Introduction

Once gas and dust coalesce: formation of stars

Stars synthese higher elements out of H, He, and whatever metals they were formed from, and partly eject them back into ISM

$\Longrightarrow$ Elemental abundances change

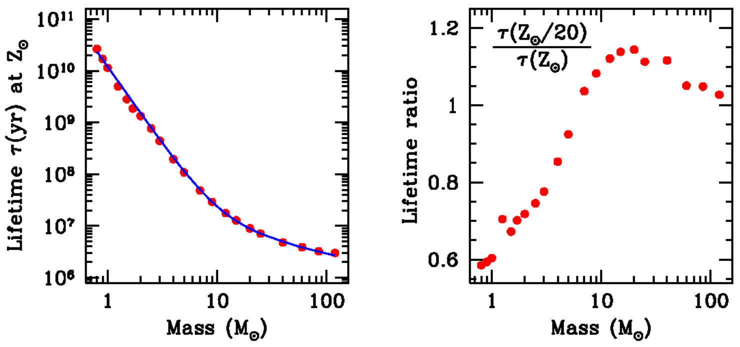
$\Longrightarrow$ Galactic chemical evolution

In contrast to previous section, now “chemistry” really means “elemental abundances”.

We will use Galaxy as example, since it is the best studied object, and then come back to what different spirals do later.

Background information: Prantzos (2008) and Pagel (2009)

Closed Box Model

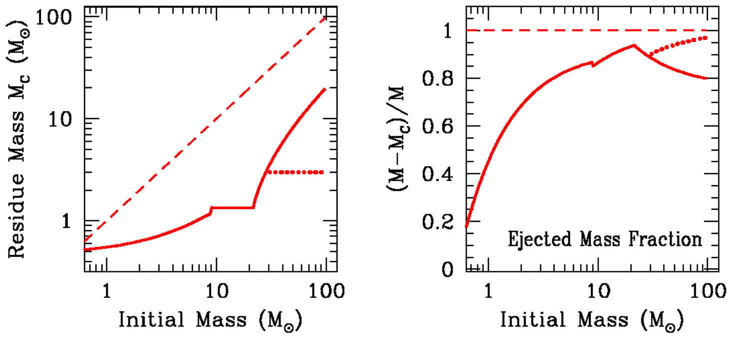


(Prantzos, 2008, Fig. 1)

Galactic metallicity evolution is influenced by:

- stellar formation rates
- stellar evolution and stellar death rates (which depend on metallicity!)

Closed Box Model



(Prantzos, 2008, Fig. 2)

Galactic metallicity evolution is influenced by:

- stellar mass ejection rates

Closed Box Model

Galactic metallicity evolution is influenced by:

- stellar evolution (see previous slides)
- inflow from outside galaxy
- ejection from galaxy
- mixing of elements within galaxy (influences populations).

Will look here at a simple model: one-zone, instantaneous recycling:

- gas well mixed
- stars return fusion products immediately
- no gas escapes/added (closed-box model)

Closed Box Model

Let

- $M_\mathrm{g}(t)$: Mass of gas in galaxy at time t
- $M_\mathrm{s}(t)$: Mass in low-mass stars and compact objects (i.e., mass locked in stellar objects throughout lifetime of Galaxy)
- $M_\mathrm{h}(t)$: Mass of metals ($Z > 2$) in galactic gas.

Then the Metal abundance is

$$Z(t) = \frac{M_\mathrm{h}(t)}{M_\mathrm{g}(t)} \tag{3.46}$$

Stellar lifetimes:

- $Z = Z_\odot$, $M = M_\odot \Longrightarrow \tau \sim$ 11.4 Gyr,
- $Z = Z_\odot$, $M =$ 0.8 M_odot: $\Longrightarrow \tau \sim$ 23 Gyr,
- $Z =$ 0.05$Z_\odot$, $M =$ 0.8 M_odot: $\Longrightarrow \tau \sim$ 13.8 Gyr

Stars with $M =$ 0.8 $M_\odot$: lowest mass stars that have ever died (=heaviest stars surviving in oldest globular clusters).

Closed Box Model

Assume formation of massive stars which produce metals. Let

- ΔM_s: mass in remnants
- $p \cdot \Delta M_\mathrm{s}$: mass returned to ISM ($p$: yield, depends on initial mass function and evolution)
- $Z \cdot \Delta M_\mathrm{s}$: metals locked in remnants

$\Longrightarrow$ change in mass of metals due to formation of stars given by

$$\Delta M_\mathrm{h} = p \cdot \Delta M_\mathrm{s} - Z \cdot \Delta M_\mathrm{s} = (p - Z)\Delta M_\mathrm{s} \tag{3.47}$$

(assuming instantaneous recycling)

$\Longrightarrow$ metallicity increases by

$$\Delta Z = \Delta\left(\frac{M_\mathrm{h}}{M_\mathrm{s}}\right) = \frac{p \cdot \Delta M_\mathrm{s} - Z\,(\Delta M_\mathrm{s} + \Delta M_\mathrm{g})}{M_\mathrm{g}} \tag{3.48}$$

where $-Z \cdot \Delta M_\mathrm{g}$ term due to exchange of mass with other regions.

Note that in the closed box case (no gas enters/leaves the system):

$$\Delta M_\mathrm{s} = -\Delta M_\mathrm{g} \tag{3.49}$$

Closed Box Model

Define as primary elements those elements for which the formation is independent of Z (i.e., p independent of Z).

For these elements and a closed box ($\Delta M_\mathrm{s} = -\Delta M_\mathrm{g}$):

$$\Delta Z = \frac{p \cdot \Delta M_\mathrm{s} - Z\,(\Delta M_\mathrm{s} + \Delta M_\mathrm{g})}{M_\mathrm{g}} = -p\frac{\Delta M_\mathrm{g}}{M_\mathrm{g}} \Longrightarrow \frac{dZ}{dt} = -\frac{p}{M_\mathrm{g}}\frac{dM_\mathrm{g}}{dt} \tag{3.50}$$

such that

$$\int_0^t \frac{dZ}{dt}\,dt = -p\int_{M(t=0)}^{M(t)} \frac{dM_\mathrm{g}}{M_\mathrm{g}} = -p\ln\frac{M_\mathrm{g}(t)}{M_\mathrm{g}(t=0)} \tag{3.51}$$

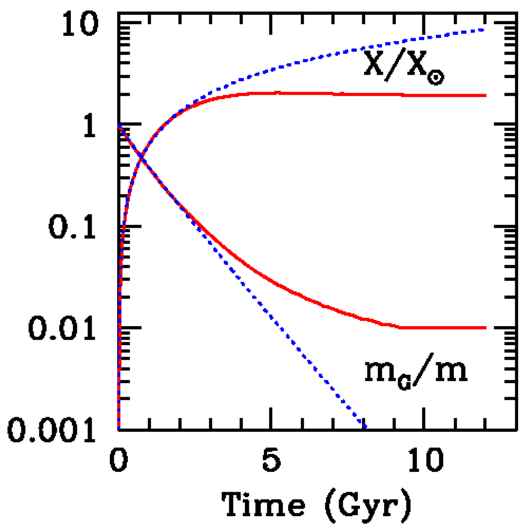
and finally

$$Z(t) = Z(t=0) + \ln\frac{M_\mathrm{g}(t=0)}{M_\mathrm{g}(t)} \tag{3.52}$$

Note that $M_\mathrm{g}(t) < M_\mathrm{g}(t=0)$, and therefore $\ln M_\mathrm{g}(0)/M_\mathrm{g}(t) > 0$, such that

- $Z(t)$ increases with time, and
- $Z(t)$ is higher in regions with less gas.

Closed Box Model

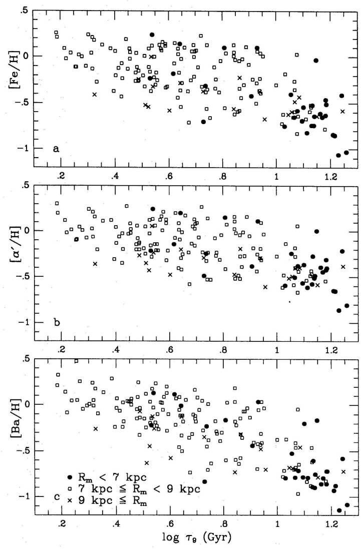


Evolution of abundance, X, and gas fraction, m_G, with time.

Calculations for closed box model in Instantaneous Recycling Approximation (IRA) and Non-IRA (stellar evolution)

(Prantzos, 2008, Fig. 12)

Closed Box Model



Younger stars in solar vicinity tend to be richer in metals.

Notation used:

$$[\mathrm{Fe/H}] = \log_{10} \frac{A_{\mathrm{Fe}}/A_{\mathrm{H}}}{A_{\mathrm{Fe},\odot}/A_{\mathrm{H},\odot}} \tag{3.53}$$

where

- A_i: abundance by number of element i, and
- $A_{i,\odot}$: solar abundance by number of element i.

α: α-process elements (esp. Mg, Si, Ca, Ti)

Edvardsson et al. (1993, Fig. 14)

Closed Box Model

We had

$$Z(t) = Z(t=0) + \ln \frac{M_{\mathrm{g}}(t=0)}{M_{\mathrm{g}}(t)} \tag{3.52}$$

But the mass in low-mass stars formed before time t is

$$M_{\mathrm{s}}(t) = M_{\mathrm{g}}(t=0) - M_{\mathrm{g}}(t) \tag{3.54}$$

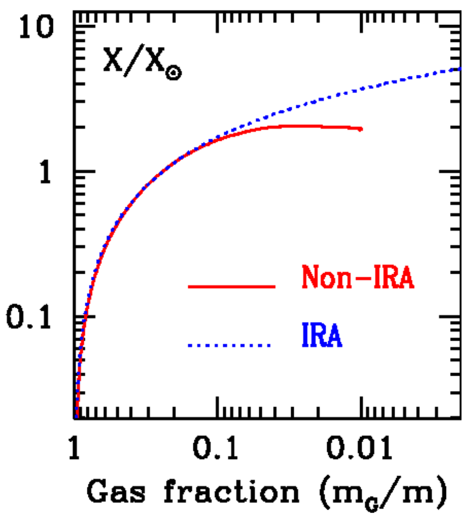
But these stars have lower metallicity. Therefore the mass in low metallicity stars is

$$M_{\mathrm{s}}(Z < Z(t)) = M_{\mathrm{g}}(t=0) \left(1 - \exp\left\{-\frac{Z(t) - Z(t=0)}{p}\right\}\right) \tag{3.55}$$

Where the gas density is high vs. number of stars, the average metallicity must be low.

This effect is seen, e.g., in Large Magellanic Cloud or as metal abundance gradient in spirals.

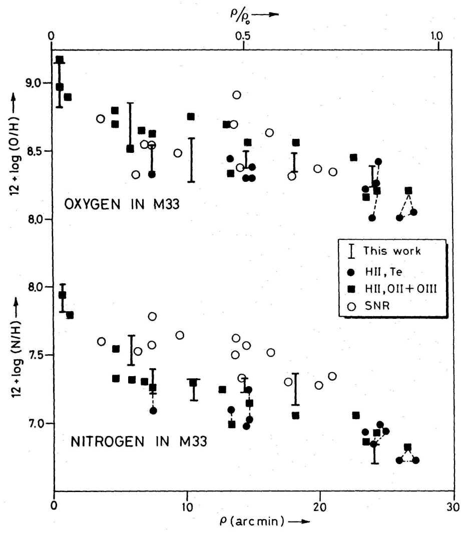
Closed Box Model



Abundance as function of gas fraction in the closed box model in Instantaneous Recycling Approximation (IRA) and Non-IRA (stellar evolution).

(Prantzos, 2008, Fig. 12)

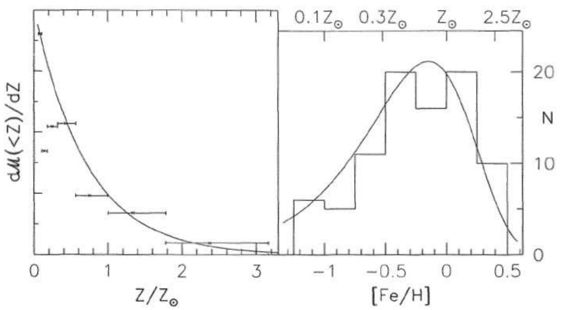
Closed Box Model



Spiral galaxies generally show abundance gradients away from their core, as predicted by closed box models.

(Vilchez et al., 1988, Fig. 9)

Closed Box Model



(Metallicity for “Baade’s Window”; SG, Fig. 4.16)

The metallicity in low-mass stars was

$$M_\mathrm{s}(<Z) = M_{\mathrm{g},0}\left(1 - e^{-\frac{Z(t)-Z_0}{p}}\right) \tag{3.55}$$

and once all gas is gone, the mass of stars with metallicity in $[Z, Z+\Delta Z]$:

$$\frac{dM_\mathrm{s}(<Z)}{dZ}\Delta Z \propto \exp\left(-\frac{Z(t)-Z(t=0)}{p}\right)\Delta Z \tag{3.56}$$

This reproduces well the metallicity distribution found in the galactic bulge (see figure), and one finds $p \sim 0.7 Z_\odot$.

Bulge seems to have managed to convert all of its gas into stars!

Problems of Closed Box

Dwarf spheroidal galaxy Leo I (next to Regulus)

1. loss of metals?
   $\Longrightarrow$ galaxies have low mass, thus escape velocity is low

(2nd explanation is preferred)

For other regions, closed box is clearly wrong

Dwarf spheroidal galaxies: very little gas, but metallicity still low.

Two explanations:

1. Possibly low formation of massive stars (=different Initial Mass Function)
   $\Longrightarrow$ little formation of metals?

Solar Neighborhood

Surface density $\Sigma = \int_{-\infty}^{+\infty} n\,d\ell$ of stuff in solar neighborhood:

- stellar density: $\Sigma = 30$–$40\,M_\odot\,\mathrm{pc}^{-2}$ ($30\,M_\odot\,\mathrm{pc}^{-2}$ in stars, $8\,M_\odot\,\mathrm{pc}^{-2}$ in stellar residues)
- gas density: $\Sigma = 13\,M_\odot\,\mathrm{pc}^{-2}$

so total surface density is $50\,M_\odot\,\mathrm{pc}^{-2}$.

n: mass density ($M_\odot\,\mathrm{pc}^{-3}$)

In neighborhood, abundance is $0.7Z_\odot$ (i.e., Sun is enriched!). Therefore

$$Z(\mathrm{now}) = 0.7Z_\odot = p\ln(50/13) \quad\Longrightarrow\quad p \sim 0.5Z_\odot \tag{3.57}$$

this is slightly lower than bulge ($p \sim 0.7Z_\odot$), but could be explained if disk is less efficient in retaining gas (galactic fountain!).

However, further problem: predicted fraction of metal poor stars

$$\frac{M_\mathrm{s}(Z<0.25Z_\odot)}{M_\mathrm{s}(Z<0.7Z_\odot)} = \frac{1-\exp(-Z_\odot/4p)}{1-\exp(-0.7Z_\odot/p)} \sim 0.52 \tag{3.58}$$

so 50% of all stars in vicinity should have low abundances.

Reality: $<$20% of all stars have $Z < 0.25Z_\odot$: G-dwarf problem

Possible solution: local region was enriched by Supernovae to $Z(0) \sim 0.15Z_\odot$.

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