The chemistry of the Milky Way disk

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The Milky Way has two disk populations

Thin disk:
- scale height: 250 pc
- normalisation: 98%

Thick disk:
- scale height: 1400 pc
- normalisation: 2%

Thick disks in external galaxies


Bulge and thin disk profiles shown, however a third diffuse component is needed to fit the luminosity distribution perpendicular to the plane, named the “Thick disk”.

![NGC 4570](image1.png)

![NGC 4350](image2.png)

![NGC 4340](image3.png)
The Milky Way as a benchmark galaxy

Milky Way is the only galaxy that can be studied in great detail and a good understanding of its stellar populations is important for our understanding of galaxy formation in general.
The Milky Way as a benchmark galaxy

Why does the Milky Way have two disk populations?

Need to characterize them in terms of

• velocities
• abundances
• ages

Not only in the solar neighbourhood, but throughout the Milky Way galaxy.
Nearby stars - no selection

- Fuhrmann’s study is 85% volume complete for all mid-F type to early K-type stars down to Mv=6.0, north of dec=-15°, within a radius d<25pc from the Sun

- Two types of stars:
  1. Old stars with high [Mg/Fe] ratios
  2. Young stars with low [Mg/Fe] ratios

Two types of stars - high-alpha & low-alpha

(data from Fuhrmann’s papers)

Two very different distributions of eccentricity and \( J_z \) for low- and high-\( \alpha \) stars

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Two very different distributions of eccentricity and \( J_z \) for low- and high-\( \alpha \) stars
Metallicities

(data from Fuhrmann’s papers)

Thin disk: $\langle [\text{Fe/H}] \rangle = 0$
(see also, e.g., Nordström et al., 2004, Casagrande et al. 2011)

Thick disk: $\langle [\text{Fe/H}] \rangle = -0.6$
(see also, e.g., Gilmore, Wyse, Jones, 1995; Carollo et al 2010)

low-$\alpha$ stars
Solar neighbourhood

Solar neighbourhood, in the plane:

~90 % thin disk
~10 % thick disk

scale-heights:
300 pc & 1000 pc, respectively

To be sure to observe thick disk stars, you need to go at least 2 kpc above/below the plane

F and G dwarf stars usually too faint for high-resolution studies at those distances!!
Kinematical criteria to select nearby thick disk stars

\[ P = X \cdot k \cdot \exp \left( -\frac{U_{\text{LSR}}^2}{2 \sigma_U^2} - \frac{(V_{\text{LSR}} - V_{\text{asym}})^2}{2 \sigma_V^2} - \frac{W_{\text{LSR}}^2}{2 \sigma_W^2} \right) \]

\[ k = \frac{1}{(2\pi)^{3/2} \sigma_U \sigma_V \sigma_W} \]

<table>
<thead>
<tr>
<th></th>
<th>( \sigma_U )</th>
<th>( \sigma_V )</th>
<th>( \sigma_W )</th>
<th>( V_{\text{asym}} )</th>
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<tbody>
<tr>
<td>Thin disk (D)</td>
<td>35</td>
<td>20</td>
<td>16</td>
<td>-15</td>
</tr>
<tr>
<td>Thick disk (TD)</td>
<td>67</td>
<td>38</td>
<td>35</td>
<td>-46</td>
</tr>
<tr>
<td>Halo (H)</td>
<td>160</td>
<td>90</td>
<td>90</td>
<td>-220</td>
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Gaussian velocity distributions, \( X \) is normalisation in solar neighbourhood (~90% thin, ~10% thick)

Probability ratios: \( P(\text{TD}/D) > 1 \) is more likely to be a thick disk star
Chemistry of the Solar neighbourhood


712 F and G dwarf stars in the Solar neighbourhood

A clear dichotomy:
- An old and alpha-enhanced population
- Less alpha-enhanced young population

A bit further away

Inner disk  
$4 < R_g < 7 \text{kpc}$

Solar neighbourhood

Outer disk  
$9 < R_g < 13 \text{kpc}$


Alves-Brito et al. (2010)


No alpha-enhanced stars in the outer disk

=> Short scale-length for the thick disk!

See also, e.g., Cheng et al. (2012), Bovy et al. (2012)
Further away and larger samples - APOGEE

- Hayden et al. (2015), based on red giants from APOGEE DR12

No alpha-enhanced stars!

Abundance gradient in the thin disk
Further away and larger samples - Gaia-ESO

Lack of alpha-enhanced stars in the outer disk!
Similar results seen in local data


- 714 F and G dwarfs in the solar neighbourhood (d<100 pc).
- Calculating stellar orbits to get
  \[ R_{\text{mean}} = \frac{R_{\text{min}} + R_{\text{max}}}{2} \]
- Almost no (old) high-alpha stars with \( R_{\text{mean}} > 9 \text{kpc} \)
- Almost no (young) low-alpha stars with \( R_{\text{mean}} < 7 \text{kpc} \)

Sizes of circles prop. to age (larger = older)
Scale-lengths in external galaxies

Luminosity profile fitting

Thick disk scale-lengths are longer than thin disk scale-lengths!
Fig. 17. Generalised abundance ratio histograms for the O, Mg, Si, Ca, and Ti for stars in the interval $-0.7 < \frac{[\text{Fe}/H]}{\text{H}} < -0.35$. Shaded histograms show stars with $T_{\text{eff}} > 5400$ K. The red dash-dotted lines show the fraction of rejected stars when selecting stars with $T_{\text{eff}} < 5400$ K.

Fig. 18. Boxplots showing the distribution of abundance ratios for 16 stars with $T_{\text{eff}} > 5400$ K and an upper age limit of 7 Gyr, in a narrow metallicity range around that of the Sun ($\pm 0.05$ dex). Because of large NLTE effects for Ba at higher temperatures, the Ba box has been restricted to stars with $T_{\text{eff}} < 6000$ K as well. In the boxplots the central horizontal line represents the median value. The lower and upper quartiles are represented by the outer edges of the boxes, i.e. the box encloses 50% of the sample. The whiskers extend to the farthest data point that lies within 1.5 times the inter-quartile distance. Those stars that do not fall within the reach of the whiskers are regarded as outliers and are marked by dots.

Fig. 19. $\frac{[\text{Ti}/\text{Fe}]}{\text{Fe}/\text{H}}$ as a function of $\frac{[\text{Fe}/\text{H}]}{\text{H}}$ selected on $T_{\text{D}}/T_{\text{D}}$ as indicated in each panel for stars with $T_{\text{eff}} > 5400$ K. To guide the eye, the red lines outline the thick disk abundance plateau and the decrease in the thin disk abundance ratio, respectively.

Figure 19 shows the $\frac{[\text{Ti}/\text{Fe}]}{\text{Fe}/\text{H}}$ – $\frac{[\text{Fe}/\text{H}]}{\text{H}}$ abundance trends for five different cuts in the thick disk-to-thin disk probability ratios ($T_{\text{D}}/T_{\text{D}}$) that indicate how much likely it is that a star belongs to the thick disk than the thin disk. The top panel shows $T_{\text{D}}/T_{\text{D}} = 1$, equal probabilities $T_{\text{D}}/T_{\text{D}} > 1$, more likely to be thick disk $T_{\text{D}}/T_{\text{D}} < 1$, more likely to be thin disk

Kinematics:

Using Gaussian velocity ellipsoids to calculate probabilities that the stars belong to either the thin or the thick disks

$T_{\text{D}}/T_{\text{D}} = 1$, equal probabilities
$T_{\text{D}}/T_{\text{D}} > 1$, more likely to be thick disk
$T_{\text{D}}/T_{\text{D}} < 1$, more likely to be thin disk

714 nearby dwarfs from Bensby et al, (2014)
Kinematic confusion

Two well-defined, but not perfectly clear trends

714 nearby dwarfs from Bensby et al, (2014)
Ages

Bensby et al, (2014)

Haywood et al, (2011)
**Kinematic confusion**

Ages seem to better discriminator between thin and thick disk, but ages are rarely available and very difficult to determine

714 nearby dwarfs from Bensby et al, (2014)
Chemistry - GESiDr4, solar cylinder R=1 kpc

Toomre diagram:

Abundance criterion produces kinematical samples that are consistent with what we currently know about the thin and thick disks in the solar neighbourhood:

* alpha-rich disk lagging the alpha-poor disk by some ~40 km/s
* alpha-rich being kinematically hotter
Dashed line:
Fraction of thick-to-thin disk stars using a 10% normalisation in the plane, and 300 pc and 1000 pc scale-heights for the thin and thick disks, respectively.

Green line:
The observed fraction of thick-to-thin disk stars, using alpha-enhancement as selection criterion.
Summary

• Milky Way appears to have two distinct disk populations

• The thick disk has a short scale-length

• Galactic scale-length estimates based on chemistry (alpha-enhancement)

• Scale-lengths in external galaxies based on morphology, giving longer thick disk scale-lengths

• Gaia, in combination with results from the large spectroscopic surveys, will allow us to explore the thin and thick disks in terms of ages - kinematics - chemistry, throughout the Milky Way