GCS catalogue.

Evidences are now accumulating that chemical evolution proceeds essentially from homogeneous ISM at all times in the disk, as testified by meteoritic presolar grains (Nittler, 2005), spectroscopic measurements through the ISM (Cartledge et al. 2006), and abundance ratios. Allowing for the effect of radial mixing as being responsible for most of the dispersion measured on stellar metallicities, implies that thin disk stars born at the solar galactocentric radius have a rather restricted range of metallicites - within [-0.2 to +0.2] dex.

It means that although the ISM is well mixed at a given radius, giving rise to similar relative abundance ratios of chemical species at all radii, the absolute level of enrichment (the metallicity) is mainly a function of galactic radius, much less a function of time. Radial migration of stars gave rise to some mixing in the disk, and thereby increased the dispersion in metallicity, while the relative ratios, being a slow function of metallicity, have remained relatively homogeneous. Together with the small age-dependence of the metallicity at the solar neighbourhood, the widening of the metallicity interval due to radial mixing and present measurements of the radial metallicity gradient suggest that the radial variation of metallicity is 3 to 4 times more important than its local temporal evolution.

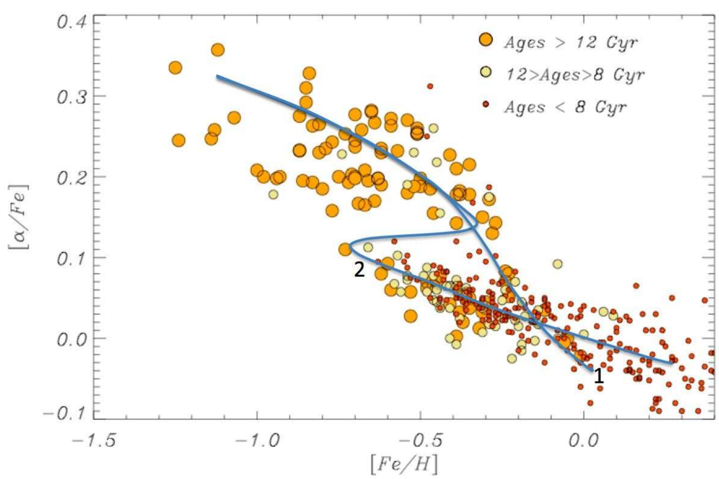

Fig. 2. Linking the thick and thin disks through α-element abundances. It has been suggested that the hiatus in metallicity could have resulted from an infall episode of gas that would have diluted metals in the ISM at the end of the thick disk formation (2). Orbital parameters of solar neighbourhood stars suggest on the contrary that the thin disk outside the metallicity interval [-0.2, +0.2] dex are objects brought to the solar radius by radial migration. It suggests that the local thin disk at solar metallicities could be the continuation and the end point of a sequence (1) starting near [Fe/H]=-1.2 dex, or lower. Samples from Reddy et al., 2003, 2006 and Gilli et al. (2006)

2.2 The parenthood between the two disks

The accurate abundance patterns now available on local stars give the best indication so far of a continuity, or parenthood, between the thin and thick disks. The hiatus in metallicity (see Fig. 2) between thick disk stars (at [Fe/H]=-0.2 dex, [α/Fe]=0.18 dex) and thin disk stars (at [Fe/H]=-0.7 dex, [α/Fe]=0.1 dex) interpreted as the signature of an infall episode in standard chemical evolution (curve (2) on Fig. 2) is in fact best understood by taking into account the kinematic behaviour of the stars. The thin disk metal-poor stars, responsible for the hiatus, have a mean rotational component and a corresponding guiding centre greater than the mean disk population (Haywood, 2008). This is best interpreted has testifying the outer disk origin of these stars (Haywood, 2008b, Schoenrich & Binney, 2008). If this interpretation is correct, these stars are outliers to the local thin disk chemical evolution, and the hiatus is not resulting from the local chemical evolution, but is a consequence of the radial redistribution of stars in the disk due to migration. The local evolution can then be seen to proceed continuously from high [α/Fe] and low metallicities to low [α/Fe] and solar metallicities (curve 1 on Fig. 2). In the ([α/Fe],[Fe/H]) plane, the thick disk seem to develop a sequence, while stars endemic of the thin disk at solar galactocentric radius are almost restricted a point (nearly centred on the sun), at the end of, but possibly separated from, the thick disk sequence.

2.3 Inconsistencies in the description of the thick disk

Chemical data of stars kinematically labeled as thick disk in the solar vicinity seem to confirm a high degree of homogeneity, as is apparent in different studies (see in particular Fuhrmann 2008, Nissen & Schuster 2008), pointing to a well-defined population. What poses a problem however is its kinematic definition. Fig. 3 shows an histogram of V space velocity values from the work of Soubiran & Girard (2005). Stars flagged as thick disk members according to probability membership based on mean kinematic properties are given as the smaller histogram. One of these properties is the rotational lag, which in the case of the thick disk is standardly assumed to be 40-50 km/s. The plot shows that the thick disk selected in Soubiran & Girard (2005) is more likely to rotate with a mean lag of 80 km/s. Similar values are found on all kinematically defined thick disk samples from solar neighbourhood stars. Notice that this is near to the value found by Arifyanto & Fuchs (2006), making it unclear if thick disk parameters are polluted by an unknown stream or if Arifyanto & Fuchs (2006) have been pointing to the 'correct' thick disk. More generally, it must be clarified how the several streams that have been found on solar neighbourhood stars (Helmi et al. (2006), Arifyanto & Fuchs (2006)) are linked to the thick disk or even if they could be part of the thick disk.

The thick disk age in the solar neighbourhood is not better known. For example, Bernkopf & Fuhrmann (2006) advocates that the thick disk stars form a coeval population formed in a single burst of star formation 12 Gyrs. Enlarged samples however seems to indicate a substantial evolution, as demonstrated in Bensby et al. (2004), Haywood (2006) and below. Obviously this point needs to be clarified, and echoes the more general challenge of identifying stars that truly make up this population.

3 Age-metallicity relations in the thick and thin disks

3.1 How to correlate age and metallicity: biases in action

Depending on the selection that is made to choose local stars, samples will include various amount of migrants from the outer or inner disk, or stars of the thick disk, and will therefore represent the local evolution accordingly. This is illustrated in Fig. 4, which shows the sample of Edvardsson et al. (1993) overplotted on our age-metallicity distribution from Haywood (2008). The sample of Edvardsson et al. (1993) was designed to be representative of the range of local metallicities, but has been often used to estimate the age-metallicity relation. The ages of the two samples were derived using the same procedure described in Haywood (2008). The sample of Edvardsson et al. is known to have provided the basis for claims of a real correlation between age and metallicity (Pont & Eyer, 2004). The age-metallicity relation evidenced in these studies stems from three different effects. The first one is the inclusion of thick disk objects. Non-differentiating the thick and thin disk stretches the relation across the two populations (down to -0.8 dex) and artificially creates a correlation that is mostly nonexistent within the thin disk. The inclusion of thin disk stars without taking account their radial origin also extends the metallicity range outside its normal interval by including metal-poor stars from

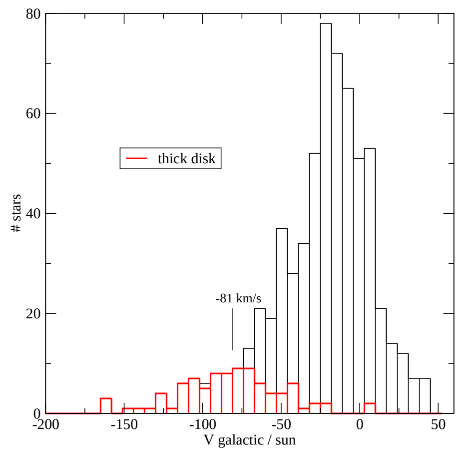

Fig. 3. Histogram of velocities in the direction of galactic rotation for the sample of Soubiran & Girard (2005). The histogram with mean at -81 km/s is representing stars flagged as thick disk using kinematic membership probability in their catalogue.

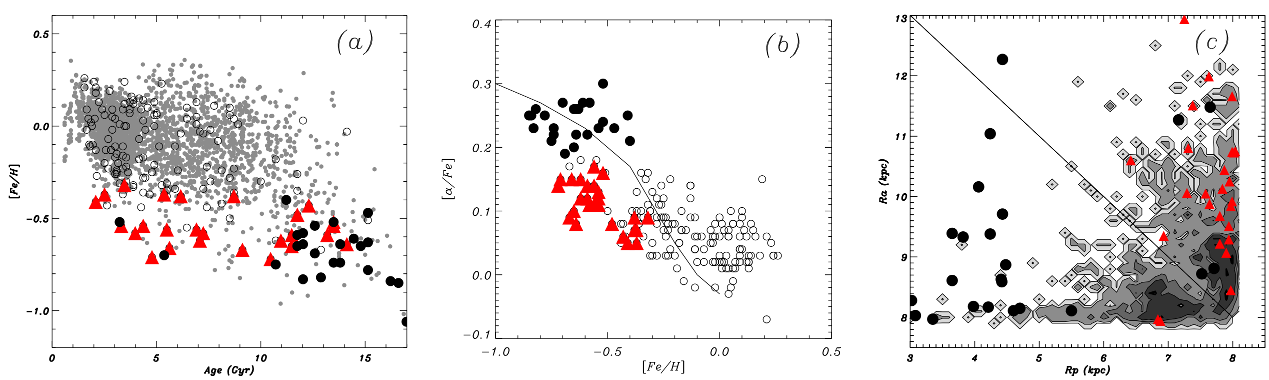

Fig. 4. (a) Stars from Edvardsson et al. (1993), overlayed to our age-metallicity distribution (small grey dots). Triangles are thin disk stars with V>-5 km/s, [Fe/H]<-0.3 dex and [α/Fe]<0.18 dex. Large black dots are thick disk object with the condition that [α/Fe]>0.18 dex. The age-metallicity distribution of the sample of Edvardsson et al. (1993) is heavily weighted towards metal-poor stars, due to the fact that it is biased against old solar metallicity or metal-rich stars, and contains both thin disk stars from the outer disk and thick disk objects, which have not contributed to the thin disk local evolution. The apparent correlation between age and metallicity that has been obtained from this sample (Pont & Eyer, 2004) is essentially due to the combination of these 3 effects. (b) Position of these two groups in the ([α/Fe],[Fe/H]) diagram, and on the (Rp, Ra) distribution.

the outer disk. Finally, Edvardsson et al. (1993) acknowledge that their selection excluded old metal-rich star, also contributing to enhance the correlation.

3.2 The thick disk as the main episode of galactic chemical enrichment

Figure 5 illustrates the different pace at which metal enrichment occurred in the galactic thin and thick disks. Metallicity has changed by about 0.3 dex in 8-10 Gyrs in the thin disk, or a factor of 2 of increase in Z. This is to compare with a factor 10 increase in 3-4 Gyr in the thick disk, and implies that most chemical enrichment in the solar neighbourhood have preceded the thin disk. Evidences are becoming more acute for a thick disk playing a central role in the building of the Milky Way. Most recently, Nissen & Schuster (2008) presented new data on solar vicinity stars at lower metallicities ([Fe/H]<-0.6 dex), showing that two distinct components (accreted and dissipative) that make up the halo. One is clearly the continuity of the thick disk at lower metallicities, possibly making a single dissipative component of the Galaxy, the other shows distinct lower abundances of α elements with a pattern that resembles closely the one observed on dwarf spheroidals. On the contrary, if stars of the thick disk are of external origin, we are left with a gap of about 1.2 dex between the metallicity of the halo and that of the old thin disk. It would also imply that the Milky Way would have been relatively exceptional in the sense of having negligible star formation activity for several Gyrs when the universe was having its most intense phase of star formation.

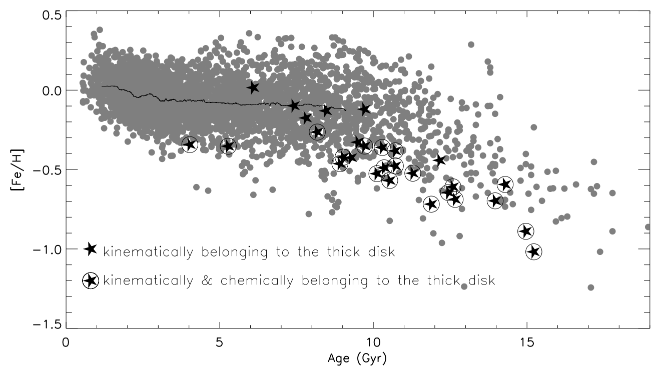

Fig. 5. Age-metallicity distribution for stars in the solar vicinity. Continuous curve is the mean metallicity of thin disk stars as a function of age. Star symbols are objects kinematically known has belonging to the thick disk (see Haywood (2006)). Symbols within circles have the additional condition that [α/Fe]>0.18 dex. The age of these objects has been derived taking into account their α-element content, which explains why they have systematically lower ages than stars of the same metallicities.

4 The new 'G dwarf problem', or the lack of metal-rich stars born at solar galactocentric radius

Contrary to what is stated in Prantzos (2008), Haywood (2006) didn't argue that the solar neigbourhood behaved like a closed box, but that its metallicity distribution, if the thick disk contribution is taken into account, is similar to a close box distribution. It does only imply that the argument that infall-must-have-occurred-because-the-MDF-is-not-closed-box is fake, but does not imply that infall did not occur. Given the difficulties that classical modelling have to go beyond the unfruitful dilemma infall *vs* closed-box model, it is encouraging that new models (Brook et al. (2007), Schoenrich & Binney (2008), Roškar et al (2008)) combining dynamical and chemical evolution have had more success to account for local distributions as resulting from a mix of both kind of processes.

How does radial mixing affects the local metallicity distribution ? Radial mixing has the effect of enlarging the range of observed metallicities at the solar radius, amounting to an approximate 10% of the stars, either metal-poor or metal-rich. As mentioned above, stars that are truly endemic of the solar galactocentric radius, have a range of metallicities of -0.2 <[Fe/H]< 0.2 dex in the thin disk, while the thick disk have [Fe/H]<-0.2 dex. How does it impact on the interpretation of the local metallicity distribution ? The 'G-dwarf' problem, in its classical form, concerns the lack of stars with 1/3 of metals of the peak population (which is at [Fe/H]≈0), or [Fe/H]≈-0.45 dex. Clearly, *there are no such stars stemming from the local evolution (at solar galactocentric radius) in the thin disk*, because at this metallicity, stars all reside in the thick disk. Since the metallicity was already -0.2 dex at the end of the thick disk phase, there is no point questioning why the thin disk has not formed stars more metal-poor than this limit, and there is no *metal-poor* G-dwarf problem in the thin disk, while there may be one in the thick disk. Unfortunately, there is no statistically meaningful sample of thick disk stars in the solar vicinity to test this prediction.

In 1974 B. Tinsley already pointed out the problem posed by the slow enrichment rate in the galactic thin disk: "Although disk-population stars of all ages have considerable dispersion in Z, the mean value is only a very slowly increasing function of birth epoch". Considering an initial gas disk with surface density at the solar galactocentric radius of 40 $M_{\odot}.pc^{-2}$, mean initial metallicity -0.2 dex, mean star formation rate $4M_{\odot}.pc^{-2}.Gyr^{-1}$, yield 2% and return gas fraction of 30%, it is expected that the present metallicity in the disk at the solar radius, would be about +0.5 dex, when at most 0.2 dex is observed. Arguably all these quantities are very uncertain, but still, there may be a 'G-dwarf metal-rich problem', to which infall would be solution, as already noted by Tinsley. In other words, infall is not necessary to explain the absence of metal-poor dwarfs in the thin disk, but may be required to explain why so few metal rich stars have formed at the solar radius.

5 Gaia prospect

The vast majority of the stars Gaia will observe are disk stars. Accurate age determinations should be achievable within 2 kpc for a typical G type main sequence star and 3 kpc for an old subgiant. The age-scale itself should also benefit from a drastic improvement in stellar physics that are expected from the availability of numerous fine calibrators that will map the entirety of the HR diagram, both from Gaia itself and present or forthcoming asteroseismology studies and complementary data. It is therefore expected that several millions of stars with accurate age determination will be available for the kind of studies that are achievable today only on a few hundreds of objects in the solar vicinity (within 50-100 pc). It implies that, complemented with high resolution, high SN spectroscopic data, a detailed map of the interface between the thick and thin disc populations should be obtainable, not only in the solar neighbourhood but also radially on several kpc. Moreover, the continuity that is lacking between local and in situ samples of the thick disk should help to characterize the properties of this population. Concerning the thin disk, particularly important will be the availability of radially distributed samples to understand the intricacy of chemical and dynamical processes as outlined here. Realistic simulations of the thin disk evolution including radial redistribution of stars and gas are just coming out in recent studies (see Roškar et al. 2008, Schoenrich & Binney 2008), and give us insights of what this complexity could be.

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