Nucleosynthesis

1. Big Bang Nucleosynthesis

We can measure the metallicity and even individual abundances in stars and in the gas of galaxies. For the Milky Way and some nearby galaxies, we can measure these quantities for individual stars or nebulae, through emission or absorption. For more distant galaxies, we measure these quantities averaged over some or many stars and individual nebulae. It is possible to make the appropriate measurements of galaxies at high redshifts, up to $z \sim 2$ in the case of emission measures and up to $z \sim 6$ in the case of absorption signatures.

The elements are a signature of the process of nucleosynthesis. Originally the Universe contained to a good approximation only hydrogen and helium, and the existence of the rest of the elements depends on stellar processes of one sort or another.

The initial abundances were determined during Big Bang nucleosynthesis. At early times, the following reactions maintain equilibrium abundances between protons and neutrons.

$$\begin{aligned} p + e^- &\rightleftharpoons n + \nu \\ p + \bar{\nu} &\rightleftharpoons n + e^+ \end{aligned} \tag{1}$$

These reactions depend on having e^+ and e^- particles in abundance. At high temperatures, photons are pair-creating them (and they are annhilating). As the Universe cools, these reactions fall out of equilibrium approximately when $kT \sim m_e c^2$; at these temperatures, the electron-positron pairs will annhilate but not be replaced by pair-creating photons.

We can estimate the relative number of neutrons and photons at this stage with the Boltzmann factor:

$$\frac{n_{\mathrm{n}}}{n_{\mathrm{p}}} \sim \exp\left(-\Delta m_{\mathrm{np}} c^2 / kT\right) \sim \exp\left(-\Delta m_{\mathrm{np}} / m_e\right) \tag{2}$$

Since $m_{\mathrm{np}} \sim m_e$, this ratio is of order unity at freeze-out. More detailed calculations yield $n_{\mathrm{n}}/n_{\mathrm{p}} \sim 0.2$.

What happens subsequently is that the neutrons and protons undergo the following reactions:

$$\begin{aligned} n + p &\rightarrow {}^2H + \gamma \\ {}^2H + {}^2H &\rightarrow {}^3H + p \\ {}^3H + {}^2H &\rightarrow {}^4He + n \end{aligned} \tag{3}$$

These reactions proceed either until the universe is not dense and hot enough to sustain them, or until no neutrons are left to fuel them (since each cycle moves two neutrons into a helium nucleus). The exercises show that the maximum mass fraction of helium that can result (based on the starting number of neutrons) is about $Y = 0.33$. If the baryon density was very high this limit would be reached. In our universe, the baryon density is low and $Y \sim 0.25$.

The amount of other elements produced in this process is tiny. By mass the deuterium fraction is about 10^{-5}, and amounts of lithium and other light elements is even smaller. Deuterium is a key indicator, because its mass fraction depends on the baryon density; a higher baryon density produces less deuterium, because the processes above continue to completion more efficiently. Although deuterium can be destroyed in stellar processes later, it can be measured in relatively pristine environments and used as a baryon fraction indicator.

2. Stellar Nucleosynthesis

Starting with H and He, stellar processes build up the higher mass elements. These processes occur in stars during their lifetimes and are returned to the interstellar medium through stellar winds and supernovae. Substantial nucleosynthesis also occurs during supernovae. More exotic phenomena, such as neutron star mergers, can also create elements (such as r-process elements), and interactions in the interstellar medium with and among cosmic rays can also affect the abundance distribution. The outlines of the processes involved can be found in the classic paper of Burbridge, Burbridge, Fowler, & Hoyle (1957).

Nuclei are only stable within the isotopic stability band, with suitable combinations of neutrons and protons. Coulomb repulsion of protons makes it necessary to include around the same number (or more) of neutrons as protons. Typically multiple isotopes of a given element can be stable. The ratios of the isotopic abundances are set by the processes that created them.

In the plane of Z and N, several different processes can occur. The first is the set of nuclear fusion reactions, which are myriad. For example, the p-p chain and CNO cycle in stellar hydrogen burning produce helium.

A second is radioactive decay. Aside from very unstable massive atoms (e.g. plutonium-239) which can fission dramatically, the dominant processes are β-decay and α-decay:

- β^+-decay: $p \rightarrow n + e^+ + \nu_e$, which is $+1$ in N and -1 in Z.
- β^--decay: $p \rightarrow n + e^+ + \nu_e$, which is -1 in N and $+1$ in Z.
- α-decay: in which a nuclei emits an α particular, which is -2 in N and -2 in Z.

A third process important for massive elements is neutron capture.

The binding energy per nucleon along this band increases from H to ^{56}Fe, and then declines after that. This means that building iron out of H will extract energy, but nucleosynthesis beyond that cannot extract energy. The maxima in the binding energy are also related to the stability of those nuclei. Thus, ^{4}He is strongly favored relative to nearby nuclei. Li, Be, and B are easily destroyed. The α-elements ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}Ar and ^{40}Ca are quite stable and favored.

All of these features shape the resulting distribution of elements. Hydrogen ($X = 0.7$) and Helium ($Y = 0.28$) are the dominant elements. By mass, the remainder is only about $Z = 0.02$ in the Galactic neighborhood (roughly the solar abundance).

Then there is a gap with Li, Be, and B having very low abundances. They are easily destroyed in stars (though they are created by spallation in cosmic rays). Note that there is a serious problem associated with lithium; there is not enough ^{7}Li by a factor three or so (Fields 2012). D is more common; it is indeed one of the most powerful indicators that BBN is correct. Its abundance is also affected by stellar processes; it is very easily destroyed in stars.

In between C and Fe the α-elements dominate. The other elements here are often referred to as odd-Z elements. All of the elements here are produced primarily in massive stars in late stages of their evolution. They are returned to the interstellar medium through core-collapse supernovae, which eject the parts of the star outside the core. The supernova itself also modifies the elemental distribution, as we will see in a second. **need figure 5.9**

The Fe group elements show a broad peak. This peak shape corresponds roughly to thermodynamic equilibrium at 10^9 K or so. These conditions can occur in the shock emerging from a core-collapse supernova. However, it can also occur when a white dwarf detonates in a Type Ia supernova. In either case, a substantial fraction of the Fe results from producing unstable ^{56}Ni which decays into ^{56}Fe.

Finally, the elements beyond the Fe peak are formed mostly through neutron capture. There are two basic mechanisms under which this happens; under "slow" neutron flux or a "rapid" neutron flux. The s-process is found in AGB stars. The r-process is found in supernovae and neutron star mergers. r and s-process are characteristically different because of the set of isotopes that each nucleus passes through.

Under a slow neutron flux, the nucleus has time to return to the valley of stability, and so comes up the valley slowly. With a rapid flux, the nucleus hugs the neutron-rich edge of the valley; basically staying near where the neutron capture rate equals the β-decay rate. This leads to characteristic differences in r-process and s-process abundances, and even to certain elements being uniquely associated with one or the other. Particularly dramatically, there are certain magic numbers of neutrons for which nuclei are particularly resistant to neutron capture. s-process hits those magic numbers at higher-Z, where the nuclei are close to stable; there is a peak in the elemental distribution there. r-process hits those at lower Z, and then they decay up to the vallay; this creates a peak slightly lower in Z than the s-process. There are three main magic numbers that are important, $N = 50$, 82, and 126, leading to pairs of r and s peaks at $A = 80$, 90, at $A = 130$, 138, and at $A = 195$, 208.

For the Sun, its abundances seem to reflect a mix of α and Fe-peak elements that reflects contributions from both Type Ia supernovae and core collapse SNe.

3. Galaxy observations

From the point of view of measurements of external galaxies, α-elements and Fe are the main observable quantities in the stars. Rarer elements, particular r- and s-process, are hard to find in galaxy spectra; high resolution spectra are required for stars, but galaxies are intrinsically blurred so you cannot obtain true high resolution spectra.

The $[\alpha/Fe]$ abundance is especially informative. Core-collapse supernovae yield α-elements preferentially, and occur promptly after star formation. SN Ia yield Fe-peak elements preferentially, and occur with a range of delay times that can extend billions of years after star formation. Therefore, *α-rich* stellar populations are presumed to have resulted from a short burst of star formation, long enough for core collapse supernova to have enriched the star forming gas but not long enough for Type Ia supernovae to have enriched the star forming gas much. In contrast, *solar abundance* stellar populations likely reult from more extended star formation history.

For elliptical galaxies, the α-enrichment increases with luminosity. The metallicity of elliptical galaxies decreases as a function of galactocentric radius, but the α abundance relative to iron remains constant.

Within the Milky Way, the distribution of elements can be more accurately traced. In the Milky Way disk, the α-enrichment increases as position Z above the Galactic plane increases, and as galactocentric distance decreases; the metallicity decreases at the same time.

Modern observations of stars can trace 10–30 elements for hundreds of thousands of stars. One goal for these studies is known as *chemical tagging*: to use these detailed observations to connect different stars to the same nucleosynthetic history and thus presumably the same series of star formation events.

- *BBFH*
- *Pagel book*

4. Order-of-magnitude Exercises

1. Show that if $n_n/n_p \sim 0.2$ at the onset of Big Bang nucleosynthesis, that the maximum helium mass fraction in the universe that can be produced is $Y \sim 0.33$.
2. How much star formation needs to have occurred to produce the amount of metals?
3. What is the balance between Ia and CC that goes into solar abundance ratios?

5. Numerics and Data Exercises

1. Elliptical galaxy abundances vs mass

2. Elliptical galaxy abundances vs position

3. MW abundances vs position

4. Helium abundances at low metallicity

5. Deuterium observations at high redshift