Radial migration and the evolution of the MW disk

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1D semi-analytical model with parametrized infall in a DM halo, SFR from H2, detailed chemical evolution (H to Ni) and radial motions of gas and stars
Probabilistic treatment of radial migration (Sellwood and Binney 2002)

A star born at radius \( r' \) at time \( t' \) may be found at time \( t \) (i.e. after time \( \tau = t - t' \)) in radius \( r \) with a probability \( P(r, r', \tau) \) given by:

\[
P(r, r', \tau) = \left(2\pi\sigma^2_\tau\right)^{-1/2} \exp\left[-\frac{(r - r')^2}{2\sigma^2_\tau}\right]
\]

\[
\sigma_{\tau, r} = (\sigma^2_b + \sigma^2_c)^{1/2}
\]

Blurring (epicycles)

\[
\langle \sigma^2_b \rangle = \frac{\langle \sigma_v(r)^2 \rangle}{\kappa^2_r}
\]

Epicyclic frequency

\[
\kappa_r = \sqrt{2} \frac{V_C(r)}{r}
\]

Radial velocity dispersion

\[
\sigma_v(r, T) = 40 \ e^{-(r-R_\odot)/8 \text{ kpc}} \text{ km/s}
\]

Churning (radial migration)

\[
\sigma_C = \alpha(r) \tau^N + \beta(r)
\]

Coefficients \( \alpha(r,t) \) and \( \beta(r,t) \) extracted from the numerical simulation of KPA2013 at \( t=2.5 \) Gyr (bar similar in size to the one of the Milky Way)
N-body+SPH simulations of a disk galaxy (Kubryk, NP, Athanassoula MNRAS 2013)

DM halo + baryonic disk + SFR + chemistry (1 «metal» + IRA), no infall

« Early type galaxy » with a strong bar, formed after the first 1.4 Gyr
Evolution of global quantities for Milky Way

Bulge (<2 kpc)

and

Disk (>2 kpc)
Comparison to average (« stacked ») evolution of van Dokkum et al. (2013) with 3D-HST and CANDELS data up to $z \sim 2.5$.
Radial migration affects a large fraction of the disk, up to 12 kpc.

In the solar neighborhood it brings stars mostly from inner regions, (on average, from 1.5 kpc inwards) mostly older than the locally formed ones (by 1.5 Gyr).
Solar neighborhood

1. Older stars come from inner regions

2. The local age-metallicity relation flattens; dispersion in Fe/H increases with age except for the oldest stars (thick disk)

3. Very little dispersion in O/Fe (best « chronometer » ?

Data: Bensby et al. 2014
Solar Neighborhood

Radial Migration

1. Modifies the apparent local SFR

2. Creates dispersion in the age-metallicity relation…

3. … much more than the epicyclic motion
Solar Neighborhood: stars with different ages and from different regions at all metallicities

\[
\frac{dN}{d[\text{Fe/H}]} \]

All stars
0–3 Gyr
3–6 Gyr
6–9 Gyr
>9 Gyr

All stars
<3 kpc
3–5 kpc
5–7 kpc
7–9 kpc
9–11 kpc

Obs (CGS)
Casagrande et al. 2011

Model
Minchev et al. 2013
Assuming that the thick disk is the old disk (>9 Gyr) we recover the $[\alpha/\text{Fe}]$ vs Fe/H behaviour and the metallicity distributions of both the thick and thin disks.

Data: Bensby et al. 2014

Data: Adibekyan et al. 2011

[Graphs showing metallicity distributions and alpha/Fe vs Fe/H plots for thick and thin disks.

$[\alpha/\text{Fe}]$ for thick and thin disks indicated.

$[\text{O/Fe}]$ for all stars in situ.

Models compared with observational data.
The yields of Nomoto et al. 2013 have some problems in the region P to V.
Evolution of thin (<9 Gyr) and thick (>9 Gyr) disks with yields NORMALISED to solar for AVERAGE LOCAL (8 kpc) STAR 4.5 Gyr old

Data: Adibekyan et al. 2011

Data: Bensby et al. 2014
Assuming that the thick disk is the old disk (>9 Gyr)

we recover the \([a/Fe] \text{ vs } \text{Fe/H} \) behaviour of both the thick and thin disks

and we reproduce the local surface densities of both disks

and the short scalelength of the thick disk (~2 kpc) which accounts for ~1/3 of the total disk mass
Abundance profiles

O

Fe

Cepheids

12 Gyr

4 Gyr

B-stars

HII-regions

PN

Young Open clusters

Radius (kpc)

Radius (kpc)
Abundance profiles in Cepheids
An odd-even effect on gradients? Not seen in observations…
Radial migration flattens the past stellar profiles (Roskar et al. 2008) bringing old and metal poor stars in the outer disk.
Impact of gas and star migration on chemical observables of the disk

LOCALLY:
- Increases dispersion in age-metallicity relation (observations require more than epicyclic motions)
  - Broadens metallicity distribution
- Modifies apparent SF histories (more in outer disk than in inner disk)
  - Creates a « two-branch » behaviour of O/Fe vs Fe/H

GALAXYWIDE:
- Flattens abundance profiles of X/H
- Modifies profiles of X/Y with X and Y produced by different sources: short-lived (0) vs long-lived (Fe or s-elements)
- Erases past radial abundance profiles of stars
- May produce a thick disk (Schoenrich -Binney 2009, Loebman et al. 2010, Minchev et al. 2013)

BUT these observables are ALSO affected to various extents by other factors e.g. infall \( \frac{dm}{dt}(R,t) \) and \( Z(R,t) \), galactic fountains/outflows, mergers, etc.

It will not be easy to disentangle those effects…
1. Because the SNIa/CCSN ratio increases in the inner disk, the Fe profile is steeper than the O one.

2. Because of radial migration, the past stellar Fe profile (as observed today locally) is much flatter than what we may observe in the gas of high redshift systems.

3. The evolution of the O profile in the gas of the MW corresponds to observations of high redshift lensed galaxies.

*Data: Tucker et al. 2014*
The Milky Way disk:

(2) Star and SFR profiles

Exponential stellar profile

\[ \Sigma(R) = \Sigma_0 \exp\left(-\frac{R}{S_R}\right) \]

with \( S_R \sim 2.5 \) kpc

Gas Mass \( \sim 10^{10} \) M\( \odot \)

Star Mass \( \sim 4 \times 10^{10} \) M\( \odot \)

Inner disk more “processed” than outer disk

(gas fraction profile)
Migration may alter significantly the results of chemical evolution.

Directly, moving outwards long-lived Nucleosynthesis sources, e.g. SNIIa.

Fe increases in outer disk and decreases in inner disk.

O/Fe profile steepens.

- 2 Gyr
- 4 Gyr
- 6 Gyr
- 8 Gyr
- 10 Gyr
Observations:
Redenning in disk outskirts (Bakos et al. 2008)

Models:
old (=red) stars from inner disk found in the outer disk through radial migration (Roskar et al. 2008)
Semi-analytical models, augmented with a probabilistic description of radial migration, can reproduce satisfactorily the results of N-body+SPH models.
N-body + SPH simulations of a disk galaxy (Loebman et al. 2010) formation of a thick disk

Local stars away from the plane are formed in the inner disk with large velocity dispersion; migrating outwards, they are found in smaller gravitational potential and, for the same velocity dispersion, they acquire larger scaleheight.
Impact of radial migration on local disk (Minchev et al. 2013, semi-analytical+N-body)
Radial migration flattens the abundance profile of old stars (Friedli et al. 1994)

...making it IMPOSSIBLE to derive the true evolution of radial profiles of stellar abundances as function of stellar age

Radial migration flattens the SFR history in the outer disk (Roskar et al. 2008) as it could be derived from observations of old stars

Hard to uncover the true history of the local SFR from observations
Most migrating particles start doing so when at corotation with the bar.
Most migrating particles start doing so when at corotation with the bar.

This concerns ~2/3 of the migrating particles.
Indirectly, removing from inner disk low-mass stars which dilute with their H-rich ejecta locally produced metals O and D increase in inner disk.

Directly, moving outwards long-lived Nucleosynthesis sources, e.g. SNIIa Fe increases in outer disk and decreases in inner disk.

Migration may alter significantly the results of chemical evolution.

O/Fe profile steepens LESS than with IRA.
Bars (and asymmetries in the gravitational potential in general) affect chemical evolution by:

1) Moving around a «passive agent» of chemical evolution: the gas

2) Moving around a tracer of chemical evolution:
   low-mass long lived stars (~1 M⊙ ~10 Gyr)

3) Moving around another «passive agent» of chemical evolution:
   Low mass long lived stars (several Gyr) which dilute metallicity by ejecting lately metal poor gas (impact on D)

4) Moving around some active agents of chemical evolution:
   long lived nucleosynthesis sources
   SNIa: Fe-peak elements
   2-1.3 M⊙ stars (1-3 Gyr): s-process elements
The Milky Way disk:

Gas profiles:
relatively flat, except for molecular gas in inner disk
Basic ingredient of chemical evolution in N-body models, or in semi-analytical ones with radial migration: Single Stellar Populations

Mass ejection rates (death rates $\times$ Yields) for 1 M$\odot$ of stars formed

Death rates for 1 M$\odot$ of stars formed

Data: Maoz et al. 2010, 2012

Nomoto et al. 2013

Iwamoto et al. 1999

- H ejection rate ($M_\odot$ Myr$^{-1}$)
- C ejection rate
- O ejection rate
- Fe ejection rate
Radial inflows induced by the bar flatten the abundance profiles in the 3-5 kpc region. They also fuel star formation which creates increased metallicity in the inner bulge.
A NEW MECHANISM FOR RADIAL MIGRATION IN GALACTIC DISKS: SPIRAL–BAR RESONANCE OVERLAP

I. Minchev and B. Famaey 2010

Only bar or spiral pattern

Both bar and spiral pattern
Radial migration and formation of thick disk (Schoenrich and Binney 2009, semi-analytical)
Probabilistic treatment of radial migration: transfer coefficients

Radial velocity dispersion

Blurring

Churning

Probability of a star born in $r_i=4, 8, 12$ kpc to be found in $r$ after
- 4 Gyr
- 8 Gyr
- 12 Gyr

Fraction of stars born in $r_i=4, 8, 12$ kpc and found in radius $r$ at $T=12$ Gyr

Fraction of stars found at $T=12$ Gyr in $r_i=4, 8$ and 12 kpc and born in radius $r$
Solar Neighborhood

Radial Migration

1. Increases the average stellar age by ~1 Gyr

2. ... and brings locally stars from ~1 kpc inwards (on average)

3. The most metal-rich local stars come from several kpc inwards and are ~4 Gyr old
Impact of radial migration and radial flows on the results

Possible text:

Impact of radial migration and radial flows on the results

Graphs showing the impact of radial migration and radial flows on various parameters (e.g., $V(Radial\ Inflow)$, $\dot{M}(Radial\ inflow)$, $f(Migr + RadInflow)/f(NoMigr + NoRadInflow)$) over different radial distances (kpc) and time periods (e.g., 6 Gyr, 8 Gyr, 10 Gyr, 12 Gyr). The graphs illustrate changes in parameters like stars, SFR, gas, SNla, gas fraction, Ia/CC, O/H, and Fe/H with respect to radial migration and radial flows.
Solar Neighborhood

Radial Migration

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