GALAXY FORMATION

Patricia B. Tissera
Universidad Andrés Bello
Chile
Lecture I
Galaxy formation: From the high-z to the Local Universe

Lecture II
Galaxy formation: models and simulations
- Basic concepts
- Main ingredients
- Disc-dominated and Bulge-dominated galaxies

Lecture III
Galaxy formation: chemical evolution
- The simple model
- Ingredients of Chemodynamical Models
- Sophisticated Chemo-dynamics Models
Growth of the structure: collapse, infall, mergers

Gas cooling and condensation

Star formation and stellar evolution

IMF

Stellar winds

Supernova feedback

AGN feedback

Galactic winds

enriched material into the ISM

Dust

enriched material into the CGM/IGM
CHEMODYNAMICAL MODEL FOR GALAXY FORMATION

KEY INGREDIENTS

- Initial conditions: how galaxies are assembled
- Star formation model: how the gas is transformed into stars
- The initial mass function
- The stellar yields: AGB, Type II and Ia Supernova-different progenitors – different life-times
- Pristine or enriched gas accretion (Infall)
- Outflows (Supernovas and AGN feedbacks)
EXPRESSING METALLICITY AND ABUNDANCES

\[ Z \equiv \frac{M_{\text{metals}}}{M_{\text{baryons}}} \]

\[ [X/Y] \equiv \log \left( \frac{N_X}{N_Y} \right) - \log \left( \frac{N_X}{N_Y} \right)_{\odot} \]

\[ 12 + \log (X/H) \equiv 12 + \log \left( \frac{N_X}{N_H} \right) \]

\[ 12 + \log (O/H) \equiv 12 + \log \left( \frac{N_O}{N_H} \right) \]

12 + \log (O/H)_{\odot} = 8.69 \quad \text{Asplund+2009}
Maniolino & Mannucci 2019

SNIa:
after 40 Myr,
Power law $t^{-1}$
Relative abundances of $[\alpha/\text{Fe}]$:

Relative abundances of SNII with respect to SNIa: formation timescale of the systems
Fig. 5.7 Predicted and observed [O/Fe] vs. [Fe/H] in the solar neighborhood for different assumptions on the DTD of the explosion times of SNe Ia. The short dashed curve refers to the DTD of the SD scenario; the continuous curve refers to the bimodal DTD of Mannucci et al. (2006); the dotted line represents the Strolger et al. (2004) DTD; the long dashed curve refers to the DTD of Pritchett et al. (2008); the dashed-dotted curve refers to the DTD of the DD scenario (wide channel) of Greggio (2005). The model results are normalized to their own predicted solar abundances. See also Fig. 4.5. Models and figure from Matteucci et al. (2009) where the references to the data can be found.
Simple one-zone model as given by Tinsely (1980)

Four Main hypothesis:

- The system is isolated: no inflows or outflows.
- The system is well mixed at all times.
- The system starts from primordial abundances: $Z(0) = 0$.
- IMF and nucleosynthesis yields are unchanged.

- Instantaneous recycling (all stars with $m < 1 M_\odot$ live forever; all stars with $m > 1 M_\odot$ die instantaneously.
\[ \mu = \frac{M_{\text{gas}}}{M_{\text{tot}}} \]

\[ M_{\text{tot}} = M_* + M_{\text{gas}}, \]

\[ Z = \frac{M_Z}{M_{\text{gas}}}, \]

**Initial conditions**

\[ M_{\text{gas}}(0) = M_{\text{tot}} \]

\[ Z(0) = 0. \]

**Equation of evolution of the gas in the system**

\[ \frac{dM_{\text{gas}}}{dt} = -\psi(t) + E(t), \]

**Rate of returning material**

\[ E(t) = \int_{m(t)}^{\infty} (m - M_R)\psi(t - \tau_m)\varphi(m)dm, \]
Assuming instantaneous recycling condition:

Return fraction
R ~ 0.20-0.50

\[ R = \int_{1}^{\infty} (m - M_{R}) \varphi(m) \, dm, \]

\[ y_{zm} \text{: yield for stellar generation} \]

\[ p_{zm} \text{ is the newly produced and ejected elements by a given stars } m \]

\[ y_{Z} = \frac{1}{1 - R} \int_{1}^{\infty} m p_{zm} \varphi(m) \, dm, \]

\[ \frac{dZ}{dM_{\text{gas}}} M_{\text{gas}} = -y_{Z}, \quad Z = y_{Z} \ln \left( \frac{1}{\mu} \right). \]
**Effective Yield vs Galaxy Mass**

Tully-Fisher: \( (M / 10^{11} M_\odot) \sim (V_{\text{rot}} / 200 \text{ km/s})^4 \)

Lower yield in small galaxies because SN ejecta escape.

\[
y_{\text{eff}} \equiv \frac{Z_{\text{obs}}}{\ln(1/\mu)} \\
\mu \approx \frac{M_G}{M_* + M_G}
\]

Garnett 2002
Tremonti+2014

- 90% lost of metals
- 50% lost of metals
**ISM Recycling Model**

\[ X = 0.75, \; Y = 0.25, \; Z = 0 \]

\[ dM_G = dM_{IN} - dM_{OUT} \]

\[ dM_G = -dM_s \]
\[ dM_Z = -Z \; dM_s \]

\[ dM_* = \alpha \; dM_s \]

\[ M_*(t) \]
lo-mass stars
+ NS, BH

From Salpeter IMF and SN1987A:
\[ Z_{SN} \approx 0.13 \]
\[ \alpha \approx 0.93 \]
Chemical evolution models

- One-zone models: perfect mixing in the homogeneous physical domain
  - Closed-box models
  - Open box models: some prescription of infall and outflows
- Multi-zone models: coupled open-box models with inter-zone mass transfer
- Chemo-dynamical models: (multi-dimensional) self-consistent treatment of the entire galaxy with all/some of the components and interactions described above.

see Molla et al. 2018 for review on analytical chemical models
There are numerous chemodynamical models for galaxy formation which have sophisticated the Simple Model (e.g. Larson 1976; Tinsley & Laron 1979; Burkert & Hensler 1988; Ferrini et al. 1992; Chiappini, Matteucci & Gratton 1997; Molla et al. 2019):

- sophisticated stellar evolution
- simple initial conditions for galaxy formation
First attempts to introduce chemical feedback in SPH simulations of MilkyWay type galaxies:

- Steinmetz & Muller (1994) → SNII; global metallicity Z
- Raiteri et al. (1996; also Berczik 1999) → SNII & SNIa; Fe & H

There are implementations that followed the metallicity Z (Springel & Hernquist 2003 and references therein)

Including chemical enrichment by **individual elements** provides a powerful tool to study galaxy formation in cosmological scenarios.

First implementations in a cosmological context:
- Kawata & Gibson (2003): SNII, SNIa, IS; Eth + Ekin
- Kobashashi (2004): detailed SE; Eth + Ekin

**Current cosmological models include a version of chemical evolution**
**STAR FORMATION SCHEME**

**Numerical space**

- **Type II SNe**
- **Type Ia SNe**
- **AGBs**

**Physical space**

- **Mstar > 8 Msun, typical life-times ~10^6 yr**
  - Produce most O, Si, Ca, etc
- **Intermediate stars/binary systems**
  - typical life-times ~1 Gyr
  - Produce most Fe
- **Intermediate stars**
  - life-times ~1-2 Gyr
  - C, N

**Need**

- IMF: SNe / long-lived stars

**Nucleosynthesis yields**
When SN explosions take place, metals are distributed according to the SPH technique (Mosconi+2001). For a given chemical element $x$ at a particle $i$,

$$M_{x,i} = \sum_j \frac{m_j}{\rho_j} M_{x,i} \ W(r_{ij}, h_{ij})$$

Neighbours will receive

$$M_{x,j} = \frac{m_j}{\rho_j} M_{x,i} \ W(r_{ij}, h_{ij})$$

Exploding star particle

Gaseous neighbours
Variation of the level of chemical enrichment with the adopted calibration.

Variation in the shape: relative level of enrichment between massive and small galaxies.

Ellison & Kewley (2008)
There are well-known LMR and MMR in the local Universe. Observations suggest evolution in the zero point and slope of both relations.

SDSS: Tremonti et al. 2004

Erb et al. 2006: $z \sim 2.5$
**Fig. 21** The fundamental metallicity relation from Mannucci et al. (2010). Left: dependence of the gas metallicity on mass, in bins of SFR. The gray shaded areas contains 68% and 95% of the full, unbinned galaxy sample. Right: dependence of metallicity on SFR in bins of stellar mass.
RESULTS FROM EAGLE PROJECT

De Rossi+2018

De Rossi et al.

Recal-L025N0752

De los Reyes+2015 (z=0.8)

Hunt+2016 (z=0.4–0.7)

Ly+2016 (z=0.5–1)

EAGLE, z=2

Maiolino+2008

Hunt+2016 (z=0.9–1.8)

Wuyts+2016 (z=0.9)

Troncoso+2014 (z=3.4)

Onodera+2016 (z=3.3)

Hunt+2016

Somers+2015 (0.5, z=2.3)

Zahid+2014b (z=1.6)

Cullen+2013 (z=2)

Wuyts+2016 (z=2.3)

Hunt+2016 (z=1.8–2.8)
MILKY WAY: STELLAR HALO

MW, Belokurov et al. 2006

Andromeda, Ibata et al. 2015

Malhan+ 2018
THE MILKY WAY STELLAR HALO

Helmi+2018
THE MILKY WAY STELLAR HALO

A Milky-Way analogue in EAGLE: the co-evolution of dynamical components
The MW stellar halo has an age of -25 Myr/kpc, with the oldest stars concentrated in the inner region.
MILKY WAY STELLAR HALO

Tissera+2014

Carollo+2018

All stars (h>5 kpc)

Accreted (h>5 kpc)
The MW halo is better reproduced if only accreted stars are considered. In situ stars contribute with slightly younger SPs which seems not to be present in the central region of the MW in large amount.
To compare models with observations:

The metallicity gradients in disc galaxies

The standard model for disc formation based on angular momentum conservation

Negative metallicity gradients

Mergers
Interactions
Migration
Secular evolution
Metallicity gradients in star-forming galaxies
Metallicity gradients in star-forming galaxies

Ho+2015

Poetrodjojo et al. 2018 (SAMI)

Belfiore et al. 2017 (MaNGA)
Star formation across the disc

- Inside-out formation scenario gas discs have negative metallicity profiles: the slope is regulated by the star formation efficiency (e.g. Mollá+2017).

- Higher SFE → weaker metallicity gradients.
Interactions and mergers

- Formation process: inside out.
- Feedback
- The assembly history: Interaction/mergers.
- Galactic fountain/material captured from the companion.

(e.g. Ruipke2010, Ho+2015, Tissera+2016:Ma+2017; Molla+2018)
We analysed the metallicity gradients in the \((100 \text{ Mpc})^3\) and \((25 \text{ Mpc})^3\) higher resolution simulations.
Disc metallicity gradients show a large variety.

Galaxies that had no merger since $z \sim 2$ show a weak trend with stellar mass.

Discs with negative gradients have slightly more recycled material.
Evolution of the oxygen abundance gradients
EAGLE galaxies: No evolution with redshift is found for $z < 2.5$. Observations show a larger variety of metallicity gradients.
Azimuthal variation of the metallicity distributions
Azimuthal variations in metallicity detected are about ~0.05-0.1 dex.

Metallicity gradients of SF regions in the arms tend to be slightly shallower.

CALIFA and MUSE observations
Azimuthal variations in the EAGLE discs

- **age < 0.5 Gyr**

- **0.5 Gyr < age < 2 Gyr**

- **age > 2 Gyr**

EAGLE galaxies