Geol. 655 Isotope Geochemistry

lecture 3 Spring 2003

NUCLEOSYNTHESIS

A reasonable starting point for isotope geochemistry is a determination of the abundances of the naturally occurring nuclides. Indeed, this was the first task of isotope geochemists (though those engaged in this work would have referred to themselves simply as physicists). We noted this began with Thomson, who built the first mass spectrometer and discovered Ne consisted of 2 isotopes (actually, it consists of three, but one of them, ^{21}Ne is very much less abundant than the other two, and Thomson's primitive instrument did not detect it). Having determined the abundances of nuclides, it is natural to ask what accounts for this distribution, and even more fundamentally, what processes produced the elements. This process is known as nucleosynthesis.

The abundances of naturally occurring nuclides is now reasonably, though perhaps not perfectly, known. We also have what appears to be a reasonably successful theory of nucleosynthesis. Physicists, like all scientists, are attracted to simple theories. Not surprisingly then, the first ideas about nucleosynthesis attempted to explain the origin of the elements by single processes. Generally, these were thought to occur at the time of the Big Bang. None of these theories was successful. It was really the astronomers, accustomed to dealing with more complex phenomena than physicists, who successfully produced a theory of nucleosynthesis that involved a number of processes. Today, isotope geochemists continue to be involved in refining these ideas by examining and attempting to explain isotopic variations occurring in some meteorites.

The origin of the elements is an astronomical question, perhaps even more a cosmological one. To understand how the elements formed we need to understand a few astronomical observations and concepts. The universe began some 10 to 20 Ga ago with the Big Bang. Since then the universe has been expanding, cooling, and evolving. This hypothesis follows from two observations: the relationship between red-shift and distance and the cosmic background radiation, particularly the former. This cosmology provides two possibilities for formation of the elements: (1) they were formed in the Big Bang itself, or (2) they were subsequently produced. In actuality, both are involved.

Our present understanding of nucleosynthesis comes from three sorts of observations: (1) the abundance of isotopes and elements in the Earth, Solar System, and cosmos (spectral observations of stars), (2) experiments on nuclear reactions that determine what reactions are possible (or probable) under given conditions, and (3) inferences about possible sites of nucleosynthesis and about the conditions that would prevail in those sites. The abundances of the elements in the Solar System are shown in Figure 3.1.

Various hints came from all three of the above observations. For example, it was noted that the most abundant nuclide of a given set of stable isobars tended to be the most neutron-rich one. We now understand this to be a result of shielding from β^--decay (see the discussion of the r-process).

Another key piece of evidence regarding formation of the elements comes from looking back into the history of the cosmos. Astronomy is a bit like geology in that just as we learn about the evolution of the Earth by examining old rocks, we can learn about the evolution of the cosmos by looking at old stars. It turns out that old stars (such old stars are most abundant in the globular clusters outside the main disk of the Milky Way) are considerably poorer in heavy elements than are young stars. This suggests much of the heavy element inventory of the galaxy has been produced since these stars formed (some 10 Ga ago). On the other hand, they seem to have about the same He/H ratio as young stars. Indeed ^{4}He seems to have an abundance of 24-28% in all stars. Another key observation was the identification of Technetium emissions in the spectra of some stars. Since the most stable isotope of this element has a half-life of about 100,000 years, it must have been synthesized in the stars. Thus the observational evidence suggests (1) H and He are everywhere uniform implying their creation and fixing of the He/H ratio in the Big Bang and (2) subsequent creation of heavier elements (heavier than Li, as we shall see) by subsequent processes.

As we mentioned, early attempts (~1930–1950) to understand nucleosynthesis focused on single mechanisms. Failure to find a single mechanism that could explain the observed abundance of nuclides, even under varying conditions, led to the present view that relies on a number of mechanisms

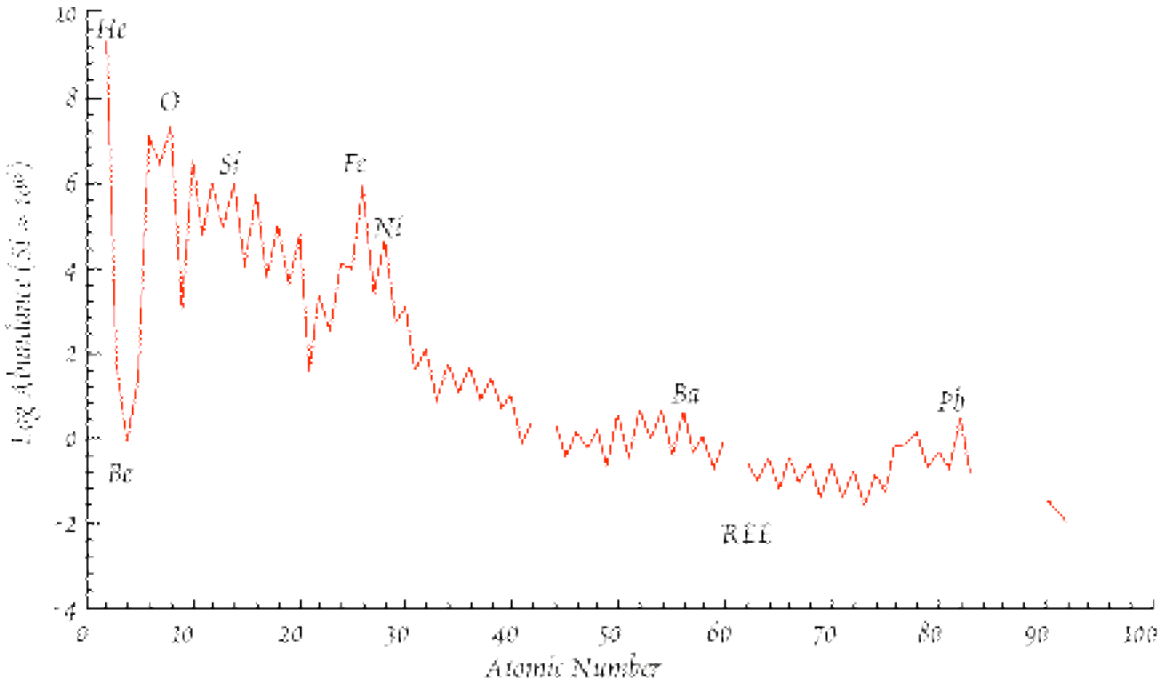


Figure 3.1. Solar system abundance of the elements relative to silicon as a function of atomic number.

operating in different environments and at different times for creation of the elements in their observed abundances. This view, often called the polygenetic hypothesis, is based mainly on the work of Burbidge, Burbidge, Fowler and Hoyle. Their classic paper summarizing the theory, "Synthesis of the Elements in Stars" was published in *Reviews of Modern Physics* in 1956. Interestingly, the abundance of trace elements and their isotopic compositions, were perhaps the most critical observations in development of the theory. An objection to this polygenetic scenario was the apparent uniformity of the isotopic composition of the elements. But variations in the isotopic composition have now been demonstrated for many elements in some meteorites. The isotopic compositions of other elements, such as oxygen and the rare gases, vary between classes of almost all meteorites. Furthermore, there are quite significant compositional variations in heavier elements among stars. These observations provide strong support for this theory.

To briefly summarize it, the polygenetic hypothesis proposes four phases of nucleosynthesis. *Cosmological nucleosynthesis* occurred shortly after the universe began and is responsible for the cosmic inventory of H and He, and some of the Li. Helium is the main product of nucleosynthesis in the interiors of normal, or "main sequence" stars. The lighter elements, up to and including Si, but excluding Li and Be, and a fraction of the heavier elements may be synthesized in the interiors of larger stars during the final stages of their evolution (*stellar nucleosynthesis*). The synthesis of the remaining elements occurs as large stars exhaust the nuclear fuel in their interiors and explode in nature's grandest spectacle, the supernova (*explosive nucleosynthesis*). Finally, Li and Be are continually produced in interstellar space by interaction of cosmic rays with matter (*galactic nucleosynthesis*). In the following sections, we examine these nucleosynthetic processes as presently understood.

COSMOLOGICAL NUCLEOSYNTHESIS

Immediately after the Big Bang, the universe was too hot for any matter to exist. But after a second or so, it had cooled to 10^{10} K so that a few protons and neutrons existed in an equilibrium dictated by the following reactions:

$$^1H + e^- \rightleftarrows n + \nu \quad \text{and} \quad n + e^+ \rightleftarrows {}^1H + \nu^\dagger$$

A somewhat worrisome question is why matter exists at all. Symmetry would seem to require production of equal number of protons and anti-protons that would have annihilated themselves by:

$$p + \bar{p} \rightarrow 2\gamma^*$$

The current theory is that the hyperweak force was responsible for an imbalance favoring matter over anti-matter. The same theory predicts a half-life of the proton of 10^{32} yrs.

It took another 3 minutes to for the universe to cool to 10^9 K, which is cool enough for ^2H, created by

$$^1H + {}^1n \rightarrow {}^2H + \gamma$$

to be stable. At about the same time, the following reactions could also occur:

$$^2H + {}^1n \rightarrow {}^3H + \gamma; \quad ^2H + {}^1H \rightarrow {}^3H + \gamma$$

$$^2H + {}^1H \rightarrow {}^3He + e^+ + \nu; \quad ^3He + n \rightarrow {}^4He + \gamma$$

and

$$^3He + {}^4He \rightarrow {}^7Be + \gamma; \quad ^7Be + e^- \rightarrow {}^7Li + \nu$$

About 24% of the mass of the universe was converted to ^4He in this way; less than 0.01% was converted to ^2H, ^3He, and ^7Li (and there is good agreement between theory and observation). Formation of elements heavier than Li was inhibited by the instability of nuclei of masses 5 and 8. Shortly afterward, the universe cooled below 10^9 K and nuclear reactions were no longer possible. Any free neutrons decayed away (neutrons outside the nucleus are unstable, having a half-life of 10 min). Thus the Big Bang created H, He and Li ($^7Li/H < 10^{-9}$). Some 300,000 years later, the universe had cooled to about 3000 K, cool enough for electrons to be bound to nuclei, forming atoms. It was at this time, called the "recombination era" that the universe first became transparent to radiation Prior to that, photons were scattered by the free electrons, making the universe opaque. It is the radiation emitted during this recombination that makes up the cosmic microwave background radiation that we can still detect today.

STELLAR NUCLEOSYNTHESIS

Astronomical Background

Before discussing nucleosynthesis in stars, it is useful to review a few basics of astronomy. Stars shine because of exothermic nuclear reactions occurring in their cores. The energy released by these processes creates a tendency for thermal expansion that, in general, exactly balances the tendency for gravitational collapse. Surface temperatures are very much cooler than temperatures in stellar cores. For example, the Sun, which is in almost every respect an average star, has a surface temperature of 5700 K and a core temperature thought to be 14,000,000 K.

Stars are classified based on their color (and spectral absorption lines), which in turn is related to their temperature. From hot to cold, the classification is: O, B, F, G, K, M, with subclasses designated by numbers, e.g., F5. (The mnemonic is '*O Be a Fine Girl, Kiss Me!*'). The Sun is class G. Stars are also divided into Populations. Population I stars are second or later generation stars and have greater heavy element contents than Population II stars. Population I stars are generally located in the main disk of the galaxy, whereas the old first generation stars of Population II occur mainly in globular clusters that circle the main disk.

On a plot of luminosity versus wavelength of their principal emissions (i.e., color), called a Hertzsprung-Russell diagram (Figure 3.2), most stars (about 90%) fall along an array defining an inverse correlation between these two properties. Since wavelength is inversely related to temperature, this correlation means simply that hot stars give off more energy (are more luminous) than cooler stars. Mass and radius are also simply related to temperature for these so-called "main sequence" stars; hot stars are big, small stars are cooler. Thus O and B stars are large, luminous, and

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† The ν (nu) is the symbol for a neutrino.

* γ (gamma) is used here to symbolized energy in the form of a gamma ray.

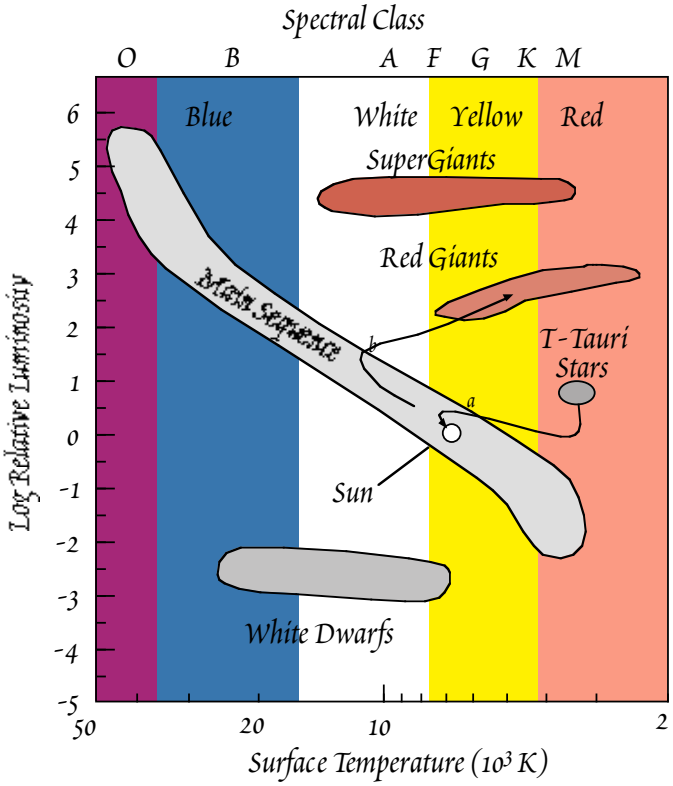


Figure 3.2. The Hertzsprung-Russell diagram of the relationship between luminosity and surface temperature. Arrows show evolutionary path for a star the size of the Sun in pre- (a) and post- (b) main sequence phases.

hot; K and M stars are small, cool, and (comparatively speaking) dark. Stars on the main sequence produce energy by 'hydrogen burning', fusion of hydrogen to produce helium. Since the rate at which these reactions occur depends on temperature and density, hot, massive stars release more energy than smaller ones. As a result, they exhaust the hydrogen in their cores much more rapidly. Thus there is an inverse relationship between the lifetime of a star, or at least the time it spends on the main sequence, and its mass. The most massive stars, up to 100 solar masses, have life expectancies of only about 10^6 years, whereas small stars, as small as 0.01 solar masses, remain on the main sequence more than 10^{10} years.

The two most important exceptions to the main sequence stars, the red giants and the white dwarfs, represent stars that have burned all the H fuel in their cores and have moved on in the evolutionary sequence. When the H in the core is converted to He, it generally cannot be replenished because the density difference prevents convection between the core and out layers, which are still H rich. The interior part of the core collapses under gravity. With enough collapse, the layer immediately above the He core will begin to 'burn' H again, which again stabilizes the star. The core, however, continues to collapse until T and P are great enough for He burning to begin. At the same time, and for reasons not fully understood, the exterior expands and cools, resulting in a *red giant*, a star that is over-luminous relative to main sequence stars of the same color. When the Sun reaches this phase, in perhaps another 5 Ga, it will expand to the Earth's orbit. A star will remain in the red giant phase for of the order of 10^6–10^8 years. During this time, radiation pressure results in a greatly enhanced solar wind, of the order of 10^{-6} to 10^{-7}, or even 10^{-4}, solar masses per years (the Sun's solar wind is 10^{-14} solar masses; i.e., in its entire lifetime, the Sun will blow off 1/10,000 of its mass through solar wind).

The fate of stars after the red giant phase (when the He in the core is exhausted) depends on their mass. Nuclear reactions in small stars cease and they simply contract, their exteriors heating up as they do so, to become *white dwarfs*. The energy released is that produced by previous nuclear reactions and released gravitational potential energy. This is the likely fate of the Sun. White Dwarfs are underluminous relative to stars of similar color on the main sequence. They can be thought of as little more than glowing ashes. Unless they blow off sufficient mass during the red giant phase, stars larger than 1.5 solar masses die explosively, in supernovae. (Novae are entirely different events which occur in binary systems when mass from a main sequence star is pull by gravity onto a white dwarf companion). Supernovae are incredibly energetic events. The energy released by a supernova can exceed that released by an entire galaxy (which, it will be recalled, consists of on the order of 10^9 stars) for a period of days or weeks!

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Nucleosynthesis in Stellar Interiors

Hydrogen, Helium, and Carbon Burning in Main Sequence and Red Giant Stars

For quite some time after the Big Bang, the universe was a more or less homogeneous, hot gas. More or less turns out to be critical wording. Inevitably (according to fluid dynamics), inhomogeneities in the gas developed. These inhomogeneities enlarged in a sort of runaway process of gravitational attraction and collapse. Thus were formed protogalaxies, thought to date to about 0.5-1.0 Ga after the big bang. Instabilities within the protogalaxies collapsed into stars. Once this collapse proceeds to the point where density reaches 6 g/cm and temperature reaches 10 to 20 million K, nucleosynthesis begins in the interior of stars, by *hydrogen burning*, or the *pp process*. There are three variants,

PP I:

$$^{1}H + {}^{1}H \rightarrow {}^{2}H + \beta^{+} + \nu; \quad {}^{2}H + {}^{1}H \rightarrow {}^{3}He + \gamma; \quad \text{and} \quad {}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2{}^{1}H + \gamma$$

PP II:

$$^{3}He + {}^{4}He \rightarrow {}^{7}Be; \quad {}^{7}Be \rightarrow \beta^{-} + {}^{7}Li + \nu; \quad {}^{7}Li + {}^{1}H \rightarrow 2{}^{4}He$$

and PP III:

$$^{7}Be + {}^{1}H \rightarrow {}^{8}B + \gamma; \quad {}^{8}B \rightarrow \beta^{+} + {}^{8}Be + \nu; \quad {}^{8}Be \rightarrow 2{}^{4}He$$

Which of these reactions dominates depends on temperature. The net result of all three reactions is the production of ^{4}He and the consumption of H as well as Li and B. All main sequence stars produce He, yet over the history of the cosmos, this has had little impact on the H/He ratio of the universe. This in part reflects the observation that for small mass stars, the He produced remains hidden in their interiors or their white dwarf remnants and for large mass stars, later reactions consume the He produced in the main sequence stage.

Once some carbon had been produced by the first generation of stars and supernovae, second and subsequent generation stars with masses greater than about 1.1 solar masses produced He by another process as well, the *CNO cycle*:

$$^{12}C(p,\gamma)\,^{13}N(\beta^{+},\nu)\,^{13}C(p,\gamma)\,^{14}N(p,\gamma)\,^{15}O(\beta^{+},\nu)\,^{15}N(p,\alpha)\,^{12}C^{\ddagger}$$

It was subsequently realized that this reaction cycle is just part of a larger reaction cycle, which is illustrated in Figure 3.3. Since the process is cyclic, the net effect is consumption of 4 protons and two positrons to produce a neutrino, some energy, and a ^{4}He nucleus. Thus to a first approximation, carbon

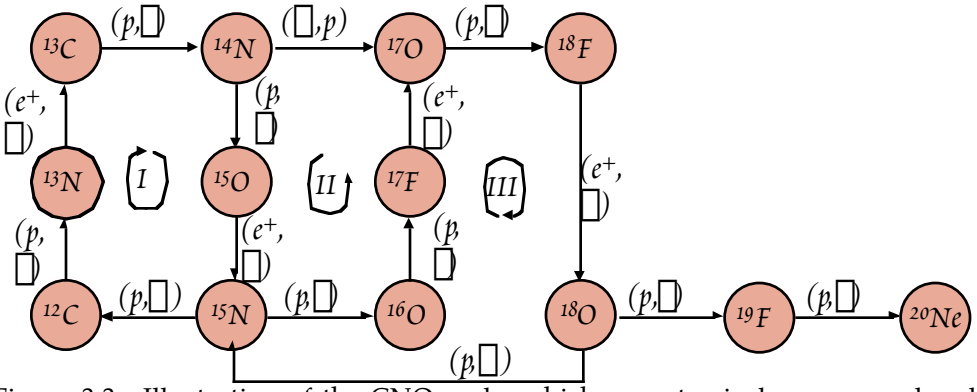


Figure 3.3. Illustration of the CNO cycle, which operates in larger second and later generation stars.

‡ Here we are using a notation commonly used in nuclear physics. The reaction:

$$^{12}C(p,\gamma)^{13}N$$

acts as a type of nuclear catalyst in this cycle: it is neither produced nor consumed. When we consider these reaction's in more detail, not all of them operate at the same rate, resulting in some production and some consumption of these heavier nuclides. The net production of a nuclide can be expressed as:

$$\frac{dN}{dt} = \text{(creation rate) - (destruction rate)}$$

Reaction rates are such that some nuclides in this cycle are created more rapidly than they are consumed, while for others the opposite is true. The slowest of the reactions in Cycle I is $^{14}N(p,\gamma)^{15}O$. As a result, there is a production of ^{14}N in the cycle and net consumption of C and O. The CNO cycle will also tend to leave remaining carbon in the ratio of $^{13}C/^{12}C$ of 0.25. This is quite different than the solar system (and terrestrial) abundance ratio of about 0.01.

The heat produced by these reactions counterbalances gravitational collapse and these reactions proceed in main sequence stars until the H in the stellar core is consumed. How quickly this happens depends on the mass of the star. Massive stars can consume their nuclear fuel in as little as 10^6 years. A small to moderate size star such as the Sun will remain on the main sequence for 10^{10} years.

Once the H is exhausted in the stellar core, fusion ceases, and the balance between gravitational collapse and thermal expansion is broken. The interior of the star thus collapses, raising the star's temperature. The increase in temperature results in expansion of the exterior and ignition of fusion in the shells surrounding the core that now consists of He. This is the *red giant* phase. Red giants may have diameters of hundreds of millions of kilometers (greater than the diameter of Earth's orbit). If the star is massive enough for temperatures to reach 10^8 K and density to reach 10^4 g/cc in the He core, *He burning* can occur:

$$^4He + {}^4He \rightarrow {}^8Be + \gamma \qquad \text{and} \qquad {}^8Be + {}^4He \rightarrow {}^{12}C + \gamma$$

The catch in these reactions is that the half-life of ^8Be is only 7×10^{-16} sec, so 3 He nuclei must collide essentially simultaneously, hence densities must be very high. Depending on the mass of the star the red giant phase can last for as much as hundred million years or as little as a few hundred thousand years, as a new equilibrium between gravitational collapse and thermal expansion sets in. Helium burning, in which He fuses with ^{12}C, also produces ^{16}O, and upon the addition of further He nuclei, ^{20}Ne and ^{24}Mg. Also, ^{14}N created during the hydrogen burning phase of second generation stars can be converted to ^{22}Ne. But note that Li, Be and B have been skipped: they are not synthesized in these phases of stellar evolution. Indeed, they are actually consumed in stars, in reactions such as PP II and PP III.

Evolution for low-mass stars, such as the Sun, ends after the Red Giant phase and helium burning. Densities and temperatures necessary to initiate further nuclear reactions cannot be achieved because the gravitational force is not sufficient to overcome coulomb repulsion of electrons. Thus nuclear reactions cease and radiation is produced only by a slow cooling and grav-

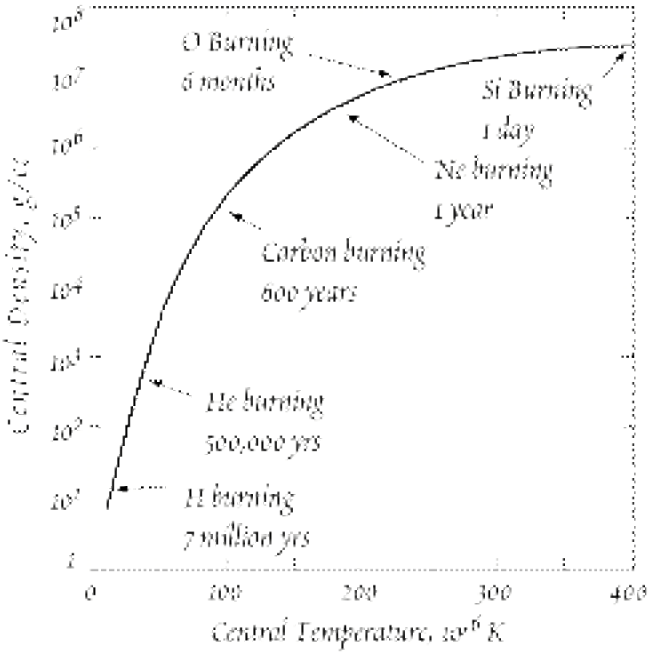


Figure 3.4. Evolutionary path of the core of star of 25 solar masses (after Bethe and Brown, 1985). Note that the period spent in each phase depends on the mass of the star: massive stars evolve more rapidly.

is equivalent to: $^{12}C + p \rightarrow {}^{13}N + \gamma$

itational collapse. Massive stars, those greater than about 1.5 solar masses, however, undergo further collapse and further evolution. Evolution now proceeds at an exponentially increasing pace (Figure 3.4), and these phases are poorly understood. But if temperatures reach 600 million K and densities 5 x 10^5 g/cc, carbon burning becomes possible:

$$^{12}C + {}^{12}C \rightarrow {}^{20}Ne + {}^{4}He + \gamma$$

The carbon burning phase marks a critical juncture in stellar evolution. As we mentioned, low mass stars never reach this point. Intermediate mass stars, those with 4-8 solar masses can be catastrophically disrupted by the ignition of carbon burning. But in large stars, the sequence of production of heavier and heavier nuclei continues. After carbon burning, there is an episode called Ne burning, in which ^{20}Ne is decomposed by ($\gamma\alpha$) reactions. The γ's are consumed by those nuclei present, including ^{20}Ne. The next phase is oxygen burning, which involves reactions such as:

$$^{16}O + {}^{16}O \rightarrow {}^{28}Si + {}^{4}He + \gamma \quad \text{and} \quad {}^{12}C + {}^{16}O \rightarrow {}^{24}Mg + {}^{4}He + \gamma$$

A number of other less abundant nuclei, including Na, Al, P, S and K are also synthesized at this time, and in the subsequent process, Ne burning.

During the final stages of evolution of massive stars, a significant fraction of the energy released is carried off by neutrinos created by electron-positron annihilations in the core of the star. If the star is sufficiently oxygen-poor that its outer shells are reasonably transparent, the outer shell of the red giant may collapse during last few 10^4 years of evolution to form a *blue giant*.

The e-process

Eventually, a new core consisting mainly of ^{28}Si is produced. At temperatures near 10^9 K and densities above 10^7 g/cc a process known as *silicon burning*, or the *e process*, (for equilibrium) begins, and lasts for days or less, again depending on the mass of the star. These are reactions of the type:

$$^{28}Si + \gamma \rightleftarrows {}^{24}Ne + {}^{4}He$$
$$^{28}Si + {}^{4}He \rightleftarrows {}^{32}S + \gamma$$
$$^{32}S + {}^{14}He \rightleftarrows {}^{36}Ar + \gamma$$

While these reactions can go either direction, there is some tendency for the build up of heavier nuclei with masses 32, 36, 40, 44, 48, 52 and 56. Partly as a result of the e-process, these nuclei are unusually abundant in nature. In addition, because of a variety of nuclei produced during C and Si burning phases, other reactions are possible, synthesizing a number of minor nuclei. The star is now a cosmic onion of sorts (Figure 3.5), consisting of a series of shells of successively heavier nuclei and a core of Fe. Though temperature increases toward the interior of the star, the structure is stabilized with respective to convection and mixing because the each shell is denser than the one overlying it.

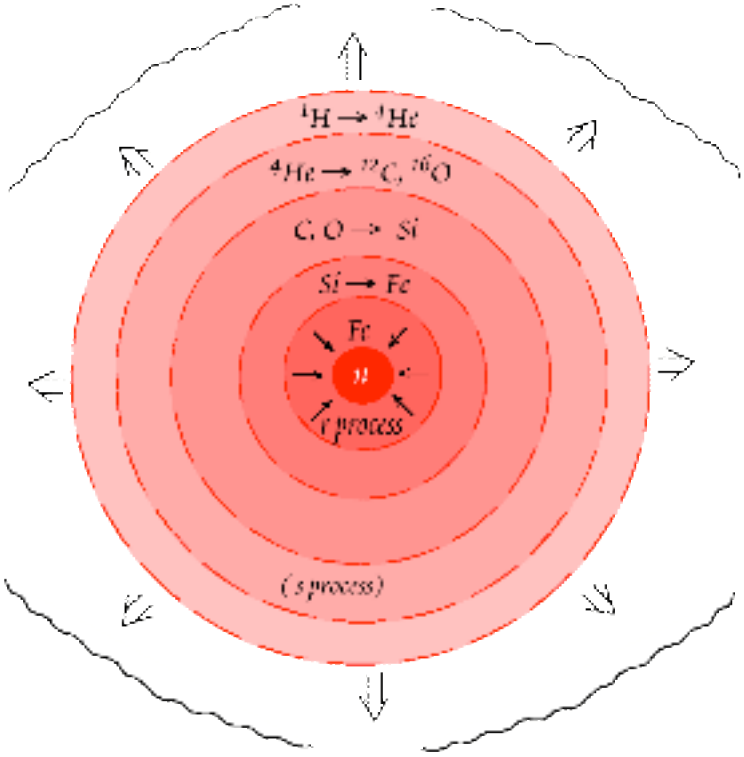


Figure 3.5. Schematic diagram of stellar structure at the onset of the supernova stage. Nuclear burning processes are illustrated for each stage.

Fe-group elements may also be synthesized by the e-process in Type I supernovae. Type I supernovae occur when white dwarfs of intermediate

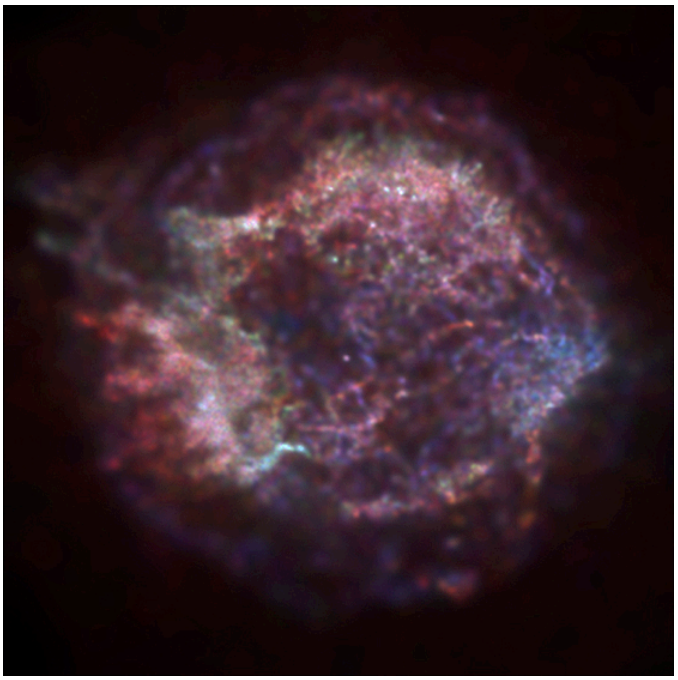


Figure 3.6. Chandra X-ray image of the supernova remnant Cassiopeia A (Cas A). The red, green, and blue regions in this Chandra X-ray image of the supernova remnant Cassiopeia A show where the intensity of low, medium, and high energy X-rays, respectively, is greatest. The red material on the left outer edge is enriched in iron, whereas the bright greenish white region on the lower left is enriched in silicon and sulfur. In the blue region on the right edge, low and medium energy X-rays have been filtered out by a cloud of dust and gas in the remnant.

mass (3-10 solar masses) stars in binary systems accrete material from their companion. When their cores reach the Chandrasekhar limit, C burning is initiated and the star explodes. This theoretical scenario has been confirmed in recent years by space based optical, gamma-ray, and x-ray observations of supernovae, such as the Chandra X-ray observatory image in Figure 3.6.

The s-process

In second and later generation stars containing heavy elements, yet another nucleosynthetic process can operate. This is the slow neutron capture or *s-process*. It is so called because the rate of capture of neutrons is slow, compared to the *r-process*, which we will discuss below. It operates mainly in the red giant phase (as evidenced by the existence of ^{99}Tc and enhanced abundances of several s-process elements) where neutrons are produced by reactions such as:

$$^{13}C + {}^{4}He \rightarrow {}^{16}O + {}^{1}n$$

$$^{22}Ne + {}^{4}He \rightarrow {}^{25}Mg + {}^{1}n$$

$$^{17}O + {}^{4}He \rightarrow {}^{20}Ne + {}^{1}n$$

(but even H burning produces neutrons; one consequence of this is that fusion reactors will not be completely free of radiation hazards). These neutrons are captured by nuclei to produce successively heavier elements. The principle difference between the r and s process is the rate of capture relative to the decay of unstable isotopes. In the s-process, a nucleus may only capture a neutron every thousand years or so. If the newly produced nucleus is not stable, it will decay before another neutron is captured. As a result, instabilities cannot be bridged as they can in the r-process discussed below. In the s-process, the rate of formation of stable species is given by

$$\frac{d[A]}{dt} = f[A-1]\sigma_{A-1}$$

where [A] is the abundance of a nuclide with mass number A, f is a function of neutron flux and neutron energies, and σ is the neutron-capture cross section. Note that a nuclide with one less proton might contribute to this build up of nuclide A, provided that the isobar of A with one more neutron is not stable. The rate of consumption by neutron capture is:

$$\frac{d[A]}{dt} = -f[A]\sigma_{A}$$

From these relations we can deduce that the ratio creation of two nuclides with mass numbers A and A-1 will be proportional to the ratio of their capture cross sections:

$$\frac{[A]}{[A-1]} = \frac{\sigma_{A-1}}{\sigma_A}$$

Here we can see that the s-process will lead to the observed odd-even differences in abundance since nuclides with odd mass numbers tend to have larger capture-cross sections than even mass number nuclides. The s-process also explains why magic number nuclides are particularly abundant. This is because they tend to have small cross-sections and hence are less likely to be consumed in the s-process. The r-process, which we discuss below, leads to a general enrichment in nuclides with N up to 6 to 8 greater than a magic number, but not to a build up of nuclides with magic numbers. That the s-process occurs in red giants is confirmed by the overabundance of elements with mainly s-process nuclides, such as those with magic N, in the spectra of such stars. On the other hand, such stars appear to have normal concentrations of elements with 25< A <75, and do show normal abundances of r-only elements. Some, however, have very different abundances of the lighter elements, such as C and N than the Sun.

EXPLOSIVE NUCLEOSYNTHESIS

The r-process

The e-process stops at mass 56. In an earlier lecture, we noted that ^{56}Fe had the highest binding energy per nucleon, i.e. it is the most stable nucleus. Fusion can release energy only up to mass 56; beyond this the reactions become endothermic, i.e. they absorb energy. Thus once the stellar core has been largely converted to Fe, a critical phase is reached: the balance between thermal expansion and gravitation collapse is broken. The stage is now set for the most spectacular of all natural phenomena: a supernova explosion, the ultimate fate of large stars. The energy released in the supernova is astounding. In its first 10 seconds, the 1987A supernova released more energy than the entire visible universe, 100 times more energy than the Sun will release in its entire 10 billion year lifetime.

When the mass of the iron core reaches 1.4 solar masses (the Chandrasekhar mass), further gravitational collapse cannot be resisted even by coulomb repulsion. The supernova begins with the col-

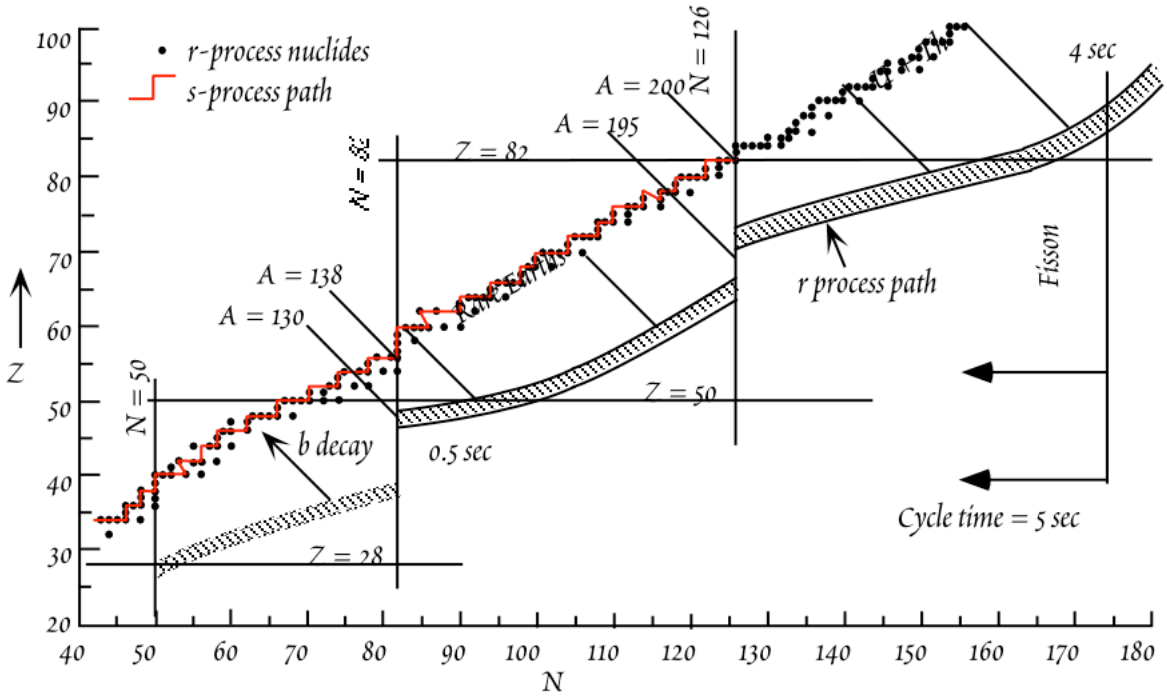


Figure 3.7. Diagram of the r process path on a Z vs. N diagram. Dashed region is r-process path; solid line through stable isotopes shows the s-process path.

lapse of this stellar core, which would have a radius similar to that of the Earth's before collapse, to a radius of 100 km or so. This occurs in a few tenths of a second. As matter in the center of the core is compressed beyond the density of nuclear matter (3×10^{14} g/cc), it rebounds, sending a massive shock wave back out less than a second after the collapse begins. As the shock wave travels outward through the core, the temperature increase resulting from the compression produces a break down of nuclei by photodisintegration, e.g.:

$$^{56}\mathrm{Fe} + \gamma \rightarrow 13\,^{4}\mathrm{He} + 4\,^{1}\mathrm{n}; \quad ^{4}\mathrm{He} + \gamma \rightarrow 2\,^{1}\mathrm{H} + 2\,^{1}\mathrm{n}$$

This results in the production of a large number of free neutrons (and protons), which is the important result. The neutrons are captured by those nuclei that manage to survive this hell. In the core itself, the reactions are endothermic, and thermal energy cannot overcome the gravitational energy, so it continues to collapse. If the original mass of the star is > 4 solar masses, the result is a neutron star, in which all matter is compressed into neutrons. Supernova remnants of masses greater than 8 solar masses can collapse to produce a singularity, where density is infinite. A supernova remnant having the mass of the sun would form a neutron star of only 15 km radius. A singularity of similar mass would be surrounded by a black hole, a region whose gravity field is so intense even light cannot escape, with a radius of 3 km.

Another important effect is the creation of huge numbers of neutrinos by positron-electron annihilations, which in turn had "condensed" as pairs from gamma rays. The energy carried away by neutrino leaving the supernova exceeds the kinetic energy of the explosion by a factor of several hundred, and exceeds the visible radiation by a factor of some 30,000. The neutrinos leave the core at nearly the speed of light. Though neutrinos, which travel at nearly the speed of light, interact with matter very weakly, the density of the core is such that their departure is delayed slightly. Nevertheless, they travel faster than the shock wave and are delayed less than electromagnetic radiation. Thus neutrinos from the 1987A supernova arrived at Earth (some 160,000 years after the event) a few hours before the supernova became visible.

The shock wave eventually reaches the surface of the core, and the outer part of the star is blown apart in an explosion of unimaginable violence. Amidst the destruction new nucleosynthetic processes are occurring.

This first of these is the *r process* (rapid neutron capture), and is the principle mechanism for building up the heavier nuclei. In the r-process, the rate at which nuclei with mass number A+1 are created by capture of a neutron by nuclei with mass number A can be expressed simply as:

$$N_A \sigma_A f$$

where N_A is the number of nuclei with mass number A, σ is the neutron capture cross section and f is the neutron flux. If the product nuclide is unstable, it will decay at a rate given by λN_{A+1}. It will also capture neutrons itself, so the total destruction rate is given by

$$\lambda N_{A+1} + N_{A+1} \sigma_{A+1} f$$

An equilibrium distribution occurs when nuclei are created at the same rate as they are destroyed, i.e.:

$$N_A \sigma_A F = \lambda N_{A+1} + N_{A+1} \sigma_{A+1} f$$

Thus the equilibrium ratio of two nuclides A and A+1 is:

$$N_A / N_{A+1} = (\lambda + \sigma_{A+1} F) / \sigma_A f$$

Eventually, some nuclei capture enough neutrons that they are not stable even for short periods (in terms of the above equation, λ becomes large, hence N_A/N_{A+1} becomes large). They β^- decay to new elements, which are more stable and capable of capturing more neutrons. This process reaches a limit when nuclei beyond Z = 90 are reached. These nuclei fission into several lighter fragments. The r-process is thought to have a duration of 1 to 100 sec during the peak of the supernova explosion. Figure 3.7 illustrates this process.

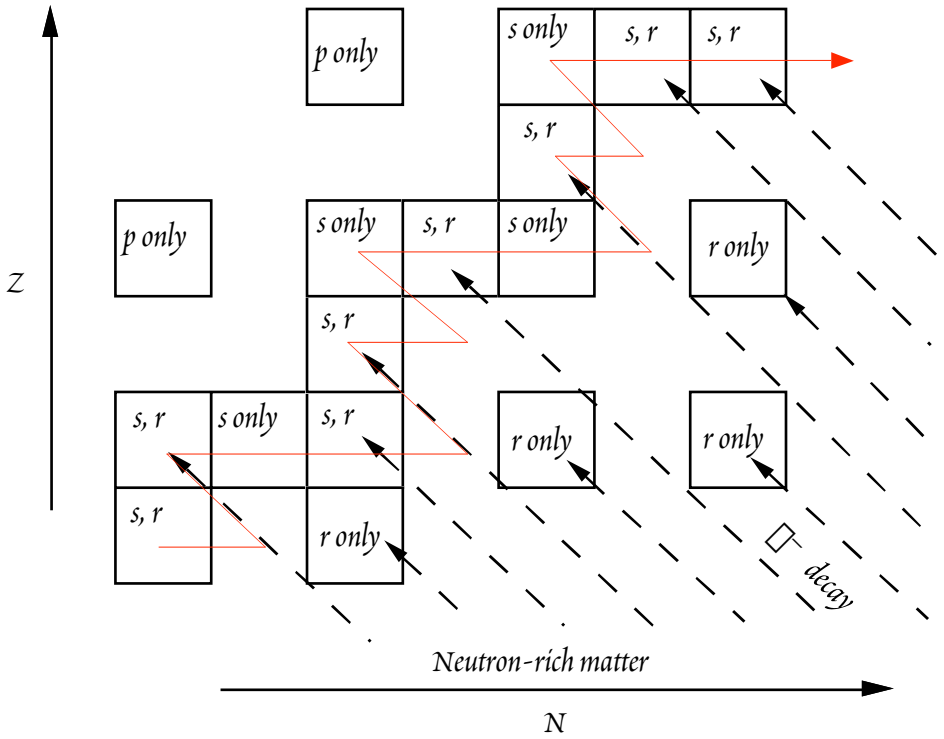


Figure 3.8. Z vs. N diagram showing production of isotopes by the r- s- and processes. Squares are stable nuclei; wavy lines are beta-decay path of neutron-rich isotopes produced by the r-process; solid line through stable isotopes shows the s-process path.

Note that there is no reason why the r-process should lead to different abundances of stable odd and even nuclides. During the r-process, temperatures are so high that capture cross section of odd- and even-mass nuclides are similar and the neutron density is so great that all nuclei will likely capture a number of neutrons. And in the extreme temperatures, all nuclei are in excited states, and relatively little systematic difference is expected in the capture cross-sections of odd and even nuclei.

That the r-process occurs in supernovae is confirmed by the observation of □-rays from short-lived radionuclides.

The p-process

The r-process tends to form the heavier isotopes of a given element. The *p-process* (proton capture) also operates in supernovae and is responsible for the lightest isotopes of a given element. The probability of proton capture is much less likely than neutron capture. The reason should be obvious. To be captured the proton must have sufficient energy to overcome the coulomb repulsion and approach to within 10^{-13} cm of the nucleus where the strong nuclear force dominates over the electromagnetic one. Since the neutron is uncharged, there is no coulomb repulsion and even low energy neutron can be captured. As a result, light, p-process only isotopes tend to be the least abundant.

Figure 3.8 illustrates how the s- r- and p-processes create different nuclei. Note also the shielding effect. If a given isotope with z protons and n neutrons, a stable neighbor exists with n+x neutrons and p-x protons, this isotope is shielded from production by the r-process. The most abundant isotopes will be those created by all processes; the least abundant will be those created by only one, particularly by only the p-process.



Figure 3.9. Rings of glowing gas surrounding the site of the supernova explosion named Supernova 1987A photographed by the wide field planetary camera on the Hubble Space Telescope in 1994. The nature of the rings is uncertain, but they may be probably debris of the supernova illuminated by high-energy beams of radiation or particles originating from the supernova remnant in the center.

SN 1987A

The discussion above demonstrates the importance of supernovae in understanding the origin of the elements that make up the known universe. On February 23, 1987, the closest supernova since the time of Johannes Kepler appeared in the Large Magellanic Cloud, a small satellite galaxy of the Milky Way visible in the southern hemisphere. This provided the first real test of models of supernovae as the spectrum could be analyzed in detail. Overall, the model presented above was reassuringly confirmed. The very strong radiation from ^{56}Co, the daughter of ^{56}Ni and parent of ^{56}Fe was particularly strong confirmation of the supernova model. There were of course, some minor differences between prediction and observation (such as an overabundance of Ba), which provided the basis for refinement of the model.

NUCLEOSYNTHESIS IN INTERSTELLAR SPACE

Except for production of ^{7}Li in the Big Bang, Li, Be and B are not produced in any of the above situations. One clue to the creation of these elements is their abundance in galactic cosmic rays: they are over abundant by a factor of 10^6, as is illustrated in Figure 3.10. They are believed to be formed by interactions of cosmic rays with interstellar gas and dust, primarily reactions of ^{1}H and ^{4}He with carbon, nitrogen and oxygen nuclei. These reactions occur at high energies (higher than the Big Bang and stellar interiors), but at low temperatures where the Li, B and Be can survive.

SUMMARY

Figure 3.11 is a part of the Z vs. N plot showing the abundance of the isotopes of elements 68 through 73. It is a useful region of the chart of the nuclides for illustrating how the various nucleosynthetic processes have combined to produce the observed abundances. First we notice that even number elements tend to have more stable nuclei than odd numbered ones — a result of the greater stability of nuclides with even Z, and, as we have noted, a signature of the s-process. We also notice that nuclides 'shielded' from β^- decay of neutron-rich nuclides during the r-process by an isobar of lower Z are underabundant. For example, ^{168}Yb and ^{170}Yb are the least abundant isotopes of Yb. ^{168}Yb, ^{174}Hf and ^{180}Ta are very rare because they 'p-process only' nuclides: they are shielded from the r-process and also not produced by the s-process. ^{176}Yb is about half as abundant as ^{174}Yb because it is produced by the r-process only. During the s-process, the flux of neutrons is sufficiently low that any ^{175}Yb produced decays to ^{175}Lu before it can capture a neutron and become a stable ^{176}Yb.

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REFERENCES AND SUGGESTIONS FOR FURTHER READING

Burbidge, E. M., G. R. Burbidge, W. A. Fowler, and F. Hoyle. 1957. Synthesis of the elements in stars, *Rev. Mod. Phys.*, 29: 547-650.

Cowley, C. R. 1995. *Cosmochemistry*. Cambridge: Cambridge University Press.

Prantzos, N., E. Vangioni-Flam and M. Cassé (ed.), 1993, *Origin and Evolution of the Elements*, Cambridge: Cambridge University Press.

Rolfs, C. E. and W. S. Rodney. 1988. *Cauldrons in the Cosmos*. Chicago: Chicago University Press.

Wasserburg, G. J., M. Busso, R. Gallino and C. M. Raiteri. 1994. Asymptotic giant branch stars as a source of short-lived radioactive nuclei in the solar nebula. *Astrophys. J.* 424: 412-428.

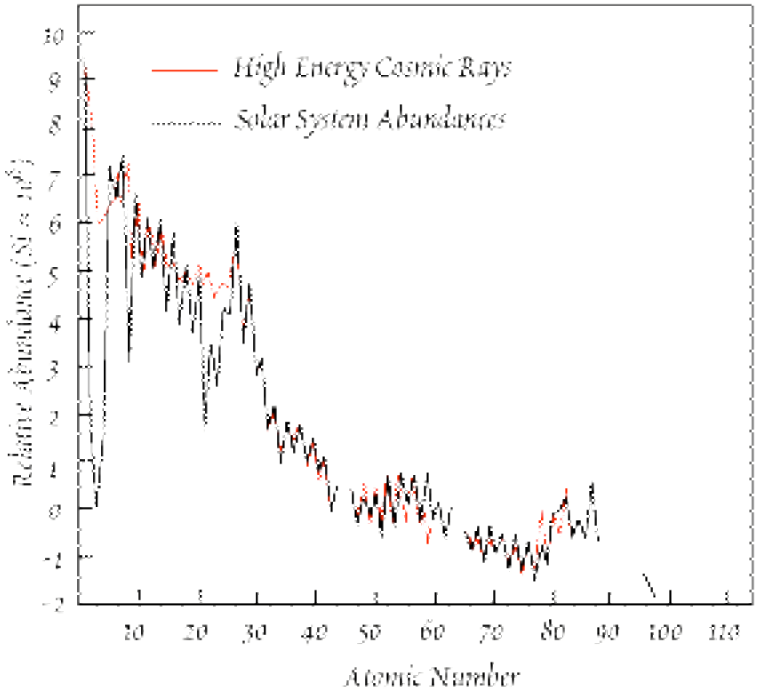


Figure 3.10. Comparison of relative abundances in cosmic rays and the solar system.

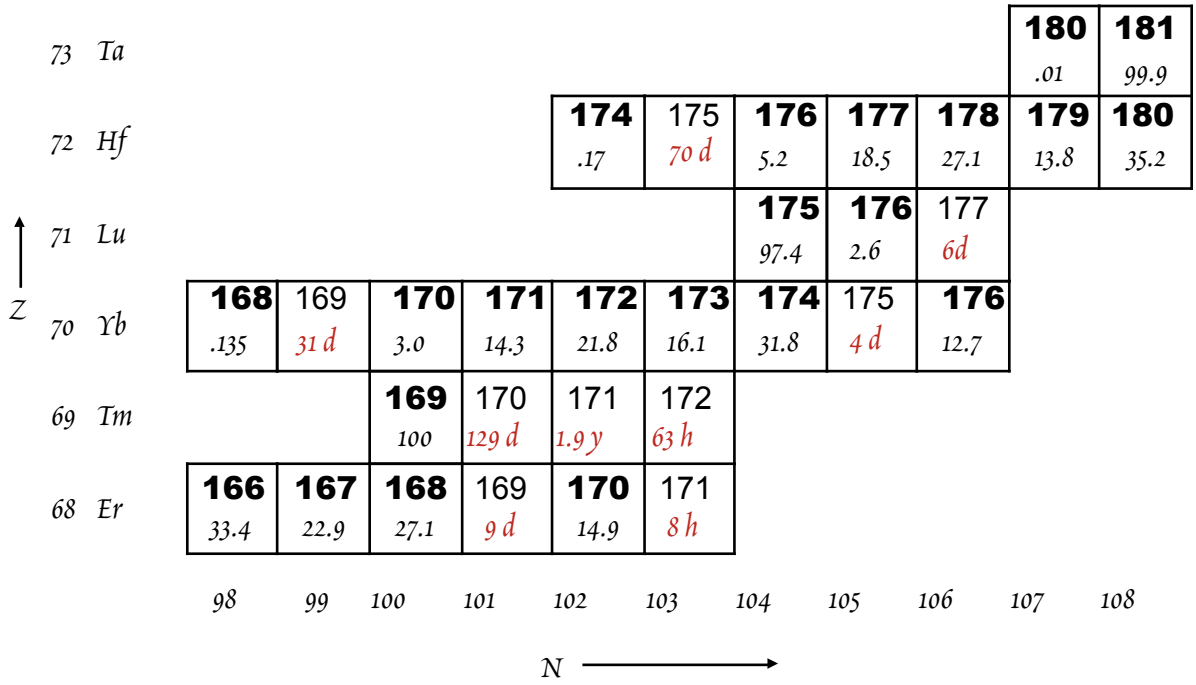


Figure 3.11. View of Part of Chart of the Nuclides. Mass numbers of stable nuclides are shown in bold, their isotopic abundance is shown in italics as percent. Mass numbers of short-lived nuclides are shown in plain text with their half-lives also given.