Chemodynamical Evolution of the Milky Way like Galaxies in N-body simulations

Daisuke Kawata
(Mullard Space Science Laboratory, UCL, UK)
Chris Brook (UAM, Madrid)
Brad Gibson (U. Central Lancashire, UK)
My very biased Big Questions to answer with Gaia and MOS

Main topic today!

• How Brook et al. (2004) thick disk scenario fit to the formation of the Milky Way disks?

• Spiral arms in the Milky Way are transient/co-rotating like the N-body simulated disk?

(5 series of papers of Grand, Kawata, Cropper, 2012-2015
Thick disk

Gilmore & Reid (1983)

log stellar density

2 \quad z \text{ distance} \quad 4 \text{ kpc}

2M ASS Showcase

thin disk

thick disk

bulge/bar

stellar halo
In-situ high-z thick disk formation in CDM Universe
(Brook, Kawata, Gibson, Freeman 2004)

thick disk ← kinematically hot gas disk
during multiple gas rich mergers of building blocks at $z>1$
before the formation of the thin disk.
high-z ($z>1$) disc are kinematically hot.

SINS survey with SINFONI/VLT
Genzel et al. (06), Förster-Schreiber et al. (09)

local discs $v/\sigma \sim 10-20$
(e.g. Dib et al. 06)
Brook et al. (2004, 5, 6)
Brook et al. (2013)
Smaller and thicker at high z (Brook et al. 2006)

Observations:
van Dokkum et al. (2013)
Milky Way progenitors

Not far from our sims in 10 years ago!
In-situ high-z thick disk formation
(Brook, Kawata, Gibson, Freeman 2004)
snapshot at z=0

solar annulus region
Properties of solar-neighbour stars in the Brook et al. simulations (2004-6)

Brook et al. (2004)

Thick disk

Increase in velocity dispersion for old stars = thick disk

Brook et al. (2005)

Log Age (Gyr)

\[ \sigma_U \]

\[ \sigma_V \]

\[ \sigma_W \]

[\( \alpha/\text{Fe} \)]

[\( \text{[Fe/H]} \)]

- Thick disk population
- Thin disk population

Brook et al. (2004)
Properties of solar-neighbour stars in observation (e.g. Haywood et al. 2013) consistent with Brook et al. (2004) scenario!

increase in velocity dispersion for old stars = thick disk

see also Adibekyan et al. (2012), Bensby et al. (2014), Recio-Blanco et al. (2014), Anders et al. (2014)
Brook, Stinson, Gibson, Kawata et al. (2012)
in-situ high-z thick disk + radial migration
followed by Stinson et al. (2013), Bird et al. (2013), Minchev et al. (2014)
Chemically defining thick and thin populations for solar annulus stars

[diagram showing mass vs. [Fe/H] for different populations]

thick population

thin population

small simulated galaxy [Fe/H] should scale up for the Milky Way

Brook et al. (2012)
Old thick populations

higher velocity dispersion

Brook et al. (2012)
Disk scale length of thick population was 1.7 kpc at z=1, but 2.3 kpc at z=0.

*radial migration!*

Old thick disk radially migrated from inner region. Younger stars come from a large range of radii. Stars at $R \sim R_{\text{solar}}$ at z=0.
e.g. Bovy et al. (2012): SDSS SEGUE

Smaller thick disk population than thin disk
“Geometric” thick disk bigger than thin disk?
(Juric et al. 2008, SDSS Milky Way Tomography)

Focus on geometric structure of all the population.
Not considering chemical properties.

<table>
<thead>
<tr>
<th></th>
<th>Scale Length</th>
<th>Scale Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>thick</td>
<td>3.6 kpc</td>
<td>0.9 kpc</td>
</tr>
<tr>
<td>thin</td>
<td>2.6 kpc</td>
<td>0.3 kpc</td>
</tr>
</tbody>
</table>
Flaring small thick + thin populations at the outer radius = large geometric thick disk

old thick population

young thin population

Numerical simulation in Rahimi, Carrell, Kawata (2014) explained positive $d[\text{Fe/H}]/dR$ and negative $d[\alpha/\text{Fe}]/dR$ at high $|z|$ (see also Bensby et al. 2011)
Flaring small thick + thin populations at the outer radius = large geometric thick disk

old thick population

young thin population

Numerical simulation in Rahimi, Carrell, Kawata (2014) explained positive $d[\text{Fe}/\text{H}]/dR$ and negative $d[\alpha/\text{Fe}]/dR$ at high $|z|$ (see also Bensby et al. 2011)
Flaring small thick + thin populations at the outer radius = large geometric thick disk

old thick population

young thin population

Numerical simulation in Rahimi, Carrell, Kawata (2014) explained positive $d[\text{Fe}/\text{H}]/dR$ and negative $d[\alpha/\text{Fe}]/dR$ at high $|z|$ (see also Bensby et al. 2011)
e.g. Anders et al. (2014): APOGEE

positive $d[M/H]/dR$  
$1.5 < z_{max} < 3$

negative $d[M/H]/dR$  
$0 < z_{max} < 0.4$

$0.8 < z_{max} < 1.5$

$0.4 < z_{max} < 0.8$

disk plane

high

negative $d[\alpha/M]/dR$

flat?
Nidever et al. (2014) APOGEE-RC

inner 5<R<7 kpc

outer 1<|z|<2 kpc

higher |z|

5<R<7 kpc

0<|z|<0.5 kpc

disk plane

7<R<9 kpc

0.5<|z|<1 kpc

9<R<11 kpc

1<|z|<2 kpc

less thick pop?

no thin pop?
Nidever et al. (2014) APOGEE-RC

no thin pop?

less thick pop?

1<|z|<2 kpc

0.5<|z|<1 kpc

0<|z|<0.5 kpc

inner

5<R<7 kpc

7<R<9 kpc

9<R<11 kpc

outer

higher |z|

disk plane

no thin pop?

thick pop

thin pop

thick pop

thin pop

517

1155

2857

Older, thicker, compact disk.

Younger, thinner, larger disk.

hz of geometrically thicker disk.

hz of geometrically thinner disk.
Flaring could be important?

NGC 3628
Summary

• Please remember Brook et al. (2004)!

• Inside-out thick-to-thin disk formation: smaller thicker older population

• Radial migration helps the initially compact thick population to be observed at solar neighbourhood

• Flaring thinner disk at outer radius → a large geometric thick disk and positive Z and negative [\(\alpha/Fe]\) gradient at high |z|

• geometric structures (exp law or not?) of chemically decomposed (mono-abundance) disk populations → constraints on the disk formation scenario

MOS+Gaia!
SNAPDORAGONS

(Stellar Numbers And Parameters Determined Routinely And Generated Observing N -body Systems)

Generating “stars” from star particles + 3D extinction (borrowing the data from Galaxia, Sharma et al. 2011) add Gaia post-launch errors (Romero-Gómez et al.) → mock Gaia data.

(Hunt, Kawata et al. arXiv:1501.01969)
SNAPDORAGONS
(Hunt, Kawata et al. arXiv:1501.01969)
N-body simulation $\rightarrow$ mock Gaia catalogue

No smoothing is applied: clear connection particle $\leftrightarrow$ stars.
old thin population came from inner region
inside-out thin disk formation:
thin population starts forming in the inner region
when thick population is forming in the outer region.
Positive (negative) migrators have $V_{\text{rot}} < V_{\text{circ}}$ ($V_{\text{rot}} > V_{\text{circ}}$), stay behind (on the front of) the spiral arm, and keep gaining (losing) Ang.Mom. till the arm disappears.

Non-migrators orbit the spiral arm, continuously moving from one side to the other, and no net-Ang.Mom. change.
stellar metallicity gradient evolution

Grand, Kawata, Cropper (2014)
gas metallicity gradient evolution

Ignore metal mixing enrichment

Grand, Kawata, Cropper (2014)
Gas motion

Grand, Kawata, Cropper (2014)
Grand, Kawata, Cropper (2014)
Swing Amplification
(Julian & Toomre 1966, Toomre 1981)

N-body spiral arm seems to form by similar mechanism to Swing Amplification. However, non-linear features, such as extreme migrators, are not described by linear perturbation theory.
Stellar motion
(example of different simulated galaxy)
trailing side going outward, and leading side going inward
private communication with Ivan Minchev (Beijing 2010)