

# Chapter 4

## Galactic Chemical Evolution

### 4.1 Introduction

Chemical evolution is the term used for the changes in the abundances of the chemical elements in the Universe over time, since the earliest times to the present day. The study of these changes is an important field in astronomy, for both our Galaxy and for other galaxies. This includes the study of the elemental abundances in stars and in the interstellar medium. A fundamental objective of studies of chemical evolution is to develop a complete understanding of how the elemental abundances correlate with parameters like time, location within a galaxy, and stellar velocities.

The term ‘chemical’ here refers to the chemical elements. It does not refer to chemistry in the broader sense: the study of interactions between molecules in the Universe is a different, distinct field called astrochemistry.

### 4.2 Chemical Abundances

The relative abundances of the chemical elements can be measured in a number of astronomical objects, in particular using spectroscopic techniques. The observed strengths of spectral lines depend on a variety of factors among which are the chemical abundances of the elements producing those spectral lines. Abundances can be measured in stellar photospheres from the strengths of absorption lines. The observed strengths of lines in a stellar spectrum depend on the abundance of the element responsible, on the effective temperature of the star, on the acceleration due to gravity at its surface and on small-scale turbulence in the atmosphere of the star. All these parameters can be solved for if there are sufficient spectroscopic observations, while the analysis becomes simpler if the temperature can be determined in advance from photometric observations. Equally, abundances can be determined from the strengths of emission lines from interstellar gas, most notably from HII regions.

It is important to define some terms and parameters that are used for the study of the abundances of chemical elements. In astronomy, for historical reasons, the term *metals* is used for all elements other than H and He; the term *heavy elements* is also used for these. Under this definition, even elements such as carbon, oxygen, nitrogen and sulphur are called metals. The term *metallicity* is used for the fraction of heavy elements, usually expressed as a fraction by mass.

It is convenient to define the fractions *by mass* of hydrogen  $X$ , of helium  $Y$ , and of heavy elements  $Z$ . Therefore,  $Z = (\text{mass of heavy elements})/(\text{total mass of all nuclei})$

in some object, objects or region of space. We therefore have  $X + Y + Z \equiv 1$ .

In many other applications, the abundances *by number* of nuclei are used. These are usually expressed relative to hydrogen. So  $N(\text{He})/N(\text{H})$  is the ratio of the abundance of helium to hydrogen by number, and  $N(\text{Fe})/N(\text{H})$  the iron-to-hydrogen ratio.

For convenience, chemical abundances in the Universe are often compared to the values in the Sun. Solar abundances give  $X = 0.70$ ,  $Y = 0.28$ ,  $Z = 0.02$  by mass. (And by number, 92 % H, 8.5 % He, 0.09 % heavy elements.) An object, such as a star, that has a heavy element fraction significantly lower than the Sun is said to be *metal poor*, while one that has a larger heavy element fraction is said to be *metal rich*.

Abundance ratios by number are expressed relative to the Sun using a parameter  $[A/B]$ , where A and B are the chemical symbols of two elements, and is defined as,

$$[A/B] = \log_{10} \left( \frac{N(A)}{N(B)} \right) - \log_{10} \left( \frac{N(A)}{N(B)} \right)_{\odot}, \quad (4.1)$$

where  $\odot$  represents the abundance ratio in the Sun. So the ratio of iron to hydrogen in a star relative to the Sun is written as

$$[\text{Fe}/\text{H}] = \log_{10} \left( \frac{N(\text{Fe})}{N(\text{H})} \right) - \log_{10} \left( \frac{N(\text{Fe})}{N(\text{H})} \right)_{\odot}. \quad (4.2)$$

The  $[\text{Fe}/\text{H}]$  parameter for the Sun is therefore, by definition, 0. A star having an iron abundance (relative to hydrogen) that is 1/10th of that of the Sun would therefore have  $[\text{Fe}/\text{H}] = -1.0$  (because  $N(\text{Fe})/N(\text{H}) = 0.10(N(\text{Fe})/N(\text{H}))_{\odot}$ , giving  $[\text{Fe}/\text{H}] = \log_{10}(0.10) = -1.0$ ). A star with a Fe abundance 1/100th that of the Sun would have  $[\text{Fe}/\text{H}] = -2.0$ .

A mildly metal-poor star in the Galaxy might have  $[\text{Fe}/\text{H}] \simeq -0.3$ , while a very metal-poor star in the halo of the Galaxy might have  $[\text{Fe}/\text{H}] \simeq -1.5$  to  $-2$ . A metal-rich star in the Galaxy might have  $[\text{Fe}/\text{H}] \simeq +0.3$ . The interstellar gas in the Galaxy has a near-solar metallicity with  $[\text{Fe}/\text{H}] \simeq 0$ . The iron-to-hydrogen number ratio is encountered more often in research papers than other ratios because iron produces large numbers of absorption lines in the spectra of late-type stars like our Sun, making iron abundances relatively straightforward to measure.

## 4.3 The Chemical Enrichment of Galaxies

Current cosmological models show that the Big Bang produced primordial gas having a chemical composition that was 93 % H, 7 % He by number, plus a trace of  $\text{Li}^7$ . This corresponds to a composition by mass that was 77 % H and 23 % He: i.e.  $X = 0.77$ ,  $Y = 0.23$ ,  $Z = 0.00$ . The baryonic material produced by the Big Bang was therefore almost pure hydrogen and helium, with 13 hydrogen nuclei for every one of helium. This production of the chemical elements in the Big Bang is known as *primordial nucleosynthesis*.

The material we find around us in the Universe today contains significant quantities of heavy elements, although these are still only minor contributors to the total mass of baryonic matter (most is hydrogen). These heavy elements have been synthesised in nuclear reactions in stars, a process known as *nucleosynthesis*.

These nuclear reactions in general occur in the cores of stars, producing enriched material in stellar interiors. Enriched material – material richer in heavy elements

than it was previously – can be ejected into the interstellar medium in the later stages of stellar evolution, through mass loss and in supernovae. Star formation therefore produces stars which, after a time delay, eject heavy elements into the interstellar medium, including heavy elements newly synthesised in the stellar interiors. Star formation from this enriched material in turn results in stars with enhanced abundances of heavy elements. This process occurs repeatedly over time, with the continual recycling of gas, leading to a gradual increase in the metallicity of the interstellar medium with time.

Supernovae are important to chemical enrichment. They can eject large quantities of enriched material into interstellar space and can themselves generate heavy elements in nucleosynthesis. Type II supernovae are produced by massive stars ( $M \gtrsim 8M_{\odot}$ ). They eject enriched material into the interstellar medium  $\sim 10^7$  yr after formation. This material is rich in C, N and O. In contrast, type Ia supernovae are probably caused by explosive fusion reactions in binary systems and eject enriched material  $\gtrsim 10^8$  yr after the initial star formation. This material is rich in iron.

The main sequence lifetime  $T_{\text{MS}}$  of a star is a very strong function of the star's mass  $M$ . Stars with masses  $M \lesssim 0.9M_{\odot}$  have  $T_{\text{MS}} >$  age of the Universe. So mass that goes into low mass stars is lost from the recycling process: it remains locked up in long-lived stars. Usefully, samples of low mass stars preserve abundances of the interstellar gas from which they formed if enriched material is not dredged up from the stellar interiors. This is true for G dwarfs for example, where the gas in the photosphere is almost unchanged in chemical composition from the gas from which they formed. So a sample of G dwarfs provides samples of chemical abundances through the history of the Galaxy. In contrast, observations of the interstellar gas in a galaxy provide information on *present-day* abundances and on the current state of chemical evolution.

## 4.4 The Simple Model of Galactic Chemical Evolution

The Simple Model of chemical evolution simulates the build up of the metallicity  $Z$  in a volume of space. The Simple Model makes some simplifying assumptions:

- the volume initially contains only unenriched gas – initially there are no stars and no heavy elements;
- the volume of space where the evolution takes place is a ‘closed box’ – no gas enters or leaves the volume;
- the gas in the volume is well mixed – it has the same chemical composition throughout;
- instantaneous recycling occurs – following star formation, all newly created heavy elements that enter the ISM from stars do so immediately;
- the fraction of newly-synthesised heavy elements ejected into the ISM after material forms stars is constant.

These assumptions, although slightly naive, allow some important predictions about the variation of the metallicity in the interstellar gas in terms of the amount of star formation that has taken place.

Consider a volume within a galaxy, small enough to be fairly homogeneous, but large enough to contain a good sample of stars. The total mass of chemical elements

in this volume at time  $t$  is  $M_{\text{total}}$ , made up of  $M_{\text{stars}}$  in stars and  $M_{\text{gas}}$  in gas. So

$$M_{\text{total}} = M_{\text{stars}} + M_{\text{gas}} . \quad (4.3)$$

Here,  $M_{\text{stars}} = M_{\text{stars}}(t)$  and  $M_{\text{gas}} = M_{\text{gas}}(t)$ . The assumption that the volume is a closed box means that  $M_{\text{total}} = \text{constant}$  at all times. Initially, at time  $t = 0$ ,  $M_{\text{stars}}(0) = 0$  and  $M_{\text{total}} = M_{\text{gas}}(0)$  (the volume contains pure gas initially).

Let  $M_{\text{metals}}$  be the mass of heavy elements in the gas within the volume at time  $t$ . Therefore the heavy element mass fraction of the gas is

$$Z \equiv \frac{M_{\text{metals}}}{M_{\text{gas}}} . \quad (4.4)$$

Consider a time interval from  $t$  to  $t + \delta t$ . Star formation will occur in this time, with gas forming stars. Let the change in  $M_{\text{stars}}$  and  $M_{\text{gas}}$  in this time be  $\delta M_{\text{stars}}$  and  $\delta M_{\text{gas}}$ . Some stars will eject enriched gas back into the interstellar medium (through supernovae and mass loss).

We firstly need to express the change  $\delta Z$  in the metallicity of the interstellar gas in terms of  $\delta M_{\text{stars}}$  and  $\delta M_{\text{gas}}$ . From Equation 4.4, we have  $Z = \text{fn}(M_{\text{metals}}, M_{\text{gas}})$ , so the differential of  $Z$  with respect to time is

$$\frac{dZ}{dt} = \frac{\partial Z}{\partial M_{\text{metals}}} \frac{dM_{\text{metals}}}{dt} + \frac{\partial Z}{\partial M_{\text{gas}}} \frac{dM_{\text{gas}}}{dt} .$$

Differentiating Equation 4.4,

$$\frac{\partial Z}{\partial M_{\text{metals}}} = \frac{1}{M_{\text{gas}}} \quad \text{and} \quad \frac{\partial Z}{\partial M_{\text{gas}}} = - \frac{M_{\text{metals}}}{M_{\text{gas}}^2} ,$$

which gives,

$$\frac{dZ}{dt} = \frac{1}{M_{\text{gas}}} \frac{dM_{\text{metals}}}{dt} - \frac{M_{\text{metals}}}{M_{\text{gas}}^2} \frac{dM_{\text{gas}}}{dt} .$$

For a small time interval  $\delta t$ , we have,

$$\delta Z = \frac{\delta M_{\text{metals}}}{M_{\text{gas}}} - \frac{M_{\text{metals}}}{M_{\text{gas}}^2} \delta M_{\text{gas}} ,$$

which gives from the definition of  $Z$  in Equation 4.4,

$$\delta Z = \frac{\delta M_{\text{metals}}}{M_{\text{gas}}} - Z \frac{\delta M_{\text{gas}}}{M_{\text{gas}}} . \quad (4.5)$$

We need to distinguish between the total mass in stars  $M_{\text{stars}}$  at time  $t$  and the total mass that has taken part in star formation  $M_{\text{SF}}$  over all periods up to time  $t$ . When a mass  $\delta M_{\text{SF}}$  goes into stars during star formation, the total mass in stars will change by an amount less than this, because material from the new stars is ejected back into the interstellar gas. So,  $\delta M_{\text{SF}} > \delta M_{\text{stars}}$ , and  $M_{\text{SF}} > M_{\text{stars}}$ .

Let  $\alpha$  be the fraction of mass participating in star formation that remains locked up in long-lived stars (and stellar remnants). So,

$$\delta M_{\text{stars}} = \alpha \delta M_{\text{SF}} \quad (4.6)$$

(with  $0 < \alpha < 1$ ).

The mass of newly synthesised heavy elements ejected back into the ISM is proportional to the mass that goes into stars (from the Simple Model assumptions listed above). Let the mass of newly synthesised heavy elements ejected into the ISM be  $p \delta M_{\text{stars}}$ , where  $p$  is a parameter known as the yield, with  $p$  set to be a constant here.

The change  $\delta M_{\text{metals}}$  in the mass of heavy elements in the gas in a time  $\delta t$  will be caused by the loss of heavy elements in the gas that goes into star formation, by the gain of old heavy elements that have gone into star formation and are then ejected back into the gas, and by the gain of newly synthesised heavy elements from stars that are ejected into the gas. The contribution to  $\delta M_{\text{metals}}$  from the loss of heavy elements in the gas going into star formation will be  $-\delta M_{\text{SF}} M_{\text{metals}}/M_{\text{gas}} = -\delta M_{\text{SF}} Z$ . The contribution from old heavy elements in the gas that have gone into star formation then are ejected back unchanged into the gas will be  $Z \delta M_{\text{SF}} \times$  (fraction of mass going into stars that is ejected back)  $= Z (1 - \alpha) \delta M_{\text{SF}}$ . The contribution from the newly synthesised heavy elements that are ejected into the gas will be  $p \delta M_{\text{stars}}$  from the definition of the yield  $p$  above. Therefore, in time  $\delta t$ :

$$\delta M_{\text{metals}} = -Z \delta M_{\text{SF}} + Z (1 - \alpha) \delta M_{\text{SF}} + p \delta M_{\text{stars}} ,$$

which gives on expanding and cancelling,

$$\begin{aligned} \delta M_{\text{metals}} &= -Z \alpha \delta M_{\text{SF}} + p \delta M_{\text{stars}} \\ &= -Z \delta M_{\text{stars}} + p \delta M_{\text{stars}} , \end{aligned} \quad (4.7)$$

on substituting for  $\alpha \delta M_{\text{SF}} = \delta M_{\text{stars}}$ . Dividing by  $M_{\text{gas}}$ ,

$$\frac{\delta M_{\text{metals}}}{M_{\text{gas}}} = -Z \frac{\delta M_{\text{stars}}}{M_{\text{gas}}} + p \frac{\delta M_{\text{stars}}}{M_{\text{gas}}} .$$

But from Equation 4.3, the changes in masses are related by  $\delta M_{\text{total}} = \delta M_{\text{stars}} + \delta M_{\text{gas}} = 0$  for a closed box. Therefore,

$$\delta M_{\text{stars}} = -\delta M_{\text{gas}} . \quad (4.8)$$

$$\therefore \frac{\delta M_{\text{metals}}}{M_{\text{gas}}} = Z \frac{\delta M_{\text{gas}}}{M_{\text{gas}}} - p \frac{\delta M_{\text{gas}}}{M_{\text{gas}}} .$$

Substituting this into Equation 4.5,

$$\begin{aligned} \delta Z &= Z \frac{\delta M_{\text{gas}}}{M_{\text{gas}}} - p \frac{\delta M_{\text{gas}}}{M_{\text{gas}}} - Z \frac{\delta M_{\text{gas}}}{M_{\text{gas}}} \\ \therefore \delta Z &= -p \frac{\delta M_{\text{gas}}}{M_{\text{gas}}} , \end{aligned} \quad (4.9)$$

Converting this to a differential and integrating from time 0 to  $t$ ,

$$\begin{aligned} \int_0^{Z(t)} dZ' &= - \int_{M_{\text{gas}}(0)}^{M_{\text{gas}}(t)} p \frac{dM'_{\text{gas}}}{M'_{\text{gas}}} \\ \therefore Z(t) - 0 &= -p \left[ \ln M'_{\text{gas}} \right]_{M_{\text{gas}}(0)}^{M_{\text{gas}}(t)} . \end{aligned}$$

This gives,

$$Z(t) = -p \ln \left( \frac{M_{\text{gas}}(t)}{M_{\text{gas}}(0)} \right) . \quad (4.10)$$

Since the  $M_{\text{gas}}(0) = M_{\text{total}}(t)$  (a constant) for all  $t$  (because we have a closed box that initially contained only gas), we can rewrite this equation using the gas fraction  $\mu \equiv M_{\text{gas}}(t)/M_{\text{total}}(t)$  as

$$Z(t) = -p \ln \mu . \quad (4.11)$$

Both  $Z$  and  $\mu$  can in principle be measured with appropriate observations, and this equation does not depend on time  $t$  or star formation rate explicitly. This is an important prediction from the theory that is discussed more in Section 4.5, where comparisons with observations are considered.

We now need to consider how the mass in stars depends on metallicity. Equation 4.10 gives the change in metallicity  $Z$  in terms of the mass of gas  $M_{\text{gas}}(t)$ . We can convert from  $M_{\text{gas}}(t)$  to  $M_{\text{stars}}(t)$  using  $M_{\text{stars}}(t) = M_{\text{gas}}(0) - M_{\text{gas}}(t)$ . This gives,

$$Z = -p \ln \left( \frac{M_{\text{gas}}(0) - M_{\text{stars}}(t)}{M_{\text{gas}}(0)} \right) , \quad (4.12)$$

which rearranges to

$$\frac{M_{\text{stars}}(t)}{M_{\text{gas}}(0)} = 1 - e^{-Z(t)/p} . \quad (4.13)$$

This is a prediction of how the fraction of the mass of the volume that is in stars varies with metallicity.  $M_{\text{stars}}(t)/M_{\text{gas}}(0)$  increases from zero at time  $t = 0$ , and can become very large if most of the gas is used up in star formation. Again we have a neat prediction of the Simple Model that involves time only through  $Z(t)$  and  $M_{\text{stars}}(t)$ . This equation does not involve the star formation rate as a function of time explicitly, which means that the predictions are much simpler to compare with observations.

Today, at time  $t_1$ , we have a metallicity  $Z_1$  and a mass in stars  $M_{\text{stars}1}$ . Therefore we have

$$\frac{M_{\text{stars}1}}{M_{\text{gas}}(0)} = 1 - e^{-Z_1/p} ,$$

at the present time. Dividing Equation 4.13 by this,

$$\frac{M_{\text{stars}}(t)}{M_{\text{stars}1}} = \frac{1 - e^{-Z(t)/p}}{1 - e^{-Z_1/p}} . \quad (4.14)$$

This is a prediction of how the mass in stars at any time varies with the metallicity.

If we observe some subsample of long-lived stars of similar mass, the number  $N(Z)$  of these stars having a metallicity  $Z$  and less will be proportional to the mass in these stars. Assuming that the fraction of these stars formed during star formation is proportional to the total mass participating in star formation, and using the result

that the total mass in stars is proportional to the mass that has participated in star formation ( $M_{\text{stars}} = \alpha M_{\text{SF}}$ ), we have  $N(Z) \propto M_{\text{stars}}(t)$ . So,

$$\frac{N(Z)}{N_1} = \frac{M_{\text{stars}}(t)}{M_{\text{stars}1}} ,$$

where  $N_1$  is the value of  $N(Z)$  today. This then gives,

$$\boxed{\frac{N(Z)}{N_1} = \frac{1 - e^{-Z(t)/p}}{1 - e^{-Z_1/p}} .} \quad (4.15)$$

This gives a specific prediction of the number of stars as a function of metallicity. In practice it is often easier to work with the differential distribution  $dN/dZ$ , which expresses the number of stars with metallicity  $Z$  as a function of  $Z$ .

## 4.5 Comparing the Simple Model with Observations: Abundances in the Interstellar Gas of Galaxies

Equation 4.11 provided a simple expression for the metallicity in the Simple Model:

$$Z = -p \ln(\text{gas fraction}) .$$

This was derived by considering the chemical evolution in a single closed box. However, this is a general result for any closed box and it can be compared with the observed metallicities and gas fractions in a number of galaxies, provided that the yield is the same in all places. This can be done using the metallicity  $Z$  of *the interstellar gas* as it is observed today (not the metallicities of old stars). This involves the metallicity of the gas at the present time only, and not what it was in the past. For example, oxygen abundances in HII regions can be measured from the emission lines.

Magellanic irregular galaxies are found to fit this relation reasonably well, and  $p$  is estimated to be  $\simeq 0.0025$  from observations. In spiral galaxies, the gas fraction in the disc increases as we go outwards, and  $Z$  is indeed observed to decrease, though perhaps more steeply than this crude model predicts.

## 4.6 Comparing the Simple Model with Observations: Stellar Abundances in the Galaxy and the G-Dwarf Problem

Equation 4.15 gives a prediction of the number of stars  $N(Z)$  having a metallicity  $\leq Z$  as a function of  $Z$  for a sample of long-lived stars, based on the Simple Model assumptions in Section 4.4. These predictions can be compared with observations.

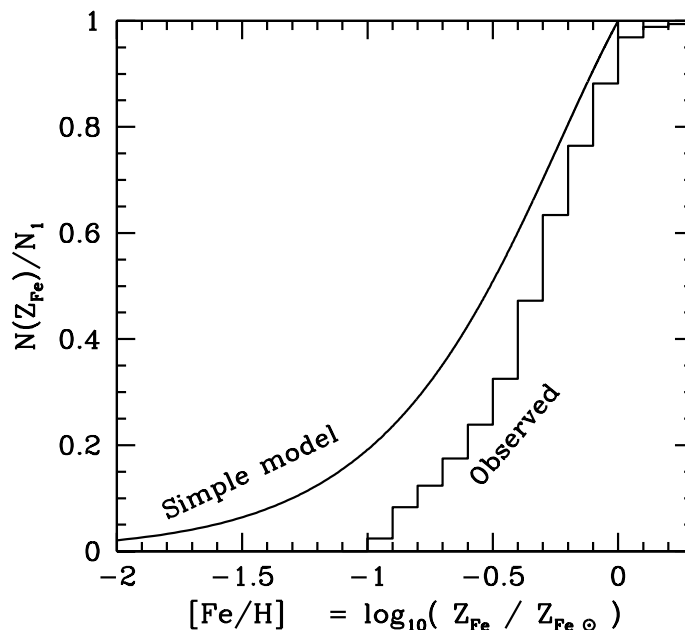
These comparisons require metallicity data for relatively large numbers of stars to ensure adequate statistics. Therefore, metallicity estimates are often made using photometric techniques, rather than using more precise spectroscopic measurements. These photometric estimates tend to measure the abundances of the elements that

produce strong absorption in the light of the stars, rather than the overall metallicity. Therefore iron abundances  $[\text{Fe}/\text{H}]$  are generally quoted for studies of the metallicity distribution.

G- or K-type main sequence stars can conveniently be used in these studies because their lifetimes are sufficiently long that they will have survived from the earliest times to the present: these stars are known as G and K dwarfs. G dwarfs have generally been used because of the advantage of their greater luminosity and because the techniques of estimating metallicities have been better calibrated.

The metallicity distribution observed for metal-poor globular clusters (where the abundance of each cluster is used instead of individual stars) gives a tolerably good fit to the Simple Model prediction. However, matters are very different for the stars in the solar neighbourhood, within the disc of the Galaxy.

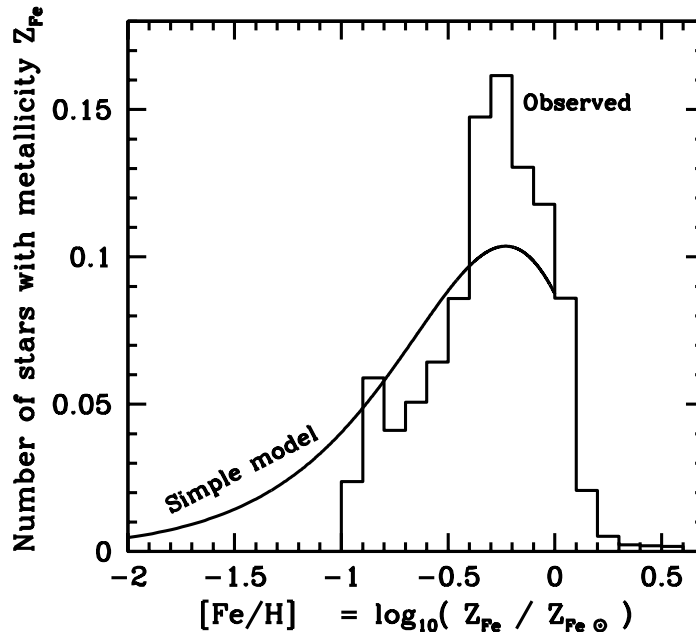
The figure below gives a comparison of the the predicted metallicity distribution of Equation 4.15 with observations of long-lived stars in the solar neighbourhood. The Simple Model prediction is found to be very different to the observed distribution. The Simple Model predicts a far larger proportion of metal-poor stars than are actually found. This has become known as the *G dwarf problem*.



The observed cumulative metallicity distribution for stars in the solar neighbourhood, compared with the Simple Model prediction for  $p = 0.010$  and  $Z_1 = Z_\odot = 0.017$ . [The observed distribution uses data from Kotoneva et al., M.N.R.A.S., 336, 879, 2002, for stars in the Hipparcos Catalogue.]

The differential metallicity distribution, representing simply a histogram of star numbers as a function of  $[\text{Fe}/\text{H}]$ , also shows the failure of the Simple Model prediction. This is shown in the figure below.





The observed differential metallicity distribution for stars in the solar neighbourhood, compared with the Simple Model prediction for  $p = 0.010$  and  $Z_1 = Z_{\odot} = 0.017$ . [The observed distribution uses data from Kotoneva et al., M.N.R.A.S., 336, 879, 2002, for stars in the Hipparcos Catalogue.]

Determining the metallicity distribution in galaxies outside our own is very difficult observationally. G dwarf stars are very faint in even the nearest Local Group galaxies.

## 4.7 Solutions to the G-Dwarf Problem

The G-dwarf problem indicates that the Simple Model is an oversimplification in the solar neighbourhood: one or more of the assumptions in Section 4.4 must be wrong. This is a very important result, but precisely which of the assumptions are wrong is difficult to say. A better fit to the observed data can be had by relaxing any of a number of the Simple Model assumptions. These include:

- the gas was not initially of zero metallicity;
- there has been an inflow of very metal-poor gas (this can help, but the value of the yield  $p$  must be adjusted);
- there has been a variable initial mass function (which could result in a change in the fraction  $\alpha$  of mass that remains locked up in long-lived stars, or in a change in the yield  $p$ );
- the samples of stars used to test the Simple Model are biased against low-metallicity stars (but considerable care is taken by observers to correct for these effects).

(The initial mass function is the number  $N$  of stars as a function of star mass  $M$  immediately following star formation. There is virtually no evidence that the initial mass function varied with time.)

One possible change to the Simple Model is to allow for a loss of gas from the volume. This is plausible, because supernovae following star formation could drive gas out of the region of the galaxy being studied. One possible prescription would be to set the outflow rate to be proportional to the rate of star formation. Therefore, the loss of gas from the volume in a time  $\delta t$  is  $c \delta M_{\text{stars}}$ , where  $c$  is a constant. In this case the total mass  $M_{\text{total}}$  in the volume varies with time, unlike in the Simple Model. However, it is found that a loss of enriched gas would make the G dwarf problem even worse: it reduces the quantity of enriched gas to make stars.

One modification to the Simple Model that can achieve a better fit between theoretical prediction and observations is to allow for the inflow of gas. This gas could be unprocessed, primordial gas. Analytic models of this type often set the inflow rate to be proportional to the star formation rate, so the inflow of gas in a time  $\delta t$  is  $c \delta M_{\text{stars}}$ , where  $c$  is a constant. This can produce a better fit between models and observations, provided the yield  $p$  is chosen appropriately.

## 4.8 Nucleosynthesis

The processes by which chemical elements are created are called *nucleosynthesis*. The elements produced in the hot, dense conditions in the Big Bang (hydrogen, helium and  $\text{Li}^7$ ) were created in *primordial nucleosynthesis*. Other isotopes and elements were produced by nucleosynthesis inside stars and in supernova explosions (including some additional helium).

The nuclear reactions responsible are complex and varied. The proton-proton chain is a series of reactions that fuse protons to form helium. In summary these reactions involve  $4\text{H}^1 \rightarrow \text{He}^4$  with the additional production of positrons, neutrinos and gamma rays. The carbon-nitrogen cycle and the carbon-nitrogen-oxygen bicycle also fuse protons to form  $\text{He}^4$  using pre-existing  $\text{C}^{12}$  in these reactions, creating N and O as (mostly) temporary byproducts which ultimately return to  $\text{C}^{12}$ . However, incomplete reactions in this series can leave behind some N, O and F.

Helium burning occurs in evolved red giant stars. In summary,  $3\text{He}^4 \rightarrow \text{C}^{12}$  through an intermediate stage involving  $\text{Be}^8$ . Reactions of this type can continue, with carbon burning and oxygen burning producing elements such as Mg and Si.

Another important process involves the capture of He nuclei by other nuclei, known as  $\alpha$ -capture (because the He nucleus is an  $\alpha$  particle). For example,  $\text{O}^{16} + \text{He}^4 \rightarrow \text{Ne}^{20}$ . Elements that are mainly in form of isotopes consisting of multiples of  $\alpha$  particles are known as  $\alpha$  elements and are relatively abundant.

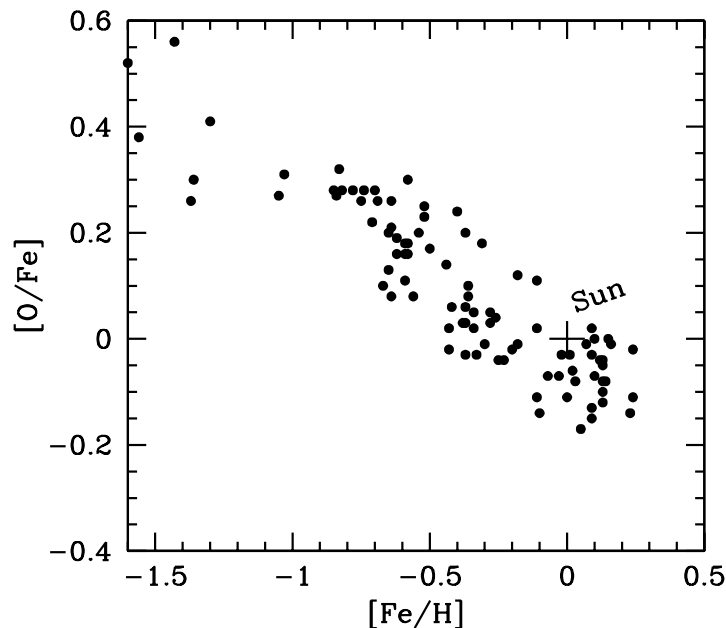
A number of isotopes are built up by *neutron capture* when neutrons are absorbed by nuclei, increasing the atomic mass by one unit. This is particularly important for very heavy elements where the large electrical charge of the nuclei makes reactions with protons and other nuclei difficult. Many heavy nuclei are unstable and decay through  $\beta$  decay (emitting an electron) soon after they are formed. There is an important distinction between the capture of neutrons by unstable nuclei depending on whether the capture takes place rapidly or slowly compared with the timescale for  $\beta$  decay. When neutron capture takes place slowly compared with the  $\beta$  decay time, it is said to take place through the *s-process*. The s-process is the main neutron capture process inside stars. Under extreme circumstances, such as in supernova explosions, neutron capture can occur rapidly compared to the  $\beta$  decay timescale and it is called the *r-process*. This happens when the flux of neutrons is very large.

Some isotopes are particularly stable, others disintegrate spontaneously through radioactive decay, while others are fragile in the high temperatures in stellar interiors (and participate readily in reactions with other nuclei, producing other isotopes). This stability/fragility affects the abundances of the elements produced during nucleosynthesis.

When the amount of an element produced by nucleosynthesis in stars does not depend on the abundances of elements in the gas that formed the stars, that element is said to be a *primary element*. On the other hand, if the amount of an element produced by nucleosynthesis does depend on the abundances in the gas that went into the star, the element is said to be a *secondary element*. For example, the amount of the isotope  $N^{14}$  produced in stars depends on the abundance of carbon in the gas that formed the stars: the more carbon, the more  $N^{14}$  can be formed as a minor byproduct of the CNO bicycle.

## 4.9 Element Abundance Ratios

The sections on chemical evolution above considered the changes in the overall metallicity  $Z$ . However, the abundances of individual elements provide very important additional information. The ratios of the abundances of individual elements, for example oxygen to iron or carbon to oxygen, have been determined by the details of nucleosynthesis and the enrichment of the interstellar medium over time, including how the relative quantities of these elements ejected into the interstellar gas has varied with time.



The  $[O/Fe]$  element abundance ratio plotted as a function of  $[Fe/H]$ . [Based on data from Edvardsson et al., *Astron. Astrophys.*, 275, 101, 1993, supplemented with data from Zhang & Zhao, *M.N.R.A.S.*, 364, 712, 2005.]

Chemical elements can be measured from the spectra of stars. Correlations are often found between abundance ratios. An important example is how the oxygen-to-iron ratio,  $[O/Fe]$ , varies with the iron-to-hydrogen ratio,  $[Fe/H]$ . Stars with metallicities similar to that of the Sun have, unsurprisingly,  $[O/Fe]$  values similar to the Sun. Metal-poor stars have  $[O/Fe]$  values that are larger than the Sun, with the  $[O/Fe]$  values increasing with decreasing  $[Fe/H]$  until a near-constant value is reached. The conventional interpretation of this is that the heavy metal enrichment that produced the material that went into very metal-poor stars was caused by type II supernovae predominantly. Type II supernovae occur soon after a burst of star formation (typically  $\sim 10^7$  yr after the burst of star formation) and produce large quantities of oxygen relative to iron. Therefore the material in very metal-poor stars had high values of  $[O/Fe]$ . Later ( $\gtrsim 10^8$  yr after the burst), type Ia supernovae produced larger quantities of iron compared with oxygen, reducing the oxygen-to-iron ratio in the interstellar gas, and increasing the  $[Fe/H]$  ratio. Later stars were therefore less metal-poor and had  $[O/Fe]$  values closer to the Sun.