The chemical evolution side

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Astrophysical scales

Crazy units: The parsec (pc)
- ~ distance to the nearest star
  1 kpc = 1000 pc

Microbe:USA = USA:pc

1 km/s ~ 1 kpc/Gyr

Sun makes one Galactic orbit (~8.2 kpc from Centre) at ~250 km/s in ~0.2 Gyr

Age of the Milky Way: ~ 12 Gyrs

So the Sun is roughly your age
The era of surveys

Astrometry
Hipparcos, Gaia
~1 billion stars + parallaxes
~10s millions stars + spectroscopy
~10 kpc spatial extent
→ Stellar positions, kinematics

Photometry
2MASS, Vista, Skymapper, SDSS
PanStarrs, etc.
→ Ages, metallicity

Spectroscopy
RAVE, SEGUE, Gaia-ESO,
Hermes/Galah, Apogee, 4MOST, LAMOST
→ Metallicity, abundances, ages

Astroseismic
Kepler, Corot, Plato, etc.
→ Ages
The simple picture

Grow a disc with increasingly larger radius by inserting stars on near-circular orbits

Disc with circular orbits becomes unstable (Toomre):
Angular momentum conserved, but move stars towards centre and outskirts
Spiral patterns „heat“ populations until disc stable
...and it will create structure

As shown in John’s talk, this disc becomes unstable

- bar, spiral patterns heat the disc radially
- Giant molecular clouds heat it vertically

Fast heating after birth, $\sigma \sim t^{0.2}$
Supernova Remnant LMC N 63A
Stars are born with between ~0.1 and ~100 times the mass of the Sun

~solar mass stars:
- core hydrogen fusion for Gyrs
- → planetary nebula → white dwarf
- structure preserves initial composition

Witness chemical evolution

Above ~8.5 solar masses:
- core hydrogen exhausted in ~10 Myrs
- full fusion to Fe peak
- → core collapse → neutron star or black hole
- pollute the galaxy

Drive chemical evolution
Why not just kinematics

I) Diffusion of stellar populations
   - possible with little heating
   - nearly un-trackable by stellar kinematics
   - dominant effects on galactic structure

II) „Hidden“ physics
    some processes in galaxies are difficult to observe
    - how do they accrete?
    - how is the gas re-distributed
    - what goes into star formation?
The metallicity distribution

\[ [\text{Fe/H}] = \log_{10} \left( \frac{n_{\text{Fe}} n_{\text{H}, \odot}}{n_{\text{H}} n_{\text{H}, \odot}} \right) \]

1 order of magnitude differences
The metallicity distribution

$$[\text{Fe/H}] = \log_{10}\left( \frac{n_{\text{Fe}}n_{\text{H},\odot}}{n_{\text{H}}n_{\text{H},\odot}} \right)$$

1 order of magnitude differences

old stars: wider distribution

young stars: lower peak

and less metal-rich than Sun
The age-metallicity relation

But the age-metallicity distribution is quite flat

Casagrande et al. (2011)
Analytic Disc Model

Feed disc from IGM

outflow/loss ~ 50% of processed gas

Majority of gas locked up in low-mass stars or lost again
→ need to feed
most baryons still reside in the inter-galactic medium (IGM)
recently observed: de Graaff et al. (2017), Tanimura et al. (2017)
Gas cycle (dynamics free)

- Gas
- Cool
- Inflow/onflow
- Outflow
- IGM
- Stars
Chemical evolution

- Gas
- Condensation
- Warm
- Cool
- Metals
- Stars
- Inflow/onflow
- Outflow
- IGM
Two ways to look at this:

- Gas exhaustion time scales $\sim 1$ Gyr
- Solar neighbourhood has $M^*/M_g > 3$

$\rightarrow$ Equilibrium metallicities reached early
Analytic Disc Model

direct onflow

outflow/loss ~ 50% of processed gas
Inflow ~ 25% of feed through disk

direct onflow ~ 75% of feed slightly pre-enriched

outflow/loss ~ 50% of processed gas
Flows influence the gradient

- Onfall
- Angular Momentum dilution
- Inflow/metal advection

Value favours accretion via hot corona

Material from large radii cannot be main source

**Equations:**
- \[ a = -0.23, b = 0.86 \]
- \[ a = 0.33, b = 0.53 \] offset + 0.14 dex

**Graphs:**
- [Graph showing data and fit lines]
- [Graph showing relationship between infall and L_z]

References:
- Luck (2011)
- Bilitewski & Schönrich (2012)
Predicted abundances from full model
Provides a map of origins

The Sun must have been born ~2 kpc further in
Problem solving progress

Steep radial metallicity profile
Flat age-metallicity relation

Inflow/advection
Short enrichment timescale

Local young stars less metal-rich than Sun

Wide metallicity distribution, widening for older stars
Analytic Disc Model

Inflow ~ 25% of feed through disk

direct onflow ~ 75% of feed slightly pre-enriched

outflow/loss ~ 50% of processed gas

Time to move the 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**
- Orbital excursions of stars
- Modelled with Torus machinery (see James' talk)
The solution: Radial migration

Sellwood & Binney (2002)

Migration is a necessity
The only question is quantification

Solway, Sellwood & Schönrich (2012)
GCS data (2007)

Best model

Model without churning

Model with neither churning nor blurring
Blurring
(stars on increasingly eccentric orbits)

radial distribution of stars blurred from
5 kpc
7.5 kpc
10 kpc
age 5 Gyrs
age 10 Gyrs

S & Binney (2009a)
Churning
(angular momentum exchange)

radial distribution of stars born at
5 kpc
7.5 kpc
10 kpc
derived from metallicity distribution function
far more important than blurring!
age 10 Gyrs

S & Binney (2009a)
Churning from the new N-body models

Aumer, Binney & S (2016)
Thin and thick disc

Juric et al. (2008)

$h_{\text{thin}} = 300 \text{ pc}$  \( L_{\text{thin}} = 2.6 \text{ kpc} \)

$h_{\text{thick}} = 900 \text{ pc}$  \( L_{\text{thick}} = 3.6 \text{ kpc} \)

$c_{\text{thick}} = 0.12$

"thin" disc exponential

"thick" disc exponential

halo upturn

Juric et al. (2008)
There is more than a single dimension

Bensby & Feltzing (2014)
Chemical evolution – elemental abundances

- Gas
- Warm
- Cool
- Metals
- IGM
- Stars
- Condensation
- Inflow/onflow
- Outflow
Chemical evolution – elemental abundances

- gas
- warm
- cool
- condensation
- inflow/onflow
- Fe-rich
- SNII+Ib,c α-rich
- IGM
- outflow
- progenitors
- stars
- SNIa
- Chemical evolution – elemental abundances

- progenitors
- stars
- SNIa
- Fe-rich
- SNII+Ib,c α-rich
- IGM
- outflow
Stellar densities in the [Fe/H]-[O/Fe] plane

stellar radial migration forms naturally the two ridges
no gap in star formation or merger needed

density contours 0.5 dex

„thick disc“
„upper“ part of ISM trajectories

ISM trajectories

10
7.5
5
2.5 kpc

not the consequence of a local ISM trajectory near „endpoints“ of ISM trajectories

density contours 0.5 dex
Density profiles from fully action conserving analytical model

Schoenrich & McMillan (2017)
Migration and disc thickening

Action conservation means (approximation):

\[
\frac{h(R_g, R)}{h(R_g, R_g)} = \left( \frac{\Sigma(R)}{\Sigma(R_g)} \right)^{-1/(2+\alpha)} = \exp \left( \frac{R - R_g}{(2 + \alpha)R_d} \right)
\]

ratio of scale heights  
adiabatic index  
disc scale length  
surface density

At constant initial scale height → thickening by a factor of 2-3 for 7 kpc

Open questions: Can secular heating provide a sufficiently hot inner disc? (Aumer et al. 2016)

Preferential migration? (Solway et al. 2012, Vera-Ciro et al.)

If a disc flares more than this → outwards migration can even cool the disc
Controlled simulations either produce no significant thick component … or too strong bars

Radial dependence of secular heating?
Can the inner disc heat up sufficiently before migrating?
Summary

- As detailed in previous talks, dynamics mix the stellar populations, i.e. information for the origin of each star is lost
- however, abundances and age give a unique origin of the star
→ Chemical evolution models decipher this information
  ... and thus measure the dynamics/re-distribution
- chemical evolution depends on Galactic structure/physics
→ data can only be fully understood with combined models
→ can shed light on previously unconstrained processes, e.g. accretion
- Chemical evolution directly encodes the history of a system
- Sun has migrated \( \sim 2 \text{ kpc} \)
- migration, mergers, early disc evolution contribute to thick disc
- Gaia data to disentangle these and unveil Galactic history
Kinematic detection

Dehnen (1998)
Dissecting Gaia DR1 in azimuthal velocity

See https://arxiv.org/abs/1712.06616
Dissecting Gaia DR1 in angular momentum

Trend → warp
But also a highly significant wave-pattern
→ disc mid-plane is swinging up and down

See https://arxiv.org/abs/1712.06616
...and this wave pattern
Likely explanation: Waves created by an infalling dwarf galaxy (Sagittarius dwarf is a likely candidate) will offer a way to get mass, trajectory of the impacting dwarf, and mass/structure of disc and halo.