Gas accretion and radial flows onto Milky Way-type galaxies: Chemical Evolution Models in the light of cosmological simulations

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Motivation: Chemical Evolution Models (CEMs)

- Compute chemical abundances of stars in galaxies; specially the **Milky Way**
- Simplifying assumptions (gas flows, SFR, stellar nucleosynthesis,...)
- Model each galaxy component separately
- Solve a set of integer-differential equations
- No dynamics involved in classical CEMs
- Highly idealized

**Evolution of gas enrichment:**

\[
\dot{G}_i(r, t) = -\psi(r, t)X_i(r, t) \\
+ \int_{M_U}^{M_{B_m}} \psi(r, t - \tau_m)Q_{mi}(t - \tau_m)\phi(m)\,dm + A_{1a} \int_{M_{B_m}}^{M_{B_M}} \phi(M_B) \\
\times \left[ \int_{0.5}^{\mu_m} f(\mu)\psi(r, t - \tau_{m2})Q_{mi}^{SN1a}(t - \tau_{m2})\,d\mu \right] dM_B \\
+(1 - A_{1a}) \int_{M_{B_m}}^{M_{B_M}} \psi(r, t - \tau_m)Q_{mi}(t - \tau_m)\phi(m)\,dm \\
+ \int_{M_{B_M}}^{M_U} \psi(r, t - \tau_m)Q_{mi}(t - \tau_m)\phi(m)\,dm \\
+ X_{A_i}A(r, t),
\]
Cosmological evolution

➢ Gas accretion is a key process in ΛCDM
  ➢ Brings fresh, uncontaminated gas
  ➢ Affects metallicity patterns
  ➢ It impacts star formation

➢ The gas accretion process is very complex
  ➢ Depends on time, not isotropic
  ➢ Different accretion channels: mergers, filamentary, smooth
  ➢ Significant variations among different galaxies

➢ Outflows can also be important

Blue: cold gas
Yellow/Red: hot gas

MW-type halo
Outline

➢ Introduction
  ➢ Main assumptions in CEMs

➢ Simulations & analysis
  ➢ The need for a MW analogue
  ➢ Simulated MW-like galaxies
  ➢ Calculation of gas fluxes onto the disc

➢ Results (Nuza+19)
  ➢ Gas accretion rate vs. time
  ➢ Accretion timescale vs. galactic radius
  ➢ Radial flows in MW analogues (preliminary...)
  ➢ Impact on CEM predictions (preliminary...)

➢ Summary
Motivation: CEM assumptions

➢ Gas accretion is a key ingredient in chemodynamical models (CEMs), as it sets the efficiency of star formation as a function of time and radius

➢ Usual assumptions for the gas accretion law for different galaxy components:
  - Decreasing function of time (exponential, gaussian, …)

\[
A(r, t) = a(r)e^{-t/\tau_H(r)} + b(r)e^{-(t-t_{\text{max}})/\tau_D(r)}
\]

\(\propto\) gas accretion rate

(e.g. Chiappini+01)
Motivation: CEM assumptions

➢ **Gas accretion** is a key ingredient in **chemodynamical models (CEMs)**, as it sets the efficiency of star formation as a function of time and radius.

➢ Usual assumptions for the **gas accretion law** for different **galaxy components**:
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\[
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\]

\[\alpha \text{ gas accretion rate}\]

1st infall

2nd infall

- **Stellar halo/Thick disk**
  - **Rapid/Violent**
    - (older stellar populations)

- **Thin disk**
  - **Long duration/Smooth**
    - (younger stellar populations)

(e.g. Chiappini+01)
Motivation: CEM assumptions

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➢ Usual assumptions for the gas accretion law for different galaxy components:
  - Decreasing function of time (exponential, gaussian, …)
  - The disc forms from the inside-out: radially-growing disks

\[ A(r, t) = a(r)e^{-t/\tau_H(r)} + b(r)e^{-(t-t_{\text{max}})/\tau_D(r)} \]

 separates the first and second infall.
Motivation: CEM assumptions

- **Gas accretion** is a key ingredient in chemodynamical models (CEMs), as it sets the efficiency of star formation as a function of time and radius.

- Usual assumptions for the **gas accretion law** for different galaxy components:
  - Decreasing function of time (exponential, gaussian, …)
  - The disc forms from the **inside-out**: radially-growing disks

\[ A(r, t) = \underbrace{a(r)e^{-t/\tau_H(r)}}_{1^{st} \text{ infall}} + \underbrace{b(r)e^{-(t-t_{max})/\tau_D(r)}}_{2^{nd} \text{ infall}} \]

(e.g. Chiappini+01)
Motivation: CEM assumptions

- **Gas accretion** is a key ingredient in **chemodynamical models (CEMs)**, as it sets the efficiency of star formation as a function of time and radius.

- Usual assumptions for the **gas accretion law** for different **galaxy components**:
  - *Decreasing function of time (exponential, gaussian, …)*

\[
A(r, t) = a(r)e^{-t/\tau_H(r)} + b(r)e^{-(t-t_{\text{max}})/\tau_D(r)}
\]

- *The disc forms from the inside-out: radially-growing disks*

\[
\tau_D = 1.033r \text{ (kpc)} - 1.267 \text{ Gyr}
\]

(e.g. Chiappini+01)
Motivation: CEM assumptions

➢ **Gas accretion** is a key ingredient in **chemodynamical models (CEMs)**, as it sets the efficiency of star formation as a function of time and radius.

➢ Usual assumptions for the **gas accretion law** for different **galaxy components**:  
  ♦ **CEMs including radial flows use ad-hoc velocity profiles**

![Graph showing velocity profiles](image)

Radial gas flows across the disk are expected from **physical considerations**.

If the infalling material has lower specific angular momentum than circular motions in the disk, mixing with disk gas induces a net radial inflow (e.g., Biliwetski & Schönrich 2012).

(e.g., Spitoni & Matteucci+11; Mott+13,...)
Motivation: CEM assumptions

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➢ Usual assumptions for the **gas accretion law** for different **galaxy components**:

   - CEMs including **radial flows** use **ad-hoc velocity profiles**

(e.g., Spitoni & Matteucci+11; Mott+13,...)
The simulated Milky Way-type galaxies

**Martig**

\[ m_{\text{gas}} = 1.5 \times 10^4 \, h^{-1} M_\odot \]
\[ m_{\text{DM}} = 3.5 \times 10^4 \, h^{-1} M_\odot \]
\[ \epsilon_g \sim 150 \, \text{pc} \]

Martig+12
Minchev+13,14

**CLUES**

\[ m_{\text{gas}} = 3.9 \times 10^5 \, h^{-1} M_\odot \]
\[ m_{\text{DM}} = 2.0 \times 10^5 \, h^{-1} M_\odot \]
\[ \epsilon_g \sim 500 \, \text{pc} \]

Nuza+14
Scannapieco+15

**Auriga**

\[ m_{\text{gas}} = 5.0 \times 10^4 \, h^{-1} M_\odot \]
\[ m_{\text{DM}} = 3.0 \times 10^5 \, h^{-1} M_\odot \]
\[ \epsilon_g \sim 369 \, \text{pc} \]

Grand+17
The simulated Milky Way-type galaxies

Martig
- *Semi* cosmological
- *High resolution*

Sticky particle model
(Bornaud & Combes 02, 03)

Martig+12, Minchev+13,14

CLUES
- *Fully* cosmological
- *Medium resolution*

GADGET-3 code
(Springel+08)

Nuza+14, Scannapieco+15

Auriga
- *Fully* cosmological
- *High resolution*

AREPO code
(Springel 10)

Grand+17
The simulated Milky Way-type galaxies

Martig

CLUES

Auriga

Gas distribution

10 kpc

10 kpc

10 kpc

g106

Martig+12

Minchev+13,14
Results: 1) Gas accretion rate vs. cosmic time

**Martig**

- **Total infall**
  - DISK ASSEMBLY
  - $\tau = (5.36 \pm 0.10) \text{ Gyr}$

- **NET**
  - $\tau = (7.37 \pm 0.50) \text{ Gyr}$

**CLUES**

- **Total infall**
  - $\tau = (6.31 \pm 0.31) \text{ Gyr}$

- **NET**
  - $\tau = (5.03 \pm 0.44) \text{ Gyr}$

Integrated over galaxy radius

Nuza+19
Results: 1) Gas accretion rate vs. cosmic time

Martig

Total infall

DISK ASSEMBLY

\[ \frac{dM(t)}{dt} \propto e^{-\frac{(t-t_{\text{max}})}{\tau_D}} \]

CLUES

Total infall

\[ \tau = (5.36 \pm 0.10) \text{ Gyr} \]

\[ \tau = (6.31 \pm 0.31) \text{ Gyr} \]

\[ \tau = (7.37 \pm 0.50) \text{ Gyr} \]

\[ \tau = (5.03 \pm 0.44) \text{ Gyr} \]
Results: 1) Gas accretion rate vs. cosmic time

- **Martig**
  - g106
  - $\tau=(7.37\pm0.50)$ Gyr

- **CLUES**
  - MW$^c$
  - $\tau=(5.03\pm0.44)$ Gyr

- **Auriga**
  - Au 6
  - $\tau=(4.89\pm0.66)$ Gyr

(PRELIMINARY!)
Results: 2) Accretion timescales onto the disk

- Accretion timescales onto the disk increase towards larger radii.
- Similar trend (but no detailed agreement) to the prescription of Chiappini+01 for $R > 4$ kpc.
- Consistent with an inside-out scenario of disk formation.

Nuza+19
Results: 2) Accretion timescales onto the disk

\[
\tau_D = 1.033r \text{ (kpc)} - 1.267 \text{ Gyr}
\]

Preliminary!
Results: 3) Radial flow velocities

- Test how this physically-motivated radial velocity profiles affect CEM predictions
Results: 3) Radial flow velocities

Radial gas flows in the disk plane

\[ \langle V_r \rangle \text{ [km s}^{-1}\text{]} \]

- Test how this physically-motivated radial velocity profiles affect CEM predictions
CEMs with time-dependent radial flows

**Metallicity gradient of the Milky Way**

- **Two-infall** gas accretion law + inside-out formation
- **Two-infall** gas accretion law + inside-out formation + time-dependent radial flows from MW-like simulations

- Significant change in the profile
- Must be always included in CEMs

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**Spitoni, Nuza+in prep.**
Summary

➢ We tested **three sensible assumptions** of CEMs for the formation of the MW disc using simulations in a cosmological context:

➢ *Exponential accretion of gas during disk assembly*
  ➢ *On average*, gas fluxes exhibit a **smooth decline** in time
  ➢ Typical disk assembly times in agreement with CEM assumptions

➢ *Inside-out formation scenario*
  ➢ Accretion timescales onto the disk increase towards larger radii
  ➢ Similar trend as postulated in CEMs
  ➢ The disk forms from the **inside-out**

➢ *Radial gas flows*
  ➢ Natural outcome of cosmological evolution of the Galaxy
  ➢ Significant impact in CEM-derived chemical gradients
  ➢ **Must be always** included in CEMs
Thanks!