

# Basics of Galactic chemical evolution

- The chemical abundances of stars provide important clues as to the evolutionary history of a galaxy.
- Astronomers usually refer to chemical elements other than hydrogen and helium as metals or heavy elements. This generalization is due to the fact that H and He are the most abundant elements in the Universe, with metals accounting for less than a few %!
- Another important aspect is that H and He were present very early in the history of the Universe, while all metals (except for a very small fraction of Li) were produced through nucleosynthesis (nuclear burning) 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  $Z_{\odot} \sim 0.02$ , while the most metal poor stars in the Milky Way have less than 1/10,000 of this amount.
- Often, we will specify the fraction of a particular element in a star with respect to that in the Sun, for example [O/Fe], or [O/H], etc. The relative fraction of element A with respect to element B is defined as:

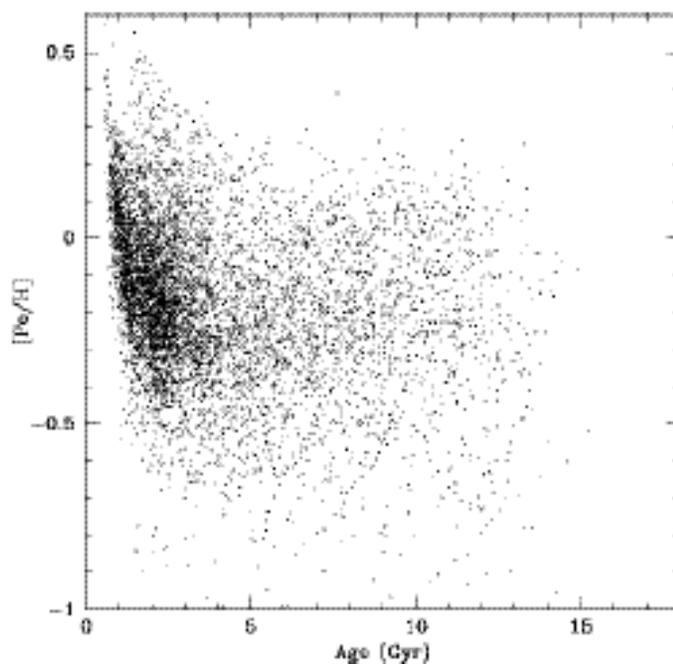
$$[A/B] = \log_{10}\left\{\frac{\# \text{ of A atoms}}{\# \text{ of B atoms}}\right\}_{\text{in star}} - \log_{10}\left\{\frac{\# \text{ of A atoms}}{\# \text{ of B atoms}}\right\}_{\text{in Sun}}$$

For example, in a star with  $[\text{Fe}/\text{H}] = -2$  dex, iron is 0.01 as abundant as in the Sun.

# Chemical evolution

- 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. If there is no gas infall from the outside, then the metal abundance of the gas, and hence of the stars, should increase in time.
- Therefore, the evolution of chemical element abundances in a galaxy provides a clock for galactic aging.

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



This figure shows a clear age-metallicity relation for nearby disk stars (dark area), but a lot of scatter for old ages (from Nordstrom et al. 2005).

# The build up of metals in a galaxy

We will now develop a simple model of the build up of metals in a galaxy over time.

We assume that

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

This approximation is known as the "**one-zone, instantaneous recycling model**".

- no gas escapes from or is added to the galaxy

- **This is a "closed-box model"**.

For simplicity we assume now that the metals maintain the same proportion relative to each other (this corresponds to assuming all stars contribute always the same amount and type of metals by the end of their lifetimes).

**The key quantities** in the description of the chemical enrichment of a galaxy are:

- $M_g(t)$ : the mass of gas in the galaxy at time  $t$
- $M_s(t)$ : the mass in low-mass stars (which have not yet evolved) and the mass in remnants from high-mass stars (white dwarfs, neutron stars, black holes) at time  $t$ . This mass is essentially locked up in these stars throughout the lifetime of the galaxy.
- $M_h(t)$ : the total mass of elements heavier than He in the galactic gas phase at time  $t$

**The metal abundance of the gas therefore is**

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

# The closed-box model

- Suppose a mass of stars  $dM_s$  is formed at time  $t$ . After the high-mass stars have evolved a mass  $dM_s$  remains locked up in low-mass stars and in remnants.
- The mass in heavy elements produced by this generation of stars is defined as  $p dM_s$ .

The quantity  $p$  is known as the yield of that stellar generation (it represents an average over all stars formed) and depends fundamentally on the initial mass function and on the details of nuclear burning.

- The mass of heavy elements  $M_h$  in the interstellar gas changes as the metals produced by the high-mass stars are returned. Some fraction of these heavy elements will still be locked up in the low-mass stars and remnants. This fraction:
  - is proportional to the mass in these stars and remnants  $dM_s$ , and
  - has the initial metallicity  $Z$  of the gas.
- Hence the total mass in heavy elements which is locked up is  $Z dM_s$ .

- Therefore, the rate of change in the metal content of the gas mass is

$$dM_h/dt = p dM_s/dt - Z dM_s/dt \quad (1)$$

$$dM_h/dt = (p - Z) dM_s/dt$$

- Mass conservation implies:

$$dM_g/dt + dM_s/dt = 0, \quad (2)$$

- The metallicity of the gas changes by

$$dZ/dt = d(M_h/M_g)/dt = dM_h/dt * 1/M_g - M_h/M_g^2 * dM_g/dt = 1/M_g * (dM_h/dt - Z dM_g/dt)$$

- 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 stars are formed and the gas is consumed**

- We can also predict the metallicity distribution of the stars. The mass of the stars that have a metallicity less than  $Z(t)$  is

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

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

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

- A closed box model seems to reproduce well the metallicity distribution of stars in the bulge of our Galaxy

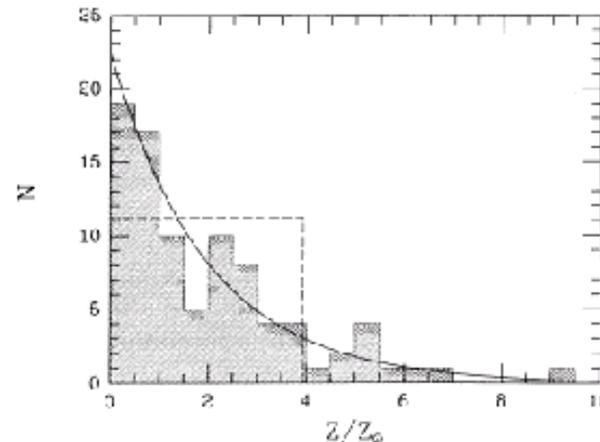


FIG. 8.—Differential abundance distribution of bulge giants compared to two limiting cases of the simple model of chemical evolution. *Solid line*: simple "closed box" model with complete gas consumption;  $\langle \tau \rangle = 2.0 \tau_{\odot}$ . *Dashed line*: Simple model, in the limiting case where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

Rich (1990)

# The closed-box model and the Solar neighbourhood

- The average metal content of the gas in the disk in the Solar neighbourhood is  $Z \sim 0.7 Z_{\odot}$ .
- The initial mass of gas near the Sun is the sum of the current mass in stars ( $\sim 35 M_{\odot}/\text{pc}^2$ ) plus the current gas mass ( $\sim 15 M_{\odot}/\text{pc}^2$ ).
- If we use the equation for the metallicity evolution of the gas, we can derive the yield  $p$

$$Z(\text{today}) \sim 0.7 Z_{\odot} = Z(0) - p \ln[15/50]$$

- Assuming that  $Z(0) = 0$ , we derive  $p \sim 0.5 Z_{\odot}$ .
- Let us now look at the predicted number of metal-poor stars in the Solar neighbourhood.

- For example, we can compute the mass in stars with 1/4 of the solar metallicity ( $Z = 0.25 Z_{\odot}$ ) to the mass in stars with the current metallicity of the gas in that volume:

$$M_s(< 0.25 Z_{\odot}) / M_s(< 0.7 Z_{\odot}) = [1 - e^{-0.25 Z_{\odot}/p}] / [1 - e^{-0.7 Z_{\odot}/p}] \sim 0.52$$

- **Thus half of all stars in the disk near the Sun should have metal-abundances less than  $0.25 Z_{\odot}$ .**
- 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, for example, 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.
  - Another possibility is that the gas itself was not chemically homogeneous, and that for example, gas has been lost through winds of stars or supernovae explosions (whose velocities can reach 1000 km/s) or that gas has been accreted. In the first case we talk about the "leaky-box model", while in the second, of the "accreting-box model".

# The leaky-box model

- The winds of very massive stars and supernovae explosions can produce shocks which drive gaseous material out of a galaxy. Whichever metals are in this gas will also be lost in this way.
- 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:

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

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

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

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

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

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

# The leaky-box model: prediction

- We can now derive the metallicity evolution. It is easy to show that as before

$$dZ/dt = p/M_g(t) * dM_s/dt$$

- where now  $dM_s/dt = -1/(1+c) dM_g/dt$ . Replacing

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

- Integrating this equation, we find

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

- Comparing to the expression derived in the case of the closed-box model, we note that **the only effect of an outflow is to reduce the yield to an effective yield =  $p/(1+c)$**

# The accreting-box model

- There is evidence that galaxies accrete gas from their surroundings. What is the consequence of this accretion on the chemical evolution of a galaxy?
- Let us assume that during some initial period, chemical evolution proceeded according to the closed-box model. At the end of this period, 90% of the gas mass is transformed into stars, and as we saw, roughly 50% of the stars are predicted to have metallicities lower than 0.25 of the solar value.
- Let us now 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  $p dM$  of metals is returned to the ISM (interstellar medium) after stars form and evolve. Thus 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  $Z = p$ . Thus, 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

- How do we formulate mathematically this process?
- Since the gas accreted is pristine, Eq (1) is still valid: the mass of heavy elements produced in a SF episode is

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

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

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

- Let us now consider the simple case in which the mass in gas in the box is constant. This implies then

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

- We can easily integrate the above equation (assuming that  $Z(0) = 0$ ) to derive

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

- Thus when  $M_s \gg M_g$ , the metallicity  $Z \sim p$ .
- The mass in stars that are more metal-poor than a given  $Z$  is therefore

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

- If we replace by the values used previously, for the metallicity of the solar neighbourhood and the yield, as well as the gas and star mass fraction, we would derive that about 3% of all dwarf stars are more metal poor than  $0.25 Z_{\odot}$ , in good agreement with the observations.