Chemo-dynamical disk modeling

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Talk outline

- Effect of disk asymmetries on disk dynamics.
- Radial migration in galactic disks.
- Chemo-dynamical disk modeling.
- Chemo-kinematic observational constraints.
Resonances in galactic disks

- Inner and outer Lindblad resonances (ILR and OLR)
- Corotation resonance (CR)
Resonances in galactic disks

- For a flat rotation curve Lindblad resonances are given by

\[ \Omega_s = \Omega_0 \pm \kappa / m \]

- Corotation is at \( \Omega_s = \Omega_0 \)

- For a 2-armed spiral structure or a bar \( m=2 \).

- For a 4-armed spiral \( m=4 \).
Stellar orbits near resonances

Near OLR

Outside OLR+CR

Near Corotation (CR)

Inside OLR+CR

Single spiral wave

2 spiral waves
Radial migration
Disk expands due to strong angular momentum transport outwards (Minchev et al. 2012a).

Formation of a pseudobulge

Simulations by P. Di Matteo
Power spectrograms reveal multiple patterns

Overlap of bar and spiral creates transient stellar mass clumps!

Existence of **multiple patterns** in disks long known in simulations:
- Tagger et al. (1987)
- Signet et al. (1988)
- Quillen et al. (2011)
- Minchev et al. (2012a)

and in observations:
- Elemegreen et al. (1992)
- Rix & Rieke (1993)
- Meidt et al. (2009)

Interaction between the bar and the spiral when reconnecting
Power spectrograms reveal multiple patterns

Quasi-steady spiral patterns of multiplicity 1-4

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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- 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!

- Milky Way disk morphology not easily reproducible in fully cosmological simulations.

Guedes et al. (2011)
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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- Recent improvements in chemical enrichment:
  - Disk
  - Spheroid
  - Inner halo
  - Outer halo

- Aquarius simulations

Tissera et al. (2012)
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).

Use present day Milky Way disk morphology and kinematics as constraints
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.
Simulations by M. Martig

Galactic disk assembly in the cosmological context

Simulation in cosmological context
Martig et al. (2009, 2012)

Stars born hot at high redshift:
Similar to Brook et al. (2012), Stinson et al. (2013), Bird et al. (2013)
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
- Only thin disk chemistry used!

Similar to Chiappini (2009)
Origin and metallicity distributions of local stars

Older populations arrive from progressively smaller galactic radii due to their longer exposure to migration.

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

The diagrams show the distribution of local stars with respect to metallicity ([Fe/H]) and age, categorized by different radial distances (kpc) and age ranges (Gyr). The highlighted regions (circled) indicate significant variations in metallicity distribution with respect to age and radial distance.
Increase of disk scale-length with age:
A legacy of inside-out formation

Simulations with strong merger activity at high redshift

- Radial migration cannot compete with inside-out formation.

Bovy et al. (2012a)

Martig et al. (2014a)
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 $[\text{Fe/H}]-[\text{O/Fe}]$ relation

Kinematical selection of thin- and thick-disk populations
The age-[\(\alpha/\text{Fe}\)] relation

Haywood et al. (2013)

This model

Mean model
The Rotational velocity - Metallicity relation

Navarro et al. (2011)

Significant migration in model, yet flat relation for thin disk.
Scale-height distribution of mono-abundance subpopulations

Bovy et al. (2012), SEGUE data

Model data
A new chemo-kinematic relation can recover the disk merger history
Vertical velocity dispersion as a function of [Mg/Fe] in RAVE

Velocity dispersion drops at [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

Velocity dispersion drops at the high-[Mg/Fe] end for each metallicity sub-population
Vertical velocity dispersion as a fn of [Mg/Fe] in RAVE

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

Model
7<r<9 kpc
0.2<|z|<0.6 kpc

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

Age [Gyr]

[Fe/H]

[Mg/Fe]

r_{Birth} [kpc]
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 mergers).

Explains inversion of vel. dispersion - [Mg/Fe] relation in RAVE and SEGUE G-dwarf data.
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Summary

- Great improvements in chemo-dynamics in cosmological simulations, however, still hard to apply to Milky Way.
- Important for disk models to match the Milky Way morphology today.
- Our chemo-dynamical model explains everything.
  - Great care taken in defining properly the “solar neighborhood”.
  - More than 30 elements available for doing Galactic Archeology (e.g., GALAH, APOGEE, 4MOST, Gaia).
- Decline in velocity dispersion found in RAVE and SEGUE at $[\alpha/Fe] \approx 0.4$ dex. Can be related to perturbations from satellite-disk interactions over the Galaxy lifetime.
- Extragalactic Archaeology will be made possible with the E-ELT!
Summary

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- Important for disk models to match the Milky Way morphology today.
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