13

Element Abundances

The chemical composition of the universe is rather simple. About 75% (by mass) of atomic matter is in the form of hydrogen, and almost all the rest is in the form of helium. All other chemical elements contribute less than 2% of the atomic mass. *Why is it that some elements are more abundant than others? And where did the elements come from in the first place?* These questions cannot be avoided, since atoms, and even atomic nuclei, could not exist in the early moments after the big bang. The challenge, then, is to understand how the elements were created by physical processes during the course of cosmic evolution.

13.1 Why Alchemists Did Not Succeed

The chemical properties of an atom are determined by the number of electrons it contains, which is equal to the number of protons residing in the nucleus. The number of protons defines the type of chemical element. For example, hydrogen has 1 proton, and gold has 79 protons. Atoms that have the same number of protons but different numbers of neutrons have almost identical chemical properties; they are called isotopes. For example, helium-4 has two protons and two neutrons in the nucleus, while helium-3 has two protons and only one neutron in the nucleus. The composition of some of the simplest atomic nuclei is shown in Fig. 13.1. There are 92 naturally occurring elements; their relative abundances in the universe are plotted in Fig. 13.2.

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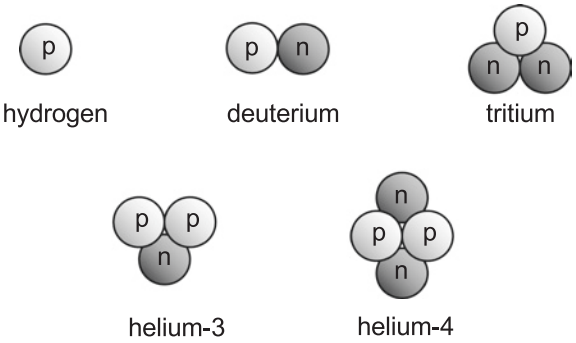

Fig. 13.1 The simplest atomic nuclei, with protons and neutrons represented by p and n, respectively. Deuterium and tritium are isotopes of hydrogen, while helium-3 and helium-4 are isotopes of the chemical element helium

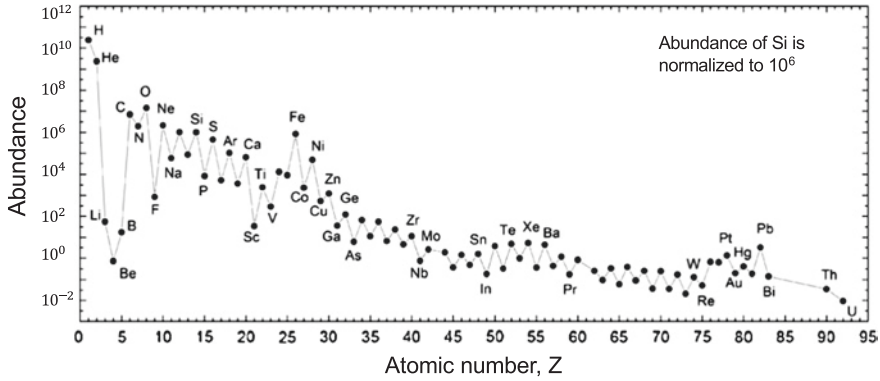

Fig. 13.2 Element abundances. The atomic number Z equals the number of protons in the nucleus

Alchemists in the Middle Ages tried to turn more abundant elements into gold. Newton also devoted much of his time to research in alchemy. Today we know there was a good reason why this research was doomed. In order to change one chemical element into another, one has to learn how to change the number of protons in the atomic nuclei. There are at least two ways to do so. First, you can hit the nucleus with something, so that it splits into two; and second, you can smash two nuclei together, hoping that they will merge and form a larger nucleus. Both methods have their problems.

The problem with the first method is that protons and neutrons are held in the nucleus by the strong nuclear force, so it takes a collision of very high energy to break a nucleus into two. The problem with the second method

is that the attractive nuclear force is strong only at very short distances, so before you can make two colliding nuclei stick together, you have to bring them very close to one another. There is, however, an electric repulsion between positively charged nuclei, and once again you need to supply very high energy to overcome this repulsion. The particle energies needed for nuclear transformations require temperatures in excess of tens of millions of degrees Kelvin. Such temperatures are naturally reached only in stellar interiors and in the early universe.

George Gamow, the founder of the hot big bang theory, suggested that elements were synthesized shortly after the big bang. He developed this idea in collaboration with Ralph Alpher and Robert Herman. It is now called *big bang nucleosynthesis*.

13.2 Big Bang Nucleosynthesis

Let us go back to a time around the first few seconds after the big bang. The temperature of the universe is several billion Kelvin and the fireball is a mix of neutrons, protons, electrons, photons, and neutrinos. At earlier times, neutrons and protons were in thermal equilibrium, converting back and forth into one another through weak nuclear processes like

$$proton + electron \leftrightarrow neutron + neutrino \tag{13.1}$$

A neutron is more massive than a proton and electron combined, so it costs extra energy to convert a proton into a neutron. As the universe expands and cools, energetic electrons needed to make the conversion become more and more rare, and neutrons become less and less numerous relative to the protons. At about one second ABB, the rates of conversion reactions become too slow to keep up with the expansion of the universe, so proton to neutron conversions effectively cease. At that time, there are approximately 6 protons for each neutron.

Isolated neutrons are unstable[1] and decay into protons and lighter particles with an average lifetime of 15 min:

$$neutron \rightarrow proton + electron + antineutrino \tag{13.2}$$

[1]Neutrons in atomic nuclei are stabilized by strong nuclear interactions.

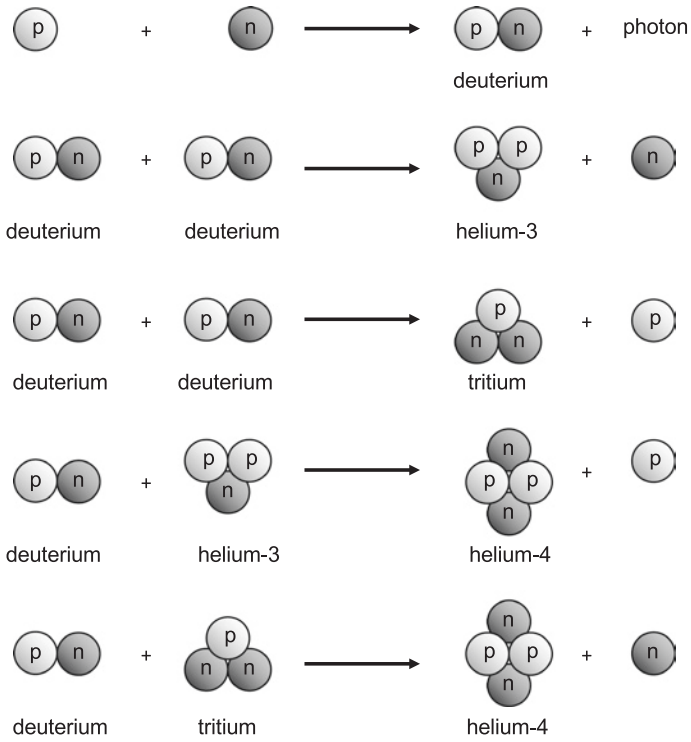

Fig. 13.3 The main nuclear reactions in big bang nucleosynthesis

Thus the universe had about 15 min to create the elements. Otherwise, it would have run out of neutrons, and the only element it would contain would be hydrogen.

The first step in nucleosynthesis is for a neutron to fuse with a proton to make deuterium, or heavy hydrogen (see Fig. 13.3). The deuterium is very fragile, but it is possible for two deuterium nuclei to fuse to make either helium-3 plus a neutron, or tritium plus a proton. There are now two ways in which helium-4 (this is the common helium nucleus consisting of two neutrons and two protons) can be formed: deuterium can fuse with helium-3 to make a stable helium-4 nucleus (plus a proton), or deuterium can fuse with tritium to form a stable helium nucleus (plus a neutron).

Early on, the main impediment to this chain of reactions is that the fragile deuterium nucleus gets destroyed by collisions with energetic photons before it combines with more deuterium to form helium-3 or tritium. But at about 1 min ABB, when the temperature dropped to one billion Kelvin, the photon energies are no longer sufficient to break deuterium. By this

time, the neutron to proton ratio has dropped to 1:7. From this point on, nucleosynthesis proceeds rather quickly, until almost all neutrons end up in helium. The process is essentially complete when the universe is about 3 min old. The abundance of helium predicted in this scenario is 25% by mass,[2] in excellent agreement with observation. The bulk of the remaining atomic mass is in the form of hydrogen.

Trace amounts of other light elements were also created during big bang nucleosynthesis. The predicted abundances of these elements are sensitively dependent on the nucleon density n_n at that epoch. Since the density changes with the expansion of the universe, it is more convenient to use the nucleon to photon ratio, $\eta = \frac{n_n}{n_\gamma}$, which is nearly independent of time. Good agreement between theoretical predictions and the observed abundances (about 10^{-5} deuterium, 10^{-5} helium-3, and $10-^{10}$ lithium-7) is achieved for $\eta \approx 6 \times 10^{-10}$ (see Fig. 13.4)[3]. Thus we should expect the universe to have about 1.6 billion photons for each nucleon.

This result has far reaching implications. Using the value of η and the present number density of CMB photons ($n_\gamma \approx 4 \times 10^8\,\mathrm{m}^{-3}$, see Sect. 11.6), we can find the present average number density of nucleons, $n_n = \eta n_\gamma \approx 0.24\,\mathrm{m}^{-3}$. Furthermore, considering that almost all the mass of atomic matter comes from nucleons (they are about two thousand times heavier than electrons), we can determine the average atomic mass density, $\rho_{at} \approx n_n m_n \approx 4 \times 10^{-28}\,\mathrm{kg/m}^3$, where $m_n \approx 1.7 \times 10^{-27}\,\mathrm{kg}$ is the nucleon mass. In terms of the critical density, this gives $\Omega_{at} = \rho_{at}/\rho_c \approx 0.05$. This value is comparable to the observed amount of matter in stars and interstellar gas—but then not much is left to account for the dark matter.

The amount of dark matter in the universe is about five times that in stars and gas, $\Omega_{dark} \approx 0.26$. Now we have to conclude that most of this matter cannot be made of ordinary atoms. It must consist of some "exotic" stable particles that have not yet been discovered.

The agreement between theory and observation for the abundances of the light elements is a remarkable accomplishment. But what about the heavy

[2]This number is easy to understand, considering that (i) there are 7 protons for each neutron (or 14 protons for 2 neutrons) and (ii) almost all neutrons end up in helium. For each helium nucleus (capturing 2 neutrons and two protons), 12 protons (hydrogen nuclei) are left free. Therefore, by mass, there is a 12:4 ratio of hydrogen to helium, which is precisely the 75% hydrogen, 25% helium prediction.

[3]The lithium abundance obtained by more accurate recent measurements is lower than predicted by about a factor of 3. The origin of this discrepancy is presently unclear; it is a subject of intense investigation.

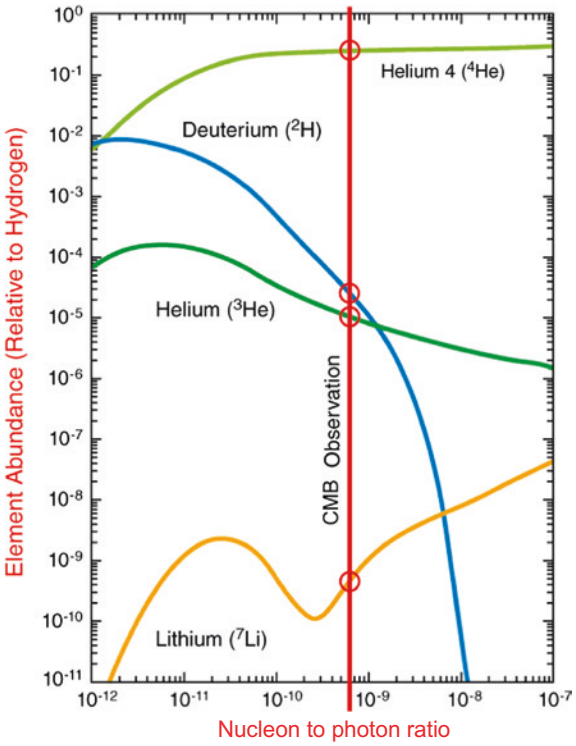

Fig. 13.4 Light element abundances. *Solid curves* indicate theoretical predictions depending on the nucleon to photon ratio. Observed element abundances are indicated by *circles*. There is only one value for the nucleon to photon ratio (*red vertical line*), which passes through all the data points. This value agrees with an independent measurement based on the CMB observations. *Credit* NASA/WMAP Science Team

elements? Here Gamow, Alpher and Hermann reached an impasse. The big bang nucleosynthesis does not progress much beyond helium. The reasons are that there are no stable nuclei consisting of 5 nucleons, and that a simultaneous attachment of two or more nucleons is highly unlikely. This "shortcoming" of the big bang model, known as the 5-nucleon gap, allowed other cosmological theories to thrive as viable alternatives, for a while.

In particular, before the big bang model was generally accepted, Fred Hoyle, Hermann Bondi and Thomas Gold proposed the *steady state* theory (as discussed in Chap. 7). According to this theory, the state of the universe has not changed over time, and the universe never went through a hot explosive stage. Hoyle suggested therefore that all elements were created in stars. While we now know that the hydrogen and helium abundances are set during the big bang, Hoyle was partly right about nucleosynthesis: elements heavier than lithium were indeed formed in stars.

13.3 Stellar Nucleosynthesis

Stars are gaseous spheres held together by gravity and heated by nuclear reactions in their interiors. Our Sun is a typical middle-size star, consisting mostly of hydrogen (71%). Its surface temperature is 6000 K and the central temperature is 10^7 K. Hydrogen is burned into helium in the central parts of stars like the Sun; helium ash is collected at the core. When all the hydrogen is burnt in the central region, the star can no longer support itself against gravity. The core begins to contract, and its temperature rises. Outside the core, a shell of hydrogen continues to burn into helium. Once the core reaches a temperature of $T \sim 10^8$ K, the helium ash starts burning to carbon and oxygen.

For a star with about the Sun's mass, nuclear reactions do not go beyond this point. Due to the heat generated in the core, the star will swell to become a red giant, and then will blow off its envelope, leaving a compact white dwarf remnant. If such a remnant happens to be in a binary pair, then it is possible for the white dwarf to accrete matter from its partner. Once a critical amount of matter is added to the star, it can undergo a supernova explosion. On the other hand, for massive stars (8 or more Solar masses), core burning can continue all the way until iron is formed. The process stops at iron, which is the most stable of all nuclei (see Fig. 13.5). Thus, more massive stars have a layered structure, with heavier elements produced at deeper levels, where the temperature is higher.

When a massive star runs out of nuclear fuel at the center, the central core collapses, reaching enormous densities and temperatures $T \sim 10^{10}$ K.

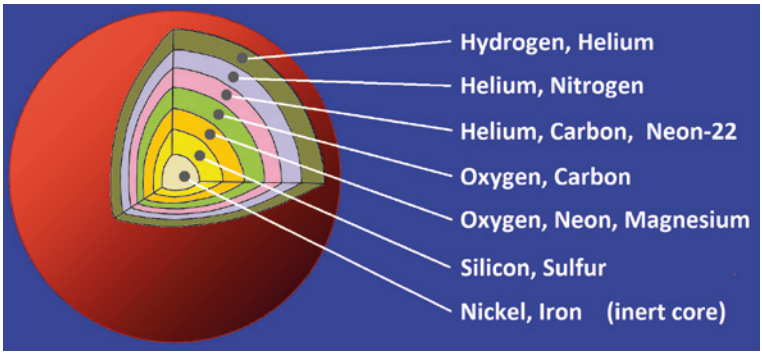

Fig. 13.5 Stellar nucleosynthesis. The heaviest element that can be synthesized in the core is iron. Other heavy elements are burnt in shell-like layers close to the center, while lighter elements continue to burn in the outer layers, where the temperature is lower

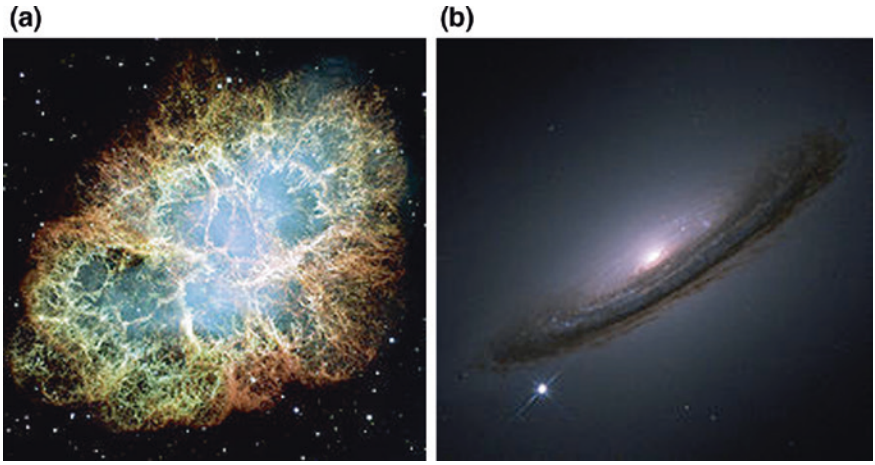

Fig. 13.6 **a** The Crab nebula is the aftermath of a supernova explosion in our galaxy, recorded in AD 1054. *Credit* STSCI, NASA, ESA, J. Hester and A. Loll (Arizona State University). **b** The bright spot on the lower left is a supernova that competes in brightness with the entire host galaxy. *Credit* NASA/ESA, The Hubble Key Project Team and The High-Z Supernova Search Team

Elements heavier than iron are forged during core collapse and the gigantic supernova explosion which immediately follows[4]. These heavy elements are expelled into the interstellar medium where they serve as raw material for new stars and planets.[5] Planets form as a natural by-product of star formation. Thus in a very real sense, we are recycled star dust—the carbon in our cells, the iron in our blood and the calcium in our bones were all made in the centers of stars, and then recycled into the universe (Fig. 13.6).

13.4 Planetary System Formation

All planetary systems, including our Solar System, are believed to have formed in about the same way. A large, slowly rotating cloud of gas begins to contract due to gravitational forces. As the cloud contracts the rotation speeds up, much like an ice-skater spins faster as her hands are pulled in

[4]If the progenitor star has a mass between 8 and 20 Solar masses, the remnant left after core collapse is a super-dense neutron star. Core collapse in stars more massive that 20 Solar masses is expected to produce black holes.

[5]We emphasize that primordial nucleosynthesis is the only explanation we have for the abundances of helium and other light elements. This particularly applies to deuterium, which can only be destroyed in stars. And the amount of helium produced in all stars is only around one percent of the total amount observed in the universe.

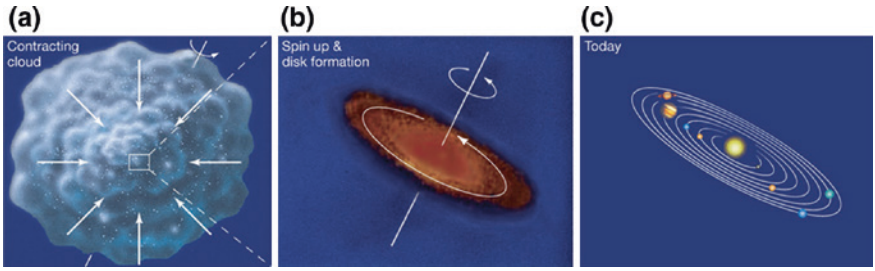

Fig. 13.7 Formation of a planetary system. **a** A rotating cloud of gas starts to collapse. **b** The collapsing material collects mostly near the center and flattens into a rotating disc at the periphery. The central material becomes a protostar and some clumps of matter start to stick together in the disk. **c** Wind from the protostar clears out most of the surrounding material. The remaining material continues to stick together to form local aggregates of matter. Planets which orbit in the same direction and in the same plane are eventually formed. *Credit* Eric Chaisson (from Astronomy Today, Eric Chaisson, Stephen McMillan, Colombus (Ohio))

towards her body.[6] The combined action of gravity and rotation causes the cloud to flatten into a thin disc. As the cloud contracts, the material becomes denser and hotter, especially towards the center, and eventually the central region becomes a star, and some of the material in the disk coalesces into a series of planets (see Fig. 13.7).

Our Solar System consists of the Sun, eight planets, an asteroid belt between Mars and Jupiter, and the Kuiper belt beyond Neptune's orbit (see Fig. 13.8). Almost all of the mass in the Solar System is concentrated in the Sun, with most of the remaining mass in the largest planet—Jupiter. The first four planets (Mercury, Venus, Earth and Mars) are called terrestrial planets as they have the same rocky makeup as the Earth; the next four planets (Jupiter, Saturn, Uranus, and Neptune) are the gaseous planets. The asteroid and Kuiper belts consist mostly of bodies that are much smaller than the planets. Jupiter's gravitational bullying prevented the material in the asteroid belt from becoming a planet, and the material in the Kuiper belt probably never collided frequently enough to coalesce into a planet.

Planets outside of the Solar System are very hard to detect, because light reflected by any planet is very dim compared to the brightness of the star it orbits. Astronomers therefore use indirect detection methods, looking for minute effects that the orbiting planet has on the spectrum and the brightness of the star. The first successful detection of an extrasolar planet was

[6]The physical principle behind the spin-up of a contracting cloud (and the ice-skater) is angular momentum conservation.

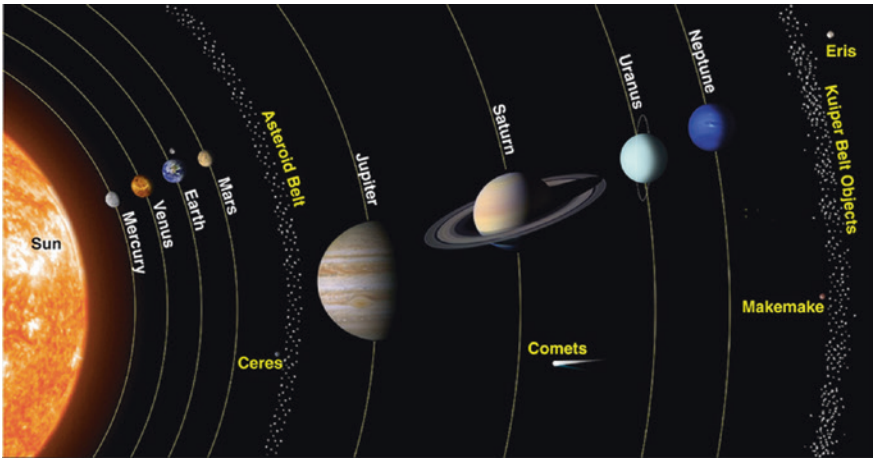

Fig. 13.8 The Solar System (not to scale). *Credit* NASA

made in 1992 using the Doppler shift method. The gravitational pull of the planet causes the star to move ever so slightly, inducing a Doppler shift in the spectrum of the star. The spectrum is periodically blue and red-shifted as the star moves forward and backward relative to the Earth. This method works best for very massive planets located in close proximity to their stars.

An alternative method is to measure how much a star dims when a planet passes in front of it. The amount of dimming is proportional to the fraction of the stellar disc blocked and grows with the size of the planet. By measuring the duration of each dimming and the time interval between them, one can also determine the revolution period and the radius of the planet's orbit. The Kepler space telescope, launched in 2009, used this method to discover thousands of extrasolar planets, indicating that planet formation is quite common in the universe. On average, the estimated number is more than one planet per star.

13.5 Life in the Universe

With a multitude of planetary systems already discovered, one cannot help but wonder how many of them might harbor life and intelligence, and what exotic forms that alien life might take. Life as we know it on Earth is based on chains of carbon atoms. This is probably not an accident: carbon is one of the most abundant elements and it has the richest chemistry. Other elements involved in life—hydrogen, oxygen and nitrogen—are also among

the most abundant in the universe (see Fig. 13.2). Another key ingredient necessary to enable biochemical reactions is liquid water, which plays the role of a solvent.[7]

There is no shortage of water on most extrasolar planets, but it is either frozen or vaporized if the planet is too far or too close to the star. Astronomers estimate that about 20% of stars have Earth-sized planets with surface temperatures allowing for the existence of liquid water. With about 10^{22} stars in the observable universe, this amounts to $N_p \sim 10^{21}$ potentially habitable planets.

This is a lot of planets, but the number of planets that are actually inhabited by living creatures is very hard to assess. Living organisms are characterized by their ability to reproduce and to undergo Darwinian evolution. Once evolution starts, species proliferate and adapt to the changing environment. This makes life very resilient: life on Earth has survived a number of catastrophic climate changes induced by asteroid impacts, massive volcano eruptions, etc. But in order to get the evolution going, the first living organism had to be formed somehow. How this could happen is presently a great mystery and a subject of ongoing scientific debate.

One can imagine that life started with a relatively short molecular chain, which could replicate itself. But the probability for such a chain to arise by chance from non-living matter is likely to be very small. Another roadblock on the way to life is the origin of the genetic code and of the complex molecular machinery that builds proteins (of which all living organisms are made) following the instructions encoded in DNA. At the present level of understanding, we cannot exclude the possibility that fluctuations necessary for the evolution of life are so rare that life on Earth is the only life that has ever evolved within our cosmic horizon.

Fossil evidence indicates that microbial life existed on Earth about 3.8 billion years ago. Prior to that, the Earth was heavily bombarded by asteroids and life was probably impossible. Thus, it seems like life emerged almost as soon as it could. At first glance, this suggests that life appears easily, and therefore the universe should be teaming with primitive life forms. But it could also be that the rare fluctuation necessary for the emergence of life was more likely to occur in the turbulent environment of the early Earth. Then the most probable time to form life would be soon after a planet forms, but only a small fraction of planets would have life.

[7]Alternative forms of biochemistry have also been hypothesized. For example, life might be based on silicon and use ammonia as a solvent. Here we focus on Earth-like life.

Even if primitive life is abundant in the universe, the chances for it to evolve intelligence are highly uncertain. Dinosaurs roamed the Earth for more than 150 million years and did not develop a technological civilization. We may soon have a better idea of how widespread intelligent life actually is. An extensive international program of observations searching for signs of extraterrestrial intelligent life, called *Breakthrough Listen*, was launched in 2016.

Summary

The lightest atomic nuclei—hydrogen, helium, and small amounts of deuterium and lithium—were formed during the first few minutes after the big bang. The theory of big bang nucleosynthesis tightly constrains the amount of atomic matter that can exist in the universe and leads to the conclusion that most of the dark matter consists of some unknown particles.

Elements up to iron are produced in the cores of stars, and heavier elements are made during violent supernova explosions, which then spew these heavy elements into the interstellar medium. New generations of stars form from the enriched interstellar gas, and planets form as by-products.

We now know that planetary systems are abundant in the universe, and astronomers estimate that there are a huge number of habitable planets. We still do not know how to estimate the probability for primitive life to arise on a generic habitable planet. Even if primitive life is common, intelligent life may still be relatively rare. If so, we may be the lone technologically advanced civilization in our cosmic horizon.

Questions

1. What determines the chemical properties of an atom?
2. If a carbon nucleus has six protons, how many electrons does a carbon atom have?
3. Why were alchemists unable to produce gold from other elements?
4. What are the two most abundant elements in the universe? When were most of these two elements formed?
5. Roughly what percentage (by mass) of atomic matter in the universe is in the form of hydrogen? And helium?
6. Where were elements heavier than lithium formed?
7. At roughly what age did the universe complete big bang nucleosynthesis?
8. The Sun consists mostly of hydrogen. What happens to the hydrogen in the central parts of the Sun?

9. Why do fusion reactions in stars need such high temperatures? Why does formation of increasingly heavy nuclei require increasingly higher temperatures?
10. How do we know what chemical elements exist in stars and interstellar gas?
11. Take note of the different elements in your surroundings, and try to imagine where these elements were created, and how they made their long journey from then to now.
12. Why did element formation stop with helium fusion in the early universe?
13. Cosmologists believe that most of the dark matter cannot be ordinary atomic matter. Can you explain how this conclusion follows from the theory of big bang nucleosynthesis?
14. How do the primordial deuterium and lithium abundances allow us to determine the current total density of atomic matter?
15. In massive stars different types of nuclear reactions take place creating a variety of different elements. Where in the star are the heaviest elements made and why?
16. When a massive star runs out of nuclear fuel at its center, what happens to the central core? What happens to the outer layers of the star?
17. Name one reason why supernovae are critical for your existence.
18. Why does a protostellar cloud heat up as it contracts?
19. A distant star, having a brightness and a radius very similar to our Sun, is observed to get dimmer by about 0.01% every 400 days, with every dimming episode lasting 12 h. Assuming that the dimmings are caused by an orbiting planet, estimate the radius of the planet, the speed of its revolution around the star, and the radius of its orbit. (Note: the radius of the Sun is 7×10^8 m.)
20. Astronomers call a planet "habitable" if it has liquid water. Does this mean the planet is actually inhabited by some living creatures? Would you expect that most "habitable" planets harbor some forms of life?