Flows and other unknowns in chemical evolution

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Questions

- relatively steep radial metallicity profiles
- inverse gradients
- peculiar abundances of groups of stars
Analytic Disc Model

Inflow ~ 25% of feed through disk

direct onflow ~ 75% of feed slightly pre-enriched

outflow/loss ~ 50% of processed gas

Churning
- mass exchange between neighbouring rings
- cold gas and stars
- no heating of the disc

Blurring
- implemented action conservation and improved kinematics
- use Torus machine for detailed kinematics
Chemical evolution vs. time
The genesis of abundance gradients

- non-saturation
- inside-out formation

- metallicity dependent yields
- radial flows  Lacey & Fall (1985)
  - resonances
  - stellar asymmetric drift
  - inflow/onfall

- F. Matteucci's models
  C. Chiappini et al., etc.

Flows influence the gradient

Onfall

Ang. Mom. dilution

Inflow/metal advection

Assume simple V law

\[ v_o(R) = V_c \left( b + a \frac{R}{R_{out}} \right) \]
The “average” onfall speed matters

Bilitewski & Schönrich (2012)
Impact of SFH

Bilfiewski & Schönrich (2012)
Chemical evolution

gas

condensation

warm - cool

evaporation

direct enrichment

Fe-rich

SNII+Ib,c
\( \alpha \)-rich

outflow

IGM

inflow/onflow

progenitors

stars

SNIa
Short-lived isotopes in the early solar system

Table 1: Mean life times and abundances of short-lived nuclides, uniform production (UP) and early solar system inventory

<table>
<thead>
<tr>
<th>Radioactive Isotope (R)</th>
<th>Reference Isotope (I)</th>
<th>Process</th>
<th>Mean Life $\tau_R$ (Myr)</th>
<th>$(N^R/N^I)_{ESS}$</th>
<th>$(N^R/N^I)_{UP}$</th>
<th>$\Delta_1 = 0$</th>
<th>$\Delta_1 = 5$ Myr</th>
<th>$\Delta_1 = 10$ Myr</th>
<th>$\Delta_1 = 70$ Myr</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}$U</td>
<td>$^{232}$Th</td>
<td>$r;r$</td>
<td>$6.45 \times 10^3; 2.03 \times 10^4$</td>
<td>0.438</td>
<td>0.388</td>
<td>0.388</td>
<td>0.388</td>
<td>0.388</td>
<td>0.388</td>
</tr>
<tr>
<td>$^{235}$U</td>
<td>$^{238}$U</td>
<td>$r;r$</td>
<td>$1.02 \times 10^4; 6.45 \times 10^3$</td>
<td>0.312</td>
<td>0.289</td>
<td>0.289</td>
<td>0.289</td>
<td>0.270</td>
<td></td>
</tr>
<tr>
<td>$^{242}$Pu</td>
<td>$^{232}$Th</td>
<td>$r;r$</td>
<td>$115; 2.03 \times 10^4$</td>
<td>$3 \times 10^{-3}$</td>
<td>$5.6 \times 10^{-3}$</td>
<td>$5.4 \times 10^{-3}$</td>
<td>$5.1 \times 10^{-3}$</td>
<td>$3.1 \times 10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>$r;r$</td>
<td>$115; 6.45 \times 10^3$</td>
<td>$6 \times 10^{-3}$</td>
<td>$1.4 \times 10^{-2}$</td>
<td>$1.3 \times 10^{-2}$</td>
<td>$1.3 \times 10^{-2}$</td>
<td>$7.6 \times 10^{-3}$</td>
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<td></td>
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<tr>
<td>$^{247}$Cm</td>
<td>$^{235}$U</td>
<td>$r;r$</td>
<td>$22.5; 1.02 \times 10^3$</td>
<td>$(&lt; 2 \times 10^{-3}; &lt; 10^{-4})$</td>
<td>$8.9 \times 10^{-3}$</td>
<td>$7.2 \times 10^{-3}$</td>
<td>$5.7 \times 10^{-3}$</td>
<td>$4 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>$^{182}$Hf</td>
<td>$^{180}$Hf</td>
<td>$r;r,s$</td>
<td>13; stable</td>
<td>$2.0 \times 10^{-4}$</td>
<td>$4.5 \times 10^{-4}$</td>
<td>$3.8 \times 10^{-4}$</td>
<td>$2.1 \times 10^{-4}$</td>
<td>$2 \times 10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>$^{146}$Sm</td>
<td>$^{144}$Sm</td>
<td>$p;p$</td>
<td>148; stable</td>
<td>$1.0 \times 10^{-2}$</td>
<td>$1.5 \times 10^{-2}$</td>
<td>$1.5 \times 10^{-2}$</td>
<td>$1.4 \times 10^{-2}$</td>
<td>$9.4 \times 10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>$^{92}$Nb</td>
<td>$^{93}$Nb</td>
<td>$p;s$</td>
<td>52; stable</td>
<td>?</td>
<td>$1.0 \times 10^{-4}$</td>
<td>$9.0 \times 10^{-5}$</td>
<td>$8.2 \times 10^{-5}$</td>
<td>$2.6 \times 10^{-5}$</td>
<td></td>
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<tr>
<td>$^{135}$Cs</td>
<td>$^{133}$Cs</td>
<td>$r,s;r,s$</td>
<td>2.9; stable</td>
<td>$1.6 \times 10^{-4}$</td>
<td>$2.1 \times 10^{-4}$</td>
<td>$3.7 \times 10^{-5}$</td>
<td>$7 \times 10^{-6}$</td>
<td>$0$</td>
<td></td>
</tr>
<tr>
<td>$^{205}$Pb</td>
<td>$^{204}$Pb</td>
<td>$s;s$</td>
<td>22; stable</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td></td>
</tr>
<tr>
<td>$^{129}$I</td>
<td>$^{127}$I</td>
<td>$r;r,s$</td>
<td>23; stable</td>
<td>$1.0 \times 10^{-4}$</td>
<td>$(2 - 5) \times 10^{-3}$</td>
<td>$(1.6 - 4.0) \times 10^{-3}$</td>
<td>$(1.4 - 3.5) \times 10^{-3}$</td>
<td>$(1 - 2) \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>$^{107}$Pd</td>
<td>$^{108}$Pd</td>
<td>$s,r,r,s$</td>
<td>9.4; stable</td>
<td>$2.0 \times 10^{-5}$</td>
<td>$6.2 \times 10^{-4}$</td>
<td>$3.7 \times 10^{-4}$</td>
<td>$2.2 \times 10^{-4}$</td>
<td>$4 \times 10^{-7}$</td>
<td></td>
</tr>
<tr>
<td>$^{56}$Fe</td>
<td>$^{56}$Fe</td>
<td>$e,e,exp,s$</td>
<td>2.2; stable</td>
<td>$(2 \times 10^{-7}; 2 \times 10^{-6})$</td>
<td>$5 \times 10^{-7}$</td>
<td>$5.2 \times 10^{-8}$</td>
<td>$5.3 \times 10^{-9}$</td>
<td>$0$</td>
<td></td>
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<tr>
<td>$^{55}$Mn</td>
<td>$^{55}$Mn</td>
<td>$p,exp;exp$</td>
<td>5.3; stable</td>
<td>$(\sim 6 \times 10^{-5}; 5 \times 10^{-6})$</td>
<td>$\sim 1 \times 10^{-4}$</td>
<td>$4 \times 10^{-5}$</td>
<td>$1.6 \times 10^{-5}$</td>
<td>$0$</td>
<td></td>
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<tr>
<td>$^{41}$Ca</td>
<td>$^{40}$Ca</td>
<td>$s,exp;exp$</td>
<td>0.15; stable</td>
<td>$1.5 \times 10^{-8}$</td>
<td>$2 \times 10^{-8}$</td>
<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
<td></td>
</tr>
<tr>
<td>$^{36}$Cl</td>
<td>$^{35}$Cl</td>
<td>$s;exp$</td>
<td>0.43; stable</td>
<td>$5 \times 10^{-6}$</td>
<td>$3.8 \times 10^{-7}$</td>
<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
<td></td>
</tr>
<tr>
<td>$^{26}$Al</td>
<td>$^{27}$Al</td>
<td>$p;exp$</td>
<td>1.03; stable</td>
<td>$5 \times 10^{-5}$</td>
<td>$\sim 10^{-7}$</td>
<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
<td></td>
</tr>
<tr>
<td>$^{19}$Be</td>
<td>$^{9}$Be</td>
<td>spallation</td>
<td>2.3; stable</td>
<td>$1 \times 10^{-3}$</td>
<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
</tr>
</tbody>
</table>

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Wasserburg et al. (2006)
Inverse radial gradients

Milky Way shows „flat“ gradients at high altitudes
(see e.g. Cheng et al. 2012, Schlesinger et al. 2012)
Inverse gradients?

Spagna et al. (2010)
Recent studies show an inverse relation between azimuthal velocity and metallicity for the thick disc, i.e. more metal-rich stars have faster azimuthal velocity.
Inverse gradients in radius claimed for external galaxies (Cresci et al. 2010)
What's going on?

Schoenrich & McMillan (2017)
Stellar profile

S & M 2017
Or inverse gas metallicity profile by flows

S & M 2017
Chemical evolution

gas

warm

condensation

evaporation

direct enrichment

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stars

\( \alpha \)-rich
Young alpha-enriched stars

Martig et al. (2015)
Young alpha-enriched stars

Martig et al. (2015)
Summary

- Only radial flows explain the observed metallicity gradient
- Current abundance gradients from Cepheids are consistent with coronal gas accretion
- Impact by resonances, “spiral“ inflow, viscosity? Onflow metallicity?
- The radial dependence of onflow differs from expectations
- Different gas phases can explain inverse metallicity profiles at early times
- Inside-out formation inverts stellar metallicity profiles
- Phase separation of yields will lead to abundance patterns, like relatively alpha enhanced young stars
- Almost no theoretical predictions for the re-distribution of stellar yields yet
- Affects stochastic chem. Evolution and chemical taggins
Giant Molecular Cloud impact

Snhd. Casagrande 2011

\( \sigma_z [\text{km/s}] \)

\( \rho / \rho(z=0) \)

\( \sigma_R [\text{km/s}] \)

\( \Sigma(R) [10^{10} \text{M}_{\odot}/\text{kpc}^2] \)

Aumer, Binney & S (2016)
Central/nuclear disc
Inside-out?

Bilitewski & Schönrich (2012) 0.5*a+b

Reference
Insideout1
Insideout2

slope in dex/kpc

-0.062

B / Gyr

Reference: Gas Scale length
Reference: Stellar Scale length
Insideout1: Gas scale length
Insideout1: Stellar scale length
Insideout2: Gas scale length
Insideout2: Stellar scale length

M_sun/Gyr

t/Gyr

2 2.2 2.4 2.6 2.8 3 3.2 3.4 3.6 3.8

0 2 4 6 8 10 12
Star formation efficiency?

Reference

low efficiency

high efficiency

factor $\sim 10$

slope in dex/kpc

$0.5^*a + b$
Impact of additional drag

Bilitewski & Schönrich (2012)

0.2 km/s
0.4 km/s
0.6 km/s

slope in dex/kpc

Reference
FixedFlow1
FixedFlow2
FixedFlow3

-0.062

0.5*a+b

Bilitewski & Schönrich (2012)
Asymmetric drift probably negligible?

Bilitewski & Schönrich (2012)
Asymmetric drift probably negligible

Bilitewski & Schönrich (2012)
Good news: Churning and resolution unimportant

Bilitewski & Schönrich (2012)
Where do galaxies get their gas from?

Bilitewski & Schönrich (2012)
Onfall profile of Marinacci et al. does not reproduce gradient.
Where do galaxies get their gas from?

Bilitewski & Schönrich (2012)