Basics of chemical evolution

- The chemical abundances of stars provide important clues as to the evolutionary history of a galaxy.

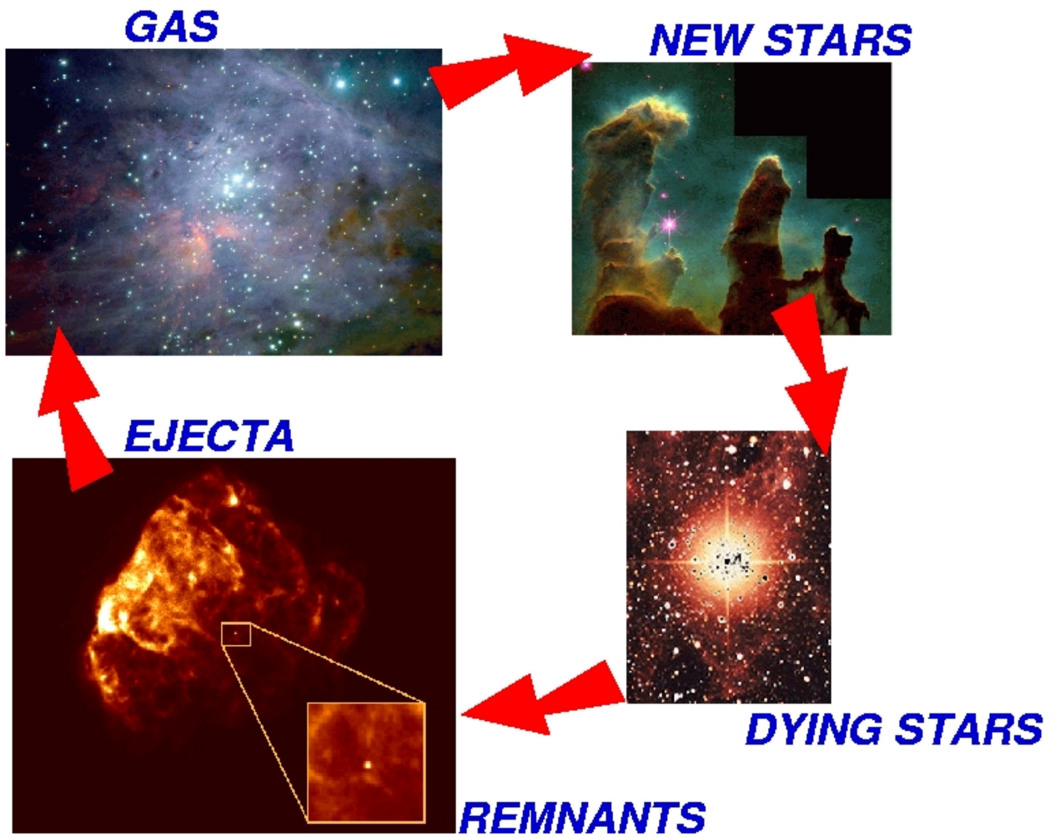
- H and He were present very early on in the Universe, while all metals (except for a very small fraction of Li) produced through nucleosynthesis in stars.

- The metals are found in very similar (but not exactly the same) proportions in all stars. The minuscule differences tell us about the material from which a particular star was made.

- The fraction by mass of heavy elements is denoted by Z.
  - The Sun's abundance $Z_{\odot} \sim 0.02$
  - most metal poor stars in the Milky Way have $< 1/10{,}000\ Z_{\odot}$ of this amount

Cycle of GAS and STARS in GALAXIES

- Gas is transformed into stars.
- Each star burns H and He in its nucleus and produces heavy elements.
- These elements are partially returned into the interstellar gas at the end of the star's life
  - through winds and supernovae explosions.
  - some fraction of the metals are locked into the remnant of the star.



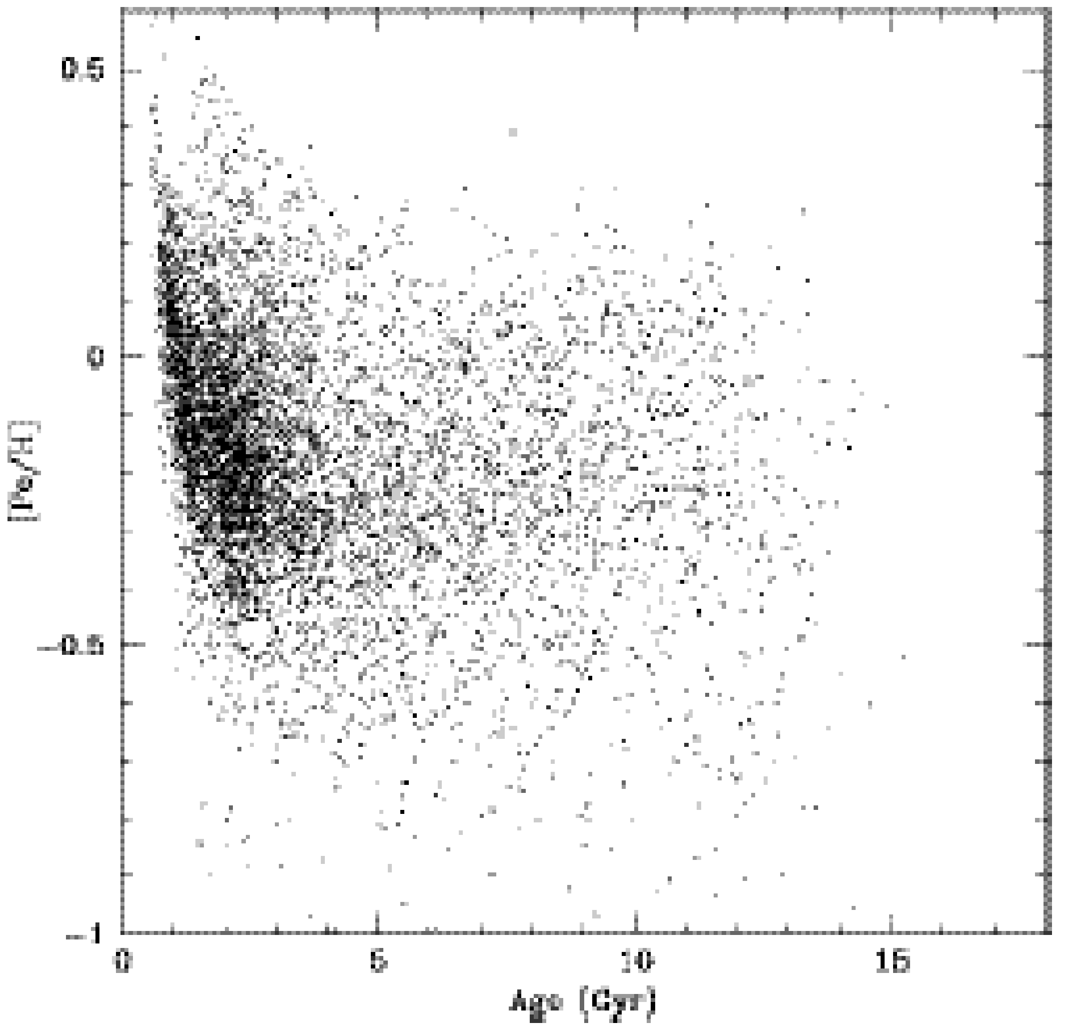
This implies that the chemical abundance of the gas in a galaxy should evolve in time

Chemical evolution

- The metal abundance of the gas, and of subsequent generations of stars, should increase in time.
  - if there is no gas infall from the outside

- The evolution of chemical element abundances in a galaxy provides a clock for galactic aging.

- Expect a relation between the ages and metal abundances of stars:
  - on average, older stars contain less iron than younger stars
  - This is partially the case for the Solar neighbourhood.



Nordstrom et al. (2005)

This figure shows a clear age-metallicity relation for nearby disk stars (dark area), but a lot of scatter for old ages

The build up of metals in a galaxy

Simple model of chemical evolution: Closed-box

Assumptions:

- the galaxy's gas is well-mixed;
- the (high-mass) stars return their nucleosynthetic products rapidly (much faster than the time to form a significant fraction of the stars)

This is the "one-zone, instantaneous recycling model".

- no gas escapes from or is added to the galaxy

We also assume that the metals maintain the same proportion relative to each other (i.e. all stars contribute always the same amount and type of metals by the end of their lifetimes).

The key quantities in a chemical enrichment model are:

- $M_g(t)$: the mass of gas in the galaxy at time t
- $M_s(t)$: the mass in unevolved low-mass stars and the mass in remnants (white dwarfs, neutron stars, black holes) at time t.
  - This mass is essentially locked up throughout the lifetime of the galaxy.
- $M_h(t)$: the total mass of elements heavier than He at time t in gas phase

The metal abundance of the gas is

$$Z(t) = M_h(t)/M_g(t)$$

The closed-box model

- Suppose mass of stars $d'M_s$ is formed at time t
- dM_s: total mass in low-mass stars and remnants.

- We define the mass in heavy elements produced by this generation of stars:

$$p\ dM_s.$$

- p is the <u>yield</u> of the stellar generation
  - depends on the initial mass function and on the details of nuclear burning.

- The fraction of heavy elements locked up in the low-mass stars and remnants is

$$Z\ dM_s$$

- The mass of heavy elements M_h in the interstellar gas changes as the metals produced by the high-mass stars are returned.

- The rate of change in the metal content of the gas mass is

$$dM_h/dt = p\, dM_s/dt - Z\, dM_s/dt$$

$$\boxed{dM_h/dt = (p - Z)\, dM_s/dt} \qquad (1)$$

- Mass conservation implies: $\boxed{dM_g/dt + dM_s/dt = 0}$ (2)

- The change in metallicity of the gas

$$\begin{aligned} dZ/dt &= d(M_h/M_g)/dt \\ &= dM_h/dt * 1/M_g - M_h/M_g^2 * dM_g/dt \\ &= 1/M_g * (dM_h/dt - Z\, dM_g/dt) \end{aligned}$$

and so

$$dZ/dt = -p/M_g \, dM_g/dt$$

- If the yield p does not depend on Z, we integrate to obtain the metallicity at time t

$$Z(t) = Z(0) - p * \ln[M_g(t)/M_g(0)]$$

The metallicity of the gas grows with time, as new stars are formed and the gas is consumed

Metallicity distribution of the stars

- The mass of the stars that have a metallicity less than $Z(t)$ is

$$M_s[< Z(t)] = M_s(t) = M_g(0) - M_g(t)$$

or

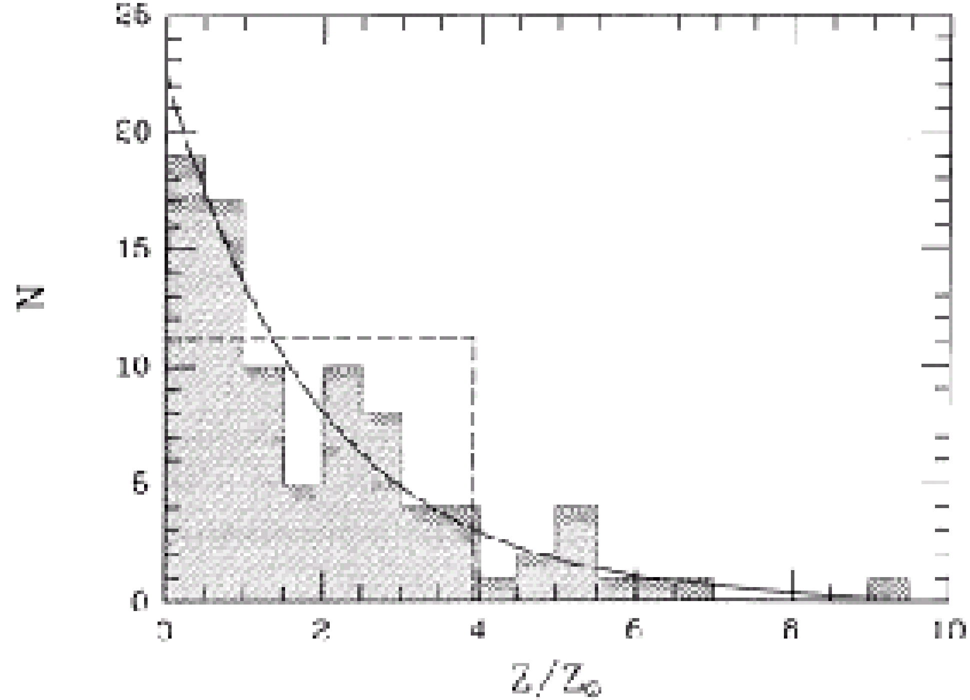
$$M_s[< Z(t)] = M_g(0) * [1 - e^{-(Z(t) - Z(0))/p}]$$

- When all the gas has been consumed, the mass of stars with metallicity Z, $Z + dZ$

-

$$dM_s(Z) \propto e^{-(Z - Z(0))/p} \, dZ$$

A closed box model reproduces well the metallicity distribution of stars in the bulge of our Galaxy



Rich (1990)

FIG. 8.—Differential abundance distribution of bulge giants compared to two limiting cases of the simple model of chemical evolution. *Solid line*: simple "closed box" model with complete gas consumption; $\langle z \rangle = 2.0 y/z_\odot$. *Dashed line*: Simple model, in the limiting case where a small fraction of the initial volume of gas is converted to stars, the remainder being lost from the system.

The closed-box model and the disk

- We derive the yield p from observations:

$$Z(\text{today}) \sim Z(0) - p \ln[M_g(\text{today})/M_g(0)]$$

- The average metal content of the gas in the disk near the Sun is
  $Z \sim 0.7\, Z_\odot$.

- The initial mass of gas $M_g(0)$ = $M_s(\text{today}) + M_g(\text{today})$ where $M_s \sim 40\, M_\odot/pc^2$ and $M_g \sim 10\, M_\odot/pc^2$).

- Assuming that $Z(0) = 0$, we derive $\mathbf{p \sim 0.43\, Z_\odot}$

Expected number of metal-poor stars in the SN

- Compute the mass in stars with $Z = 0.25\ Z_\odot$ compared to the mass in stars with the current metallicity of the gas :

  $M_s(< 0.25\ Z_\odot)\ /\ M_s(< 0.7\ Z_\odot) = [1 - e^{-0.25\ Z_\odot/p}] / [1 - e^{-0.7 Z_\odot/p}] \sim 0.54$

- Half of all stars in the disk near the Sun should have $Z < 0.25\ Z_\odot$

- However, only 2% of the F - G dwarf stars in the SN have such low metallicities

- This discrepancy is known as the **G-dwarf problem.**

- Whenever such a discrepancy arises we need to turn to the assumptions that have been made to see which one could have been incorrect.

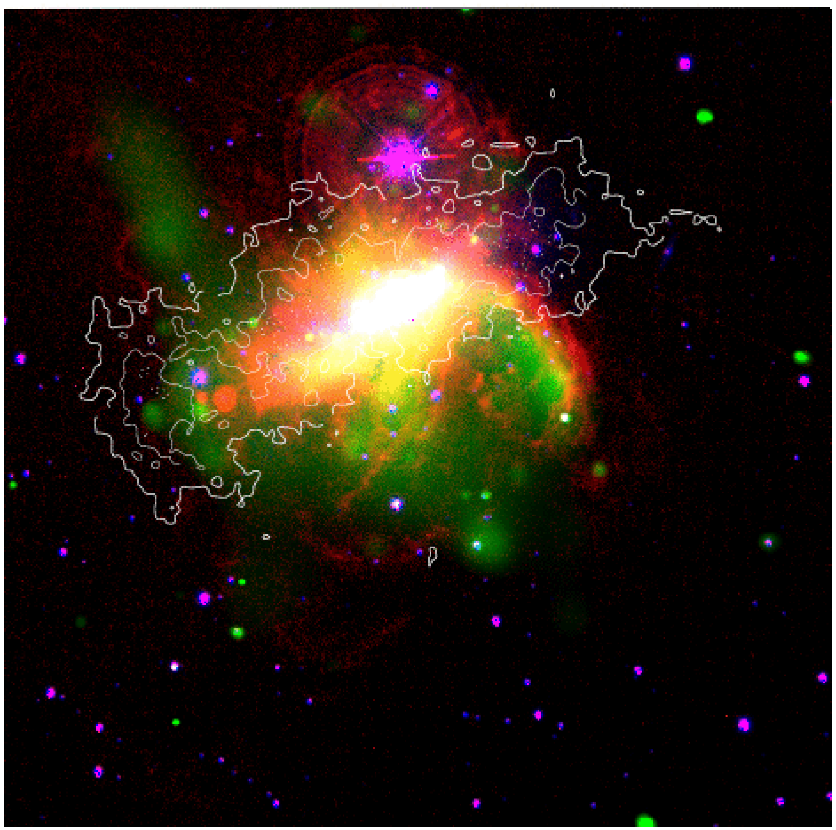
- In this case, one of the critical assumptions made was that the initial gas was metal-free.
  - If we assume there was some initial pre-enrichment in the gas, i.e. if we set $Z(0) = 0.15\ Z_{\odot}$, the metallicity distribution of stars is much better reproduced.

- Other possibilities are:
  - Gas itself was not chemically homogeneous
  - Gas has been lost through winds of stars or supernovae explosions (whose velocities can reach 1000 km/s) : "leaky-box model",
  - Gas has been accreted: the "accreting-box model".

The leaky-box model

- The winds of very massive stars and supernovae explosions can drive gaseous material out of a galaxy.

- Metals in this gas will also be lost in this way.



The leaky-box model

- If there is an outflow of processed material $g(t)$, the first fundamental equation for the rate of change in the metal content of the gas mass (Eq. 1) now becomes:

$$dM_h/dt = p\, dM_s/dt - Z\, dM_s/dt - Z\, g \qquad (1')$$

- While the conservation of mass (Eq. 2) is

$$dM_g/dt + dM_s/dt + g(t) = 0, \qquad (2')$$

- As an example, assume that the rate at which the gas flows out of the box is proportional to the star-formation rate:

$$g(t) = c\, dM_s/dt$$

  - c is a constant
  - dM_s/dt is the SFR (for example in solar masses per year).

The leaky-box model: predictions

We now derive the metallicity evolution.

- As before $dZ/dt = p/M_g(t) * dM_s/dt$
  where $dM_s/dt = -1/(1+c)\, dM_g/dt$. Replacing

$$dZ/dt = -p/\ (1 + c) * 1/M_g * dM_g\ /dt$$

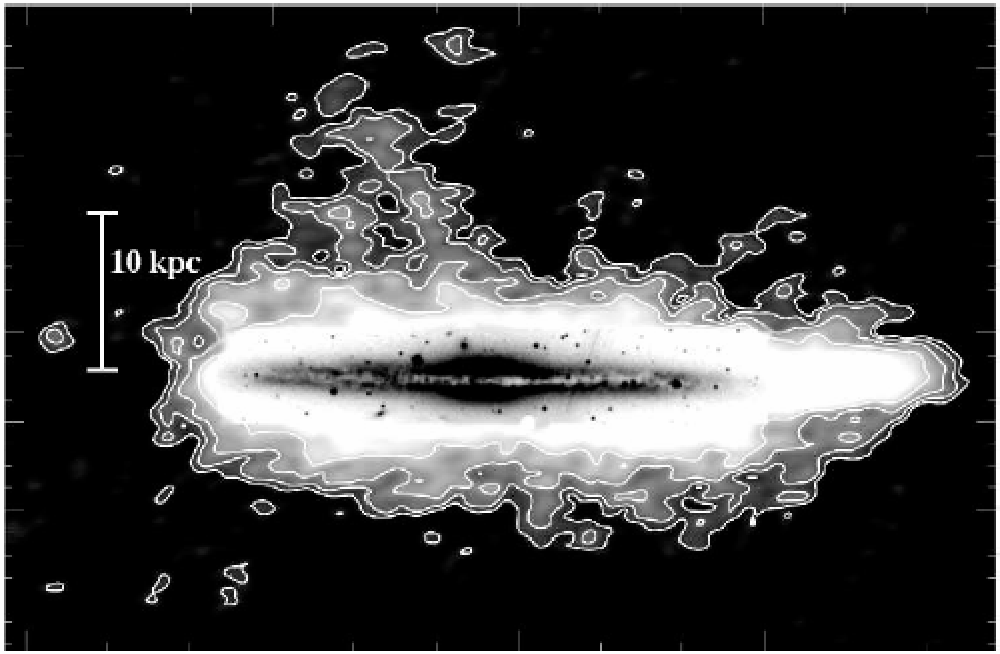
- Integrating this equation:

$$Z(t) = Z(0) - p/(1+c) * \ln[M_g(t)/M_g(0)]$$

The only effect of an outflow is to reduce the yield to an <u>effective yield</u> = p/(1+c)

The accreting-box model

- Galaxies accrete gas from their surroundings
- This has consequences on the chemical evolution of a galaxy



Fraternali et al (2007)

Fig. 1. Optical DSS image (grey-scale) and total HI map (contours+negative grey-scale) of NGC 891. HI contours are: 1, 2, 4, 8, 16 $\times 10^{19}$ atoms cm^{-2}. The beam size is $25'' = 1.15$ kpc.

The accreting-box model

- Let us feed pristine (metal-free) gas to the box at the same rate at which gas is turned into stars.
- Consider a dM of gas inflow, so that the mass pdM of metals is returned to the ISM (interstellar medium) after stars form and evolve.
- The global effect is to remove a gas mass of metallicity Z (transform it into stars) and return the same mass at metallicity p.
- If this process is continued eventually the metallicity of the gas will be $Z = p$.
- After a very long time, the fraction of metal-poor stars will become negligible (since essentially all stars will have metallicity p).

The accreting-box model: formulation

- Since the gas accreted is pristine, Eq (1) is still valid: the mass of heavy elements produced in a SF episode is

$$dM_h /dt = (p - Z)\, dM_s /dt \qquad (1'')$$

- However, Eq.(2) for the conservation of mass in the box becomes:

$$dM_g/dt = -dM_s /dt + f(t) \qquad (2'')$$

- Consider the simple case in which the mass in gas in the box is constant. This implies then

$$dZ/dt = 1/M_g * [(p - Z)\, dM_s/dt - Z\, dM_g/dt] = 1/M_g * [(p - Z)\, dM_s/dt]$$

- Integrating and assuming that $Z(0) = 0$

$$Z = p \left[1 - e^{-M_s/M_g} \right]$$

- Therefore when $M_s \gg M_g$, the metallicity $Z \sim p$.

- The mass in stars that are more metal-poor than Z is

$$M_s(< Z) = -M_g \ln \left(1 - Z/p \right)$$

- In this case, for $M_g \sim 10\ M_\odot/pc^2$ and $M_s \sim 40\ M_\odot/pc^2$, and for $Z = 0.7\ Z_\odot$, then $p \sim 0.71\ Z_\odot$. Thus the fraction of stars more metal-poor than $0.25\ Z_\odot$ is $M(<0.25)/M(<0.7) \sim 10\%$, in much better agreement with the observations.