Understanding the formation of the Milky Way in the era of Gaia

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Talk outline

- Effect of disk asymmetries on stellar orbits.
- Radial migration in galactic disks.
- Chemo-dynamical disk modeling.
- On the formation of galactic thick disks.
Resonances in galactic disks

Inner and outer Lindblad resonances (ILR and OLR)

Corotation resonance (CR)
Resonances in galactic disks

Inner and outer Lindblad resonances (ILR and OLR)

Corotation resonance (CR)

Both bar and spirals present in the Milky Way
Stellar orbits near resonances

Near OLR

Near Corotation (CR)

Outside OLR+CR

Inside OLR+CR

Single spiral wave

2 spiral waves

Minchev & Quillen (2007)
Stellar orbits near resonances

Near OLR

Outside OLR+CR

Near Corotation (CR)

Inside OLR+CR

Single spiral wave

2 spiral waves

Minchev & Quillen (2007)
Radial migration
N-body Tree-SPH Simulations by P. Di Matteo
Formation of a pseudobulge

N-body Tree-SPH Simulations by P. Di Matteo

Disk expands due to strong angular momentum transport outwards (Minchev et al. 2012a).

Formation of a pseudobulge
Disk expands due to strong angular momentum transport outwards (Minchev et al. 2012a).
Chemo-dynamical evolution modeling of the Milky Way
Classical chemical evolution modeling


- Stars assumed to die close to their birth places.
Stars move away from their birth places (Sellwood and Binney 2002).

Classical chemical evolution modeling hampered by radial migration.
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Classical chemical evolution modeling hampered by radial migration

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- We need to recover the migration efficiency as a function of Galactic radius and time.
Disk formation in cosmological simulations

- Traditionally a challenge (e.g., Navarro and Benz 1991; Abadi et al., 2003):
  - Extreme angular momentum loss during mergers.
  - Overly-concentrated mass distributions and massive bulges.

Abadi et al. (2003)
Recent improvements

- Increase in resolution and better modeling of star formation and feedback produce **MW-mass galaxies with reduced bulge fractions** (e.g., Agertz et al. 2011; Guedes et al. 2011; Martig et al. 2012).

- However, no chemical treatment!
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- However, no chemical treatment!

- Milky Way disk morphology not easily reproducible in fully cosmological simulations.
Recent improvements in chemical enrichment

- **Simulations including chemical treatment** – Raiteri et al. (1996), Mosconi et al. (2001), Lia et al. (2002), Kawata and Gibson (2003), Kobayashi (2004), Scannapieco et al. (2005), Martínez-Serrano et al. (2008), Oppenheimer and Davé (2008), Wiersma et al. (2009), Few et al. (2012)

- **Encouraging results recently** – global observed trends reproduced:
  - The mass-metallicity relation (e.g., Kobayashi et al. 2007)
  - Metallicity trends between different galactic components (e.g., Tissera et al. 2012)

- However, still a challenge to reproduce the properties of the Milky Way, e.g., the typical metallicities of the different components – Tissera et al. (2012).
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Seek an alternative approach to circumvent problems with fully self-consistent simulations

- Radial migration must be considered in the disk’s chemical evolution (Sellwood and Binney 2002, Schonrich and Binnery 2009a,b).

Try to use present day Milky Way disk morphology and kinematics as constraints
Model ingredients

- A high-resolution simulation of a disk assembly in the cosmological context:
  - Gas infall form filaments and gas-rich mergers
  - Merger activity decreasing toward redshift zero

- Disk properties at redshift zero consistent with the dynamics and morphology of the Milky Way:
  - The presence of a Milky Way-size bar
  - A small bulge
  - Bar’s Outer Lindblad Resonance at ~2.5 disk scale-lengths

- A detailed chemical evolution model:
  - Matching several observational constraints in the Milky Way.
Stars born hot at high redshift:
Similar to Brook et al. (2012), Stinson et al. (2013), Bird et al. (2013)
Disk evolution in the cosmological context

- t = 2.2 Gyr
- t = 4.44 Gyr
- t = 6.7 Gyr
- t = 8.94 Gyr
- t = 11.2 Gyr

Bar strength

- Mean over 0.5<r<1.5 kpc

- 0.6
- 4.1
- 7.6
- 11.2 Gyr

Velocity [km/s]

- r [kpc]

- x [kpc]
- y [kpc]
- z [kpc]

Stars

- Δt = 0.52 Gyr

- ΔL [kpc]
Chemical model

Constrained by:

- The solar and present day abundances of more than 30 elements
- The present SFR
- The current stellar, gas and total mass densities at the solar vicinity
- The present day supernovae rates of type II and Ia
- The metallicity distribution of G-dwarf stars

Similar to Chiappini (2009)
Older populations arrive from progressively smaller galactic radii due to their longer exposure to perturbation causing radial migration (e.g., satellites interactions, spirals, bar).

Minchev, Chiappini & Martig (2013)
Origin and metallicity distributions of local stars

Gyr
- 0<Age<2
- 2<Age<4
- 4<Age<6
- 6<Age<8
- 8<Age<10
- Age>10

kpc
- 1.0<r_0<3.0
- 3.0<r_0<5.0
- 5.0<r_0<7.0
- 7.0<r_0<9.0
- 9.0<r_0<11
- 11<r_0<16

[Fe/H]
The metallicity distribution

For both model and observations the MDF peak shifts to lower \([Fe/H]\) with distance from the disk plane.
The $[\text{Fe/H}]-[\text{O/Fe}]$ relation

Kinematical selection of thin- and thick-disk populations

Ramírez et al. (2013)

- Thick disk
- Thin disk
The [Fe/H]-[O/Fe] relation

Kinematical selection of thin- and thick-disk populations

Ramírez et al. (2013)

Minchev et al. 2013 Model

Thick disk
Thin disk

[Fe/H]
[O/Fe]
The vertical metallicity gradient

\begin{center}
\includegraphics[width=\textwidth]{graph.png}
\end{center}

Schlesinger et al. (2012)
Rix and Bovy (2013)
Minchev et al. (2013)

$6 < r < 10$ kpc
Scale-height distribution of mono-abundance subpopulations

Bovy et al. (2012), SEGUE data

Model data
Variation of velocity dispersion with [Mg/Fe]

Velocity dispersion drops at the high-[Mg/Fe] end for each metallicity sub-population
The age-[\(\alpha/\text{Fe}\)] and age-[\(\text{Fe/H}\)] relations

Comparison between the Adibekyan + Haywood sample and Minchev et al. (2013) model

\[\delta[\text{Fe/H}] = 0.1\] convolved in model.

\[\delta \text{ age} \sim 1 \text{ Gyr}\] according to Haywood

(need to be added to model data)
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The age-[α/Fe] and age-[Fe/H] relations

Haywood et al. (2013)

This model

Mean model

δ[Fe/H] = 0.1 convolved in model.

δ age ~ 1 Gyr according to Haywood

(need to be added to model data)

Blurring may be insufficient to explain scatter in AMR

Comparison between the Adibekyan + Haywood sample and Minchev et al. (2013) model

Migrators removed in model
On the formation of galactic thick disks
Thick disks are extended

NGC 4762 - a disk galaxy with a bright thick disk (Tsikoudi 1980)
Thick disks are extended

NGC 4762: a disk galaxy with a bright thick disk (Tsikoudi 1980)

Streich et al. (in prep)
Chemically/Age defined Milky Way thick disk centrally concentrated (e.g., not extended)

Bovy et al. (2012)
Chemically/Age defined Milky Way thick disk centrally concentrated (e.g., not extended)

Simulations with strong merger activity at high redshift

Bovy et al. (2012)

Martig et al. (2014)
Simulated disks always flare
(for a single stellar population)

Mergers flare disks

Migration flares disks

But observed edge-on disks do not flare
(de Grijs 1998; Comerón et al. 2011)!
Disk flaring in inside-out formation

Martig sims       Scannapieco sims

Age \[\text{Gyr}\]

Model1

Age = 1.6 Gyr

Model2

Disk flaring in inside-out formation
Disk flaring in inside-out formation

Martig sims       Scannapieco sims

Δ Age = 1.6 Gyr

Model1

Model2

Thick disk

Thin disk

$h_r / h_d$

$r / h_d$

Age [Gyr]
The structure of simulated thick disks

Martig sims       Scannapieco sims

Age gradient in thick disk predicted
[\alpha/\text{Fe}] gradient away from disk plane in APOGEE data

Anders + APOGEE (2014)
[\alpha/Fe] gradient away from disk plane in APOGEE data

1.5 < \mid z \mid < 3.0 \text{kpc}

0.8 < \mid z \mid < 1.5 \text{kpc}
[α/Fe] gradient in the thick disk of NGC891?

Data are currently being reduced

Calar Alto proposal led by M. Martig
Great improvements in chemo-dynamics in cosmological simulations, however, still hard to apply to Milky Way.

Our hybrid chemo-dynamical model consistent with a wide range of observational constraints.

- Great care taken in defining properly the solar radius.
- Technique can be used to probe a range of chemical evolution histories.
- More than 30 elements available for doing Galactic Archeology (e.g., GALAH, APOGEE, Gaia + 4MOST+WEAVE).

Thick disks composed of the flares of populations of different ages:
- explains extended morphologically defined thick disks in external galaxies.
- explains the centrally concentrated older populations in the MW.
- explains the inversion of metallicity and [$\alpha$/Fe] gradients away from the disk midplane.

Summary
A new chemo-kinematic relation can recover the disk merger history
Vertical velocity dispersion as a fn of $[\text{Mg/Fe}]$ in RAVE

Velocity dispersion drops at $[\text{Mg/Fe}] > 0.4$ dex

Minchev + RAVE (2014)
Vertical velocity dispersion as a fn of [Mg/Fe] in RAVE

Separate into [Fe/H] sub-populations

-1.0 [Fe/H]
-0.8 dex
-0.45
-0.3
-0.17
-0.04

Velocity dispersion drops at the high-[Mg/Fe] end for each metallicity sub-population

Minchev + RAVE (2014)
Vertical velocity dispersion as a function of [Mg/Fe] in RAVE

Minchev + RAVE (2014)
Origin of stars currently in the solar neighborhood

Model
7<r<9 kpc
0.2<|z|<0.6 kpc
Model
$7 < r < 9 \text{ kpc}$
$0.2 < |z| < 0.6 \text{ kpc}$

Origin of stars currently in the solar neighborhood

$[\text{Fe/H}]$:
-1.0
dex
-0.8
dex
-0.45
dex
-0.3
dex
-0.17
dex
-0.04
dex
Origin of stars currently in the solar neighborhood

For a given metallicity bin, stars coming from the inner disc are kinematically colder and older.
Cool old stars arrive from inner disk during mergers

Old stars coming from the inner disk are **cooler than locally born stars** by up to 30 km/s.

Slope becomes negative for the last several Gyr (no significant merger activity).

Cool old stars arrive from the inner disk during mergers.

Explains inversion of velocity dispersion - $[\text{Mg/Fe}]$ relation in RAVE and SEGUE G-dwarf data (Minchev + RAVE 2014).
Comparison between SFH in chemical model and in simulation
Recycled gas flows

- Gas migrates similar to stars.
- The effect of inward and outward flows mostly cancel out.

Minchev, Chiappini & Martig (2014)
The radial metallicity gradient

Minchev, Chiappini & Martig (2014)
The radial metallicity gradient

Interplay among different age groups is important.
Vertical disk scale-heights

- $h_1 = 0.33$ kpc
- $h_2 = 1.20$ kpc

$7 < r < 9$ kpc
The effect of migration on the chemical gradients

- Strong impact on the old stars
- In the last 2 Gyr gradients almost unaffected
- Bar corotation acts as a pivot point
Migrators’ contribution to the disk velocity dispersion in the absence of mergers

- Some increase in velocity dispersion from outward migrators.
- Some decrease in velocity dispersion resulting from inward migrators.
- Negligible overall effect to disk thickening.

Vertical disk cooling!

Minchev et al. (2012b)
Conservation of vertical action

Vertical and radial actions conserved if:

- Vertical motion decouples from the radial motion
- Stars migrate (change guiding radii) slower than vertical and epicyclic oscillations.

Then

\[ J_z = \frac{E_z}{\nu} = \text{Const.} \]

Vertical energy \quad Vertical epicyclic frequency

From Gauss’ law and Poisson’s equation

\[ \Sigma \sim \exp\left(-\frac{r}{r_d}\right) \quad \nu(r) \sim \exp\left(-\frac{r}{2r_d}\right) \]

Therefore, to preserve vertical action

\[ \langle E_z \rangle \sim \sigma_z^2 \sim \exp\left(-\frac{r}{r_d}\right) \]
Migration cools the disk during mergers

Migration works against disk flaring

No effect on the vertical velocity dispersion.

Minchev, Chiappini and Martig (2014)