Geochemistry

Notes V: Origin of the Elements

I. Temperature and Entropy (qualitative)
II. Solar and Cosmic abundances of the Elements
III. Moments after the Big Bang
IV. Nuclear reactions in stars
  A. Main sequence stars
  B. After the main sequence
  C. Red Giants
  D. Super novae

In order to have a qualitative understanding of the set of nuclear reactions that we will discuss, we need to understand two competing factors affecting nuclear reactions. (1) At higher temperature, matter with higher entropy is favored. (2) There is a tendency for matter to react so that binding energy is maximized.

Graphs of solar abundances of the elements have been constructed (see Figure 2.2 in your text). Solar abundances are equivalent to solar system abundances because the sun contains virtually all of the mass in the solar system. As it turns out solar abundances are also very similar to abundances in the average star, so that solar abundances are sometimes referred to as cosmic abundances. Solar abundances have been put together with data (Frauhofer lines) from the sun and from carbonaceous chondrites. The graph of solar abundances has a number of features that must be explained by any theory for the origin of the elements.

1. H is the most abundant element, followed closely by He.
2. There is a general trend to lower abundance with increasing Z.
3. Even Z elements have higher abundances than odd Z elements.
4. There is a relative maximum in abundance at Fe.

(see also expanded list on p.15, 16 of text).

The accepted idea for the origin of the elements is the formation of H and most He during the moments following the Big Bang and the formation of the other elements in stars. This general idea has support from the following sources:

1. H and He have much higher concentrations that the other elements and therefore could have been produced early, then used, in small part, as the raw materials for the higher Z elements.
2. Older stars have much lower concentrations of the elements other than H and He than younger stars.
3. Models of the Big Bang indicate very high temperatures initially, then rapidly falling temperatures. Conditions are hot long enough to form H and He, but not hot long enough to form appreciable quantities of heavier elements.
4. Our knowledge of nuclear reactions and conditions inside stars indicates that <u>fusion</u> reactions, the products of which are higher Z elements do take place in stars.

One second after the Big Bang, temperatures fell to 10^{10} K. Minutes later the temperature had fallen through 10^9 K. At about this temperature, atomic nuclei could form via the following reactions:

$p + n = {}^{2}H + \gamma$

${}^{2}H + {}^{2}H = {}^{3}H + p$

${}^{2}H + {}^{2}H = {}^{3}He + n$

${}^{3}He + n = {}^{4}He + \gamma$

${}^{3}H + p = {}^{4}He + \gamma$

However, temperatures fell too quickly (in minutes) for heavier elements to form. By mole, the predicted ratio of H/He is about 10. The fact that this is very close to the observed cosmic H/He ratio is support for the Big Bang Theory and models simulating the Big Bang.

Stars form when a large enough mass and mass density of gas and dust reach critical values so that material is pulled together by gravitational contraction. Our early solar system was a disk of high temperature rotating gas with most of the mass concentrated in the center as the sun. Besides the sun, the rest of the solar system formed from the cooling of this gas. As the gas cooled, solids formed from it. Those solids banged into each other, eventually forming among other objects, the planets and meteors (including carbonaceous chondrites).

The early solar system was hot because the potential energy from contraction is transformed largely into heat (gravitational energy). Stars initially are hot for the same reason. When temperatures and pressures get high enough fusion reactions commence, generating their own heat. It is important to understand the interplay between heat from these two sources (gravitational, fusion) in stars. For example the interior of a star initially is hot because of gravitational energy. As temperatures get high enough for fusion to take place, the star generates heat from fusion. Temperatures can rise causing expansion. Expansion causes heat to be transformed into gravitational potential energy, cooling the star.

As a star forms and temperatures (10^7 K) and pressures exceed critical values, hydrogen fusion begins (p.17):

$^{1}H + ^{1}H = ^{2}H + \beta^{+}$

$^{2}H + ^{1}H = ^{3}He + \gamma$

$^{3}He + ^{3}He = ^{4}He + ^{1}H + ^{1}H$

19.8 MeV released during whole process.

In younger stars, fusion can take place through the CNO cycle. The CNO cycle only takes place in younger stars that are made from the remnants of older stars because ^{12}C from these earlier stars is needed to start the cycle (p.17):

$^{12}C + ^{1}H = ^{13}N + \gamma$

$^{13}N = ^{13}C + \beta^{+}$

$^{13}C + ^{1}H = ^{14}N + \gamma$

$^{14}N + ^{1}H = ^{15}O + \gamma$

$^{15}O = ^{15}N + \beta^{+}$

$^{15}N + ^{1}H = ^{12}C + ^{4}He$

total: $4\ ^{1}H = ^{4}He + 3\gamma + 2\ \beta^{+}$

The CNO process occurs at a faster rate than standard H fusion, but also requires higher temperatures and ^{12}C present initially. Although both the CNO and H fusion process take place in the sun, the H fusion process is dominant. The CNO process is dominant in ^{12}C-bearing stars that are more massive than the sun, and therefore hotter.

Stars can be classified in a Hertzsprung-Russell (H-R) Diagram, which is a plot of luminosity (inherent or absolute) vs. surface temperature (see handout and Fig.2.1). A grouping of stars plotting diagonally across the figure is called the Main Sequence. All of these stars burn H through one or both of the processes described above. The most luminous of these are more massive, burn H faster and have short lifetimes (millions of years). The sun is a medium sized star that will stay on the Main Sequence for about 10 billion years (until 5 billion years from now). Smaller stars will stay on the main sequence for well over 10 billion years. What happens after H-burning is complete, depends on the mass of the star.

After the H in the core of a star has been converted to He (for our sun, about10 billion years from birth or about 5 billion years from now), the core cools as "H" burning slows. The cooling is accompanied by contraction, which causes heating (from the reduction of gravitational potential energy). This heats the core of the star, and when temperatures reach 10^8 K, the He "ash" left from the "burning" of H, itself begins to "burn". In the process of shifting from H "burning" to He "burning". Because He "burning" takes place at hotter temperatures than H "burning", heat transfer to the surface is more rapid. Thus, the outer layers of the star expand. The star leaves the main sequence and becomes a red giant. He-burning cannot take place in stars significantly less massive than the sun. He-burning reactions include:

$^{4}He + {}^{4}He = {}^{8}Be$

$^{8}Be + {}^{4}He = {}^{12}C$

(triple alpha process)

^{8}Be is radioactive with a half-life of 10^{-16} s, so the second reaction above needs to take place right away after the first is completed. Because of the triple alpha process, elements heavier than He can be produced. As ^{12}C builds up in the core of the star, the following reaction takes place:

$^{12}C + {}^{4}He = {}^{16}O$

Stars only burn He for about 1% of the time that they spent on the main sequence. When He is largely used up, in stars at least 4 times as massive as the sun, carbon and oxygen "burning" can take place at temperatures of 10^9 K. At this point, our sun will contract, heat rapidly, throw off its outer layers, and become a white dwarf. Carbon "burning" reactions include:

$$\begin{aligned} 2\,{}^{12}\mathrm{C} &= {}^{20}\mathrm{Ne} + {}^{4}\mathrm{He} \\ &= {}^{23}\mathrm{Na} + {}^{1}\mathrm{H} \\ &= {}^{23}\mathrm{Mg} + \mathrm{n} \\ &= {}^{24}\mathrm{Mg} + \gamma \end{aligned}$$

Oxygen burning reactions include:

$$\begin{aligned} 2\,{}^{16}\mathrm{O} &= {}^{28}\mathrm{Si} + {}^{4}\mathrm{He} \\ &= {}^{31}\mathrm{P} + {}^{1}\mathrm{H} \\ &= {}^{31}\mathrm{S} + \mathrm{n} \\ &= {}^{32}\mathrm{S} + \gamma \end{aligned}$$

When oxygen and carbon burning have been completed, Si burning may commence in stars massive enough to attain core temperatures of 3×10^9 K. At these temperatures, ^{4}He nuclei are released from some nuclei and are available to react with other nuclei.

$${}^{28}\mathrm{Si} + {}^{4}\mathrm{He} = {}^{32}\mathrm{S}$$
$${}^{32}\mathrm{S} + {}^{4}\mathrm{He} = {}^{36}\mathrm{Ar} \text{ and so on.}$$

In this way, elements as heavy as Fe can be produced. In the latter stages of a red giant's life, neutron fluxes may be high enough to produce isotopes of elements heavier than Fe by the "slow" or s-process (see Fig. 2.3).

Once no more energy can be obtained through Si "burning", the core of the star cools and contracts causing temperatures to rise. The rising temperatures cause the nuclei in the core to react to make smaller nuclei and nucleons. This absorbs energy causing catastrophic contraction (at up to 0.2 times the speed of light). The outer portion of the star bounces off a dense core and is ejected out into space as a tremendous explosion called a supernova. The r-process and p-process take place during this explosion.

The ejected material can then be re-cycled into another star. Stars that contain material from a supernova explosion are called "generation II" stars. Our sun is a "generation II" star as it is still on the main sequence (burning H), but contains heavy elements. Those elements could not have formed within the sun and therefore must have been formed in earlier stars.