Statistical analysis of large scale surveys for constraining the Galaxy evolution

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Outline

• Introduction
  - Thick disc
• The Besançon Galaxy Model
• SEGUE data
  - SEGUE plates
  - Simulations
  - Sample selection
  - Results from the SEGUE analysis
    - The metallicity distribution
    - Distances
    - MCMC-ABC analysis
• Conclusions
• Perspectives
• Preliminary analysis of the Gaia-ESO survey
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Milky Way thick disc

- **Milky Way** → We can study the chemical composition and the Galactic dynamics based on individual star measurements.

- **The thick disc** → Old component of the Galaxy
  → Remnant of the early galaxy formation and evolution.

- The first stages of galaxy formation are printed in the chemical and kinematic properties of the thick disc.

- To understand the Milky Way formation and evolution it is crucial to understand thick disc formation.
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The Besançon Galaxy Model

**SFR:**
- **Thin disc:** Constant
- **Thick disc:** One burst
- **Halo:** One burst

**Thick disc** → Modified exponential (parabolic + exponential)
- A short scale length: \( \sim 2.3 \) kpc
- Scale height: \( \sim 530 \) pc
- Position of the change: \( \xi \sim 660 \) pc

Robin et al. (2014)

**Age metallicity relation:** Haywood (2006)

**Thin disc:**
Implicit vertical metallicity gradient:
\( \sim -0.06 \) dex kpc\(^{-1}\)

**Age-scale height relation**
**Age-metallicity relation**

<table>
<thead>
<tr>
<th>Age (Gyr)</th>
<th>([Fe/H]) (dex)</th>
<th>(d[Fe/H]/dR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disc</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–0.15</td>
<td>0.01 ± 0.12</td>
<td></td>
</tr>
<tr>
<td>0.15–1</td>
<td>0.03 ± 0.12</td>
<td></td>
</tr>
<tr>
<td>1–2</td>
<td>0.03 ± 0.10</td>
<td></td>
</tr>
<tr>
<td>2–3</td>
<td>0.01 ± 0.11</td>
<td>-0.07</td>
</tr>
<tr>
<td>3–5</td>
<td>-0.07 ± 0.18</td>
<td></td>
</tr>
<tr>
<td>5–7</td>
<td>-0.14 ± 0.17</td>
<td></td>
</tr>
<tr>
<td>7–10</td>
<td>-0.37 ± 0.20</td>
<td></td>
</tr>
<tr>
<td>Thick disc</td>
<td>-0.78 ± 0.30</td>
<td>0.00</td>
</tr>
<tr>
<td>Stellar halo</td>
<td>-1.78 ± 0.50</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Robin et al. (2003)
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SEGUE data

- Low latitude plates of the SEGUE survey.

Table 5.1:
SEGUE survey plates used for the present analysis

<table>
<thead>
<tr>
<th>Plate bright/faint</th>
<th>l (°)</th>
<th>b (°)</th>
<th>Ra (°)</th>
<th>Dec (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2534/2542</td>
<td>50</td>
<td>14</td>
<td>277.60</td>
<td>21.33</td>
</tr>
<tr>
<td>2536/2544</td>
<td>70</td>
<td>14</td>
<td>286.66</td>
<td>39.11</td>
</tr>
<tr>
<td>2537/2545</td>
<td>110</td>
<td>10.5</td>
<td>334.17</td>
<td>69.39</td>
</tr>
<tr>
<td>2538/2546</td>
<td>110</td>
<td>16</td>
<td>323.07</td>
<td>73.64</td>
</tr>
<tr>
<td>2554/2564</td>
<td>94</td>
<td>14</td>
<td>302.97</td>
<td>60.01</td>
</tr>
<tr>
<td>2555/2565</td>
<td>94</td>
<td>8</td>
<td>312.39</td>
<td>56.59</td>
</tr>
<tr>
<td>2556/2566</td>
<td>94</td>
<td>-8</td>
<td>330.15</td>
<td>45.06</td>
</tr>
<tr>
<td>2668/2672</td>
<td>187</td>
<td>-12</td>
<td>79.49</td>
<td>16.61</td>
</tr>
<tr>
<td>2678/2696</td>
<td>187</td>
<td>8</td>
<td>98.13</td>
<td>26.67</td>
</tr>
<tr>
<td>2681/2699</td>
<td>178</td>
<td>-15</td>
<td>71.50</td>
<td>21.98</td>
</tr>
</tbody>
</table>
• **Spectroscopy (dr8)**
  - Bright \( (g = 15 - 18) \) and faint \( (g = 17.5 - 19.5) \) plates are treated separately.

• **Simulations**
  - Correct the magnitudes and color of stars with modified extinction model. Martins et al. (submitted)
  - We apply the same selection function to simulations (Selection of the stars that will receive fibers).
  - S/N and spectral parameters errors are simulated.
  - Errors are 0.23 dex, 180 k and 0.24 dex respectively for metallicity, effective temperature and \( \log g \) (Smolinski et al. (2011))

• **Compare to observations** → selected stars in bins of \( g \) and \( g-r \).
Sample selection

Main Sequence Turn-Off stars

Spatial coverage

- We cover regions: $6.0 \, \text{kpc} < R_{\text{gal}} < 14.0 \, \text{kpc}$
- $0.15 \, \text{kpc} < |Z| < 1.5 \, \text{kpc}$
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Results from the SEGUE analysis

Observations vs simulations

Faint plate $\rightarrow l = 110^\circ$, $b = 10.5^\circ$
Observations vs simulations

Results from the SEGUE analysis
Distances

- **Main Sequence Turn-Off stars** ➢ from the model we fit a relation between temperature $T_{\text{eff}}$ and absolute magnitude ($M_V$).

- The relation is established independently in three metallicity bins.

  - $[\text{Fe/H}] < -0.5$ dex →

  - $-0.5$ dex < $[\text{Fe/H}] < 0.0$ dex →

  - $[\text{Fe/H}] > 0.0$ →

Results from the SEGUE analysis
$[\text{Fe/H}] < -0.5 \text{ dex}$

$-0.5 \text{ dex} < [\text{Fe/H}] < 0.0 \text{ dex}$

$[\text{Fe/H}] > 0.0$
Distances

- Compute the absolute magnitude for the obs/sim
  - Compute the distance modulus.
- Extinction is taken in account.
- The same bias
- A clear bias
  \[ d > 4.0 \text{ kpc} \]

Results from the SEGUE analysis

Fitting method

- We use the log-likelihood (Bienaymé et al. 1987).
\[ L_r = \sum_{i=1}^{N} q_i \left( 1 - R_i + \ln(R_i) \right) \]

- The data and simulations are binned in the distance metallicity space.

- The log-likelihood is a statistical distance (pseudolikelihood) so we have to use an ABC/MCMC (Approximate Bayesian Computation) method, where the sampling is done by a Metropolis-Hasting algorithm.

MCMC/ABC Fitting method

For iter=1 to maxiter do
   Repeat
   Generate \( \theta' \) from the prior distribution \( \pi(\cdot) \)
   Generate \( z \) from the likelihood \( f(\cdot|\theta') \)
   until \( \rho \leq \varepsilon \)
   set \( \theta_i = \theta \)
end for


Results from the SEGUE analysis

- Bin \([\text{Fe/H}]\) = 0.25 dex
- Bin \([\text{distance}]\) = 1.0 kpc
Results

- We fit for the thin and thick disc:
  - Local [Fe/H]
  - Radial metallicity gradients
  - Dispersion

- We fit:
  i. Thick disc.
  ii. Thick disc along with the thin disc
  iii. Thick disc along with the old thin disc.

- We have analyzed three cases for point ii.
  - Case 1: We use all fields.
  - Case 2: We don't use the anticenter fields.
    - $l = 187^\circ; \ l = 178^\circ$
  - Case 3: We don't use the inner fields.
    - $l = 50^\circ; \ l = 70^\circ$
Results from the SEGUE analysis

Results - Thick disc along with the old thin disc

- Considering 10 independent runs:
  - The results are the mean.
  - The $\sigma$ is the standard deviation.

<table>
<thead>
<tr>
<th>Case</th>
<th>$[Fe/H]<em>{SN</em>{thick}}$ (dex)</th>
<th>$d[Fe/H]/dR$ (dex kpc$^{-1}$)</th>
<th>Disp (dex)</th>
<th>$[Fe/H]<em>{SN</em>{old thin}}$ (dex)</th>
<th>$d[Fe/H]/dR$ (dex kpc$^{-1}$)</th>
<th>Disp (dex)</th>
<th>$\mathcal{L}$</th>
<th>BIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.465</td>
<td>-0.008</td>
<td>0.319</td>
<td>-0.116</td>
<td>-0.079</td>
<td>0.135</td>
<td>-511.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\pm 0.033$</td>
<td>$\pm 0.015$</td>
<td>$\pm 0.029$</td>
<td>$\pm 0.012$</td>
<td>$\pm 0.015$</td>
<td>$\pm 0.011$</td>
<td>$\pm 16.63$</td>
<td>1084.66</td>
</tr>
<tr>
<td>2</td>
<td>-0.449</td>
<td>0.031</td>
<td>0.319</td>
<td>-0.116</td>
<td>-0.086</td>
<td>0.135</td>
<td>-269.10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\pm 0.028$</td>
<td>$\pm 0.025$</td>
<td>$\pm 0.032$</td>
<td>$\pm 0.021$</td>
<td>$\pm 0.040$</td>
<td>$\pm 0.011$</td>
<td>$\pm 9.08$</td>
<td>587.18</td>
</tr>
<tr>
<td>3</td>
<td>-0.418</td>
<td>-0.030</td>
<td>0.304</td>
<td>-0.113</td>
<td>-0.076</td>
<td>0.135</td>
<td>-440.37</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\pm 0.024$</td>
<td>$\pm 0.050$</td>
<td>$\pm 0.038$</td>
<td>$\pm 0.017$</td>
<td>$\pm 0.017$</td>
<td>$\pm 0.011$</td>
<td>$\pm 16.10$</td>
<td>931.85</td>
</tr>
</tbody>
</table>

Case 1

A. M. M. Martins et al. submitted
Results from the SEGUE analysis

Correlations

- Correlation: $-0.3802$
- Correlation: $-0.5827$
Thin disc metallicity distribution from the literature
Thick disc metallicity distribution from the literature
The age of the thick disc

Case 1 → All fields

Table 8.11:
Sum of the likelihood values, for different ages of the thick disc, for the spectroscopic parameters (MSTO stars) with the fitted parameters.

<table>
<thead>
<tr>
<th>Age</th>
<th>[Fe/H]</th>
<th>$\sigma$</th>
<th>$T_{\text{eff}}$</th>
<th>$\sigma$</th>
<th>$\log g$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 Gyr</td>
<td>-734.31</td>
<td>23.34</td>
<td>-1133.74</td>
<td>49.38</td>
<td>-424.284</td>
<td>17.06</td>
</tr>
<tr>
<td>9 Gyr</td>
<td>-693.68</td>
<td>10.78</td>
<td>-1032.26</td>
<td>10.84</td>
<td>-400.93</td>
<td>5.780</td>
</tr>
<tr>
<td>10 Gyr</td>
<td>-695.19</td>
<td>15.90</td>
<td>-990.16</td>
<td>39.27</td>
<td>-449.12</td>
<td>14.49</td>
</tr>
<tr>
<td>11 Gyr</td>
<td>-695.84</td>
<td>10.09</td>
<td>-969.23</td>
<td>10.22</td>
<td>-388.55</td>
<td>6.63</td>
</tr>
<tr>
<td>12 Gyr</td>
<td>-605.94</td>
<td>11.72</td>
<td>-790.60</td>
<td>13.46</td>
<td>-361.15</td>
<td>9.108</td>
</tr>
<tr>
<td>13 Gyr</td>
<td>-706.82</td>
<td>13.56</td>
<td>-1025.64</td>
<td>31.84</td>
<td>-448.57</td>
<td>13.79</td>
</tr>
</tbody>
</table>
Results

- If thick disc has a single epoch formation
  - 12 Gyr is the best age for this population.
  - The isochrone from Bergbusch and vandenbergen (1992) that best fits these data is the one with Fe/H = -0.5 and age of 12 Gyr.

- We tried to fit two radial metallicity gradients in the thick disc adding a parameter $R_{\text{change}}$. Results are compatible with no slope in the thick disc.
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Discussion – Thick disc formation scenarios

- The confirmation of a null radial metallicity gradient in the thick disc
  → **Radial mixing in gas or stars is important**

  ➢ **Gas mixing**
  - High SFI → strong turbulent gaseous disc  
    Brook et al. (2004), Lehnert et al (2009), Bournaud et al. (2009), Haywood et al. (2013)

  *Thick disc was formed in a highly mixed gas producing a chemically homogeneous thick disc*

  ➢ **Star + Gas mixing**
  - Radial migration (Sellwood & Binney (2002), Schönrich & Binney (2009a), Schönrich & Binney (2009b)) can also flatten gradients
  - The radial mixing in a disc can be also a consequence of the minor mergers  
    Kazantzidis et al. (2008), Quillen et al. (2009), Bird et al. (2012).
    - Radial mixing becomes **stronger at large |z|**. Explains a flat gradient in the thick disc, not found in the thin disc.

  ➢ **Direct accretion of stars** (Statler (1988), Toth & Ostriker (1992), Quinn et al. (1993), Velazquez & White (1999) and Abadi et al. (2003)).
    - Results cannot rule out this scenario
Conclusions

- The thin disc local metallicity and radial metallicity gradient are in agreement with literature.
- The thick disc local metallicity is found to be around -0.5 dex in SEGUE.
  - There is no radial metallicity gradient in the thick disc.
    - This result indicates the existence of radial mixing in gas or stars.
  - An inversion of the thick disc radial metallicity gradient seems less probable.

- The method allowed the study of correlations.
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Perspectives

- The GES analysis (DR2) will be performed on future releases with larger samples and improved calibrations.
  - Use the [Fe/H] vs [α/Fe] sequence
- Apply the analysis tools and techniques, developed with SEGUE and Gaia ESO survey, to APOGEE.
- Combine the results from different surveys.

It will help to constrain better:

- Vertical metallicity gradients.
- SFH of the thick disc.
- Explore chemical evolution in thick disc phase

- Increase the precision of our results.
Perspectives

- Use of kinematical data combined with metallicity distributions to understand the thick disc formation.
  - Study the rotational velocity as a function of metallicity
  - $\sigma_{u,v,w}$ as a function of metallicity
  - Study the eccentricity as a function of metallicity
Thanks