Simulations of the Formation of Thick Discs in Galaxies

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Current paradigm of galaxy formation

Larger structures are formed after mergers of smaller systems

simulations by J.P. Gardner
Milky Way structure

<table>
<thead>
<tr>
<th>Component</th>
<th>$10^{10} M_{\odot}$</th>
<th>R kpc</th>
</tr>
</thead>
<tbody>
<tr>
<td>thin disc</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>thick disc</td>
<td>1</td>
<td>$\sim 15$ (?)</td>
</tr>
<tr>
<td>bulge</td>
<td>1.6</td>
<td>3</td>
</tr>
<tr>
<td>stellar halo</td>
<td>0.1</td>
<td>3 (1/2 mass)</td>
</tr>
<tr>
<td>dark halo</td>
<td>100</td>
<td>150 (1/2 mass)</td>
</tr>
</tbody>
</table>
MW thick disc in a nutshell

- **Structure**
  - scale-height: 0.7-1.5 kpc (2x-3x thin)
  - scale-length: 2.8-4.5 kpc (~1x thin)
  - normalisation: 2-11%

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- **Kinematics**
  - $(\sigma_R, \sigma_\phi, \sigma_z) \sim (65, 54, 38)$ km/s (2x thin)
  - rotates fast $\sim 180$ km/s

- **Age**
  - composed of old stars $> 10$ Gyr

See: Chiba & Beers 2001
Nordstrom et al. 2004
Alcobe & Cubarsi 2005
Vallenari et al. 2006
Veltz et al. 2008

Quillen & Garnett 2000
(but see Holmberg et al. 2007)
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- **Chemistry**
  more metal poor
  higher \(\alpha\)-abundance

Bensby et al. 2003, 2004, 2005
Thick discs in other galaxies

Tsikoudi 1980

Dalcanton & Bernstein 2002

Elmegreen & Elmegreen 2006

... and in many other galaxies!

see also:
van der Kruit & Searle 1981
van Dokkum et al. 1994
de Grijs & Peletier 1997
Tikhonov & Galazutdinova 2005
Formation models for thick discs

"born-thick"

- Star formation during gas-rich mergers (Brook et al. 2004)
- Collapse of large gaseous clumps in turbulent early gas-rich discs (Bournaud et al. 2007)

"born-thin" (pre-existing disc needed)

- Radial mixing of stars by spiral arms (Schoenrich & Binney 2008) (Roskar et al. 2008)
- Disc heated during merger with a satellite (Quinn et al. 1993)
- Accretion of several small satellites (Abadi et al. 2003)
Formation model studied: **disc-heating**

Why the disc-heating scenario?
- such a merger process is **unavoidable** in \( \Lambda \)CDM

In the case of the Milky Way:
- supported by the presence of **substructure** in the thick disc
- it naturally explains the **high rotation** of the thick disc

Set-up of $N$-body simulations

Main features:

- merger mass ratios 5:1 and 10:1
- 3 initial inclinations ($0^\circ$, $30^\circ$, $60^\circ$)
- satellite in “cosmological” orbit
- prograde/retrograde orbits
- “discy”/spherical satellites
- mergers at redshifts $z=0$ and $z=1$
- gas is not included
Movie
Morphological properties of simulated thick discs

disc-heating scenario predicts boxy surface brightness contours in the outskirts

(edge-on views)

22.5, 24.2, 26, 27.7 mag arcsec$^2$ in V

6 mag below central s.b.
Morphological properties of simulated thick discs

Disc-heating scenario predicts boxy surface brightness contours in the outskirts

Dalcanton & Bernstein 2002
Structural properties of simulated thick discs

*vertical* structure of the remnants: 2 sech² components give better fit ("thin" + thick)
Kinematical properties of simulated thick discs

decomposition of velocity distributions into “thin” and thick components

- fit 1 component, $\chi^2 = 0.68$
- fit 2 component, $\chi^2 = 0.47$

![Graph showing velocity distributions with fits for thin and thick components.](image)
Kinematical properties of simulated thick discs

ratio $\sigma_z/\sigma_R$ of thick disc stars could be a good indicator of the initial inclination of the satellite

- Observed in Solar neighbourhood: $\sigma_z/\sigma_R \sim 0.6$
Kinematical properties of simulated thick discs

vertical gradient of rotational velocity in thick disc is stronger for lower initial inclinations of the satellite.

- Observed gradient in the MW's thick disc in the range -18 to -30 km/s/kpc (Chiba & Beers 2000, Girard et al. 2006, Ivezic et al. 2008)
Heliocentric line-of-sight velocities, $V_{los}$

Traces of disc-heating scenario in the phase-space structure of thick disc stars?

- final thick disc (face-on view)
- sampling thick disc stars within small spherical volumes
Heliocentric line-of-sight velocities, $V_{\text{los}}$

- sinusoidal shape:
thick disc stars retain the nearly circular orbits from the pre-existing disc

- the different behaviour of heated disc and satellite stars is clear after subtracting the rotation.

grey: heated disc
black: satellite
Heliocentric line-of-sight velocities, $V_{\text{los}}$

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Is it possible to detect the contribution of satellite stars in the wings?
Wings of $V_{\text{los}}$ distributions around long. $\sim 140^\circ$

- Solid circles: probability that a certain peak occurs by chance.
- Open circles: fraction $N_{\text{sat}}/N_{\text{total}}$ in each bin.

Simple statistical test is able to:
- Identify non-Gaussian peaks
- Detect presence of accreted stars
Conclusions

• What general structural and kinematical observations could support the disc-heating scenario?
  - boxiness of low surface brightness contours
  - value of \( \sigma_z / \sigma_R \) in the solar neighbourhood
  - presence of strong vertical gradient of mean rotation

• Is the pre-existing disc fully heated during the merger?
  - No. There is a cold/thin remnant with 15-25% of the total mass (old thin disc?)

• If the MW’s thick disc was formed according to this model, which orbits of the satellite are favoured?
  - this model favours a merger with low/intermediate inclination (~30°) based on value of \( \sigma_z / \sigma_R \) and the presence of strong vertical gradient of mean rotation

• Are there traces of disc-heating scenario in the phase-space structure of thick disc stars?
  - sinusoidal shape of \( V_{\text{los}} \) as a function of Galactic longitude
  - wings of \( V_{\text{los}} \) distributions are mainly populated by satellite stars