Lecture 1: Stellar Evolution for Astrobiology

Aims of Lecture

(1) To summarise our understanding of the formation of stars and planets

(2) To outline our understanding of stellar evolution, and its role in the production of the biologically important chemical elements

(3) To illustrate how this material has become incorporated within the planets of our Solar System, and the implications for the formation of other planetary systems in the Galaxy

Fig. 1. The Helix nebula, a planetary nebula located about 450 light-years away. Note the white dwarf in the centre, which was once the core of a solar-type star! (NASA/NOAO/STScI)

Contents of Lecture

1. In the beginning....

According to the current Big Bang theory, our Universe began between approximately 13.8 Gyr ago, when all the matter and energy of the Universe was created in a huge ‘explosion’ (the reasons for which are unknown and perhaps unknowable). However, the Big Bang did not directly lead to the production of chemical elements suitable for forming planets or living things.

Within a few minutes of the Big Bang, the creation of atomic nuclei (‘nucleosynthesis’) from the energy released by the Big Bang itself had come to an end, and at this time the Universe consisted of 75% hydrogen and 25% helium (by mass), with just a trace (about one atom in a billion) of lithium, element number 3. All the heavier elements, so important for building planets, and the complex chemical compounds on which life depends, were produced later in stars.

2. The importance of stellar evolution

An understanding of the life cycles of stars is important for astrobiology for multiple reasons:

- Stars produce essentially all the elements in the Universe heavier than helium
- The manner in which stars end their lives determines how these heavier elements are recycled into later generations of stars and planets
- Some stars produce small solid particles (interstellar ‘dust’) that is probably essential for the construction of planets;
- The evolutionary state of a star determines the likely habitability of any planetary system which may have formed around it, and the time for which such planets may remain habitable.

3. Star and planet formation

The formation of stars was discussed in Lecture 3 of 'Foundations of Astronomy', and you may wish to revisit those notes to refresh your memory. A brief summary is given here. Stars form from the gravitational collapse of interstellar clouds of gas and dust. In the early universe, these would have contained only hydrogen and helium from the Big Bang, but as time has gone on they have come increasingly to contain small quantities (a few percent) of heavier elements and micron-sized ‘dust’ particles which render them opaque (Fig. 2). Typically these clouds are a few light-years in size (where 1 light-year is 9.5×10^{15} m), with internal temperatures between 10 to 100 K. As the collapse proceeds, central temperatures and densities rise (Fig. 3). Once the temperature reaches about 10 million degrees, nuclear fusion reactions begin to convert hydrogen into helium, releasing energy in the process. At this point, thermal energy in the interior balances the force of gravity, the gravitational collapse ceases and a star is born.

Fig. 2. A dark interstellar cloud seen silhouetted against the background of stars in the Milky Way. Before they collapse, such clouds are typically several light years across. The prominent cluster of blue stars nearby has probably formed from a similar cloud within the last few tens of millions of years (image by David Malin/Anglo-Australian Observatory).

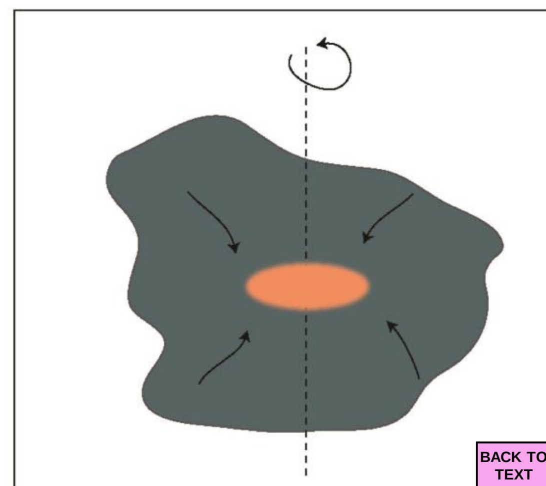


Fig. 3. As an interstellar cloud collapses under gravity (arrows) the internal temperature rises (orange). Eventually temperatures will be sufficient for nuclear fusion to begin and a star will be born. If the cloud is rotating as shown, rotation will speed up as the collapse proceeds, eventually resulting in a flattened disk around the new star within which planets may form.

Planet formation was discussed in Geology of the Solar System II and, again, only a brief summary is given here. Planets form in the disk of gas and dust (the so-called ‘proto-planetary disk’) that orbits the new star because it has too much angular momentum to fall into it (Fig. 4). Dust particles that were present in the original interstellar cloud, or which have condensed from the cooling gas in the protoplanetary disk (or both), collide and stick together gradually forming larger particles. Once these particles have reached km sizes (so-called ‘planetesimals’) gravitational interactions between them can speed up the process of planet formation, but timescales then lengthen as the number of larger bodies in the disk, and thus the chances of collisions between them, continually decrease.

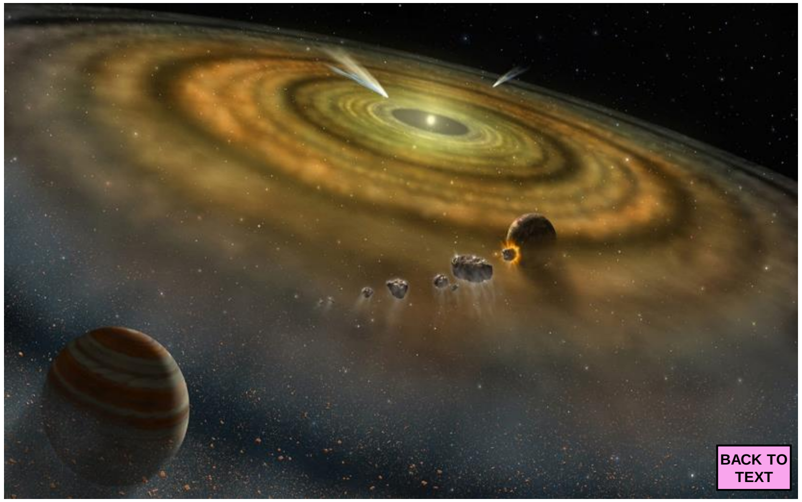


Fig. 4. Artist’s drawing of a forming planetary system. See text for discussion (Lynette Cook/NASA).

The final stage terrestrial planet formation is marked by the violent collision of planetesimals (as illustrated in Fig. 4) and is thought to take 50-100 Myr to complete. At distances greater than a few astronomical units from the star (the so-called ‘snow line’) ices condense on the dust particles, greatly increasing their mass and facilitating the rapid (few Myr) accretion of the cores of giant planets, which are able to accrete H and He gas from the disk before it dissipates. In our Solar System at least, icy planetesimals that were never incorporated into planets remain as Kuiper Bely objects and comet nuclei. Some of these have probably been responsible for bringing water and possibly organic materials into the inner Solar System (see Fig. 4).

The discovery that nearly all stars have planets (Lecture 10) shows that planet formation is a natural, and probably inevitable, consequence of star formation.

4. Stellar evolution and nucleosynthesis

All stars start out by converting hydrogen into helium in their cores, at which time they lie on the 'zero-age main sequence' (ZAMS) in a Hertzsprung-Russell (HR) diagram (Fig. 5). Subsequent evolution depends on their mass.

4.1 Low-mass stars

For most of their lives (i.e. while they occupy the 'main sequence' in an HR diagram), low-mass stars like the Sun produce energy through the so-called proton-proton (p-p) chain of reactions (Fig. 6). The total energy released by this set of reactions is 4.3×10^{-12} Joules, so countless trillions occur every second to power a star like the Sun (with a luminosity of 3.9×10^{26} W).

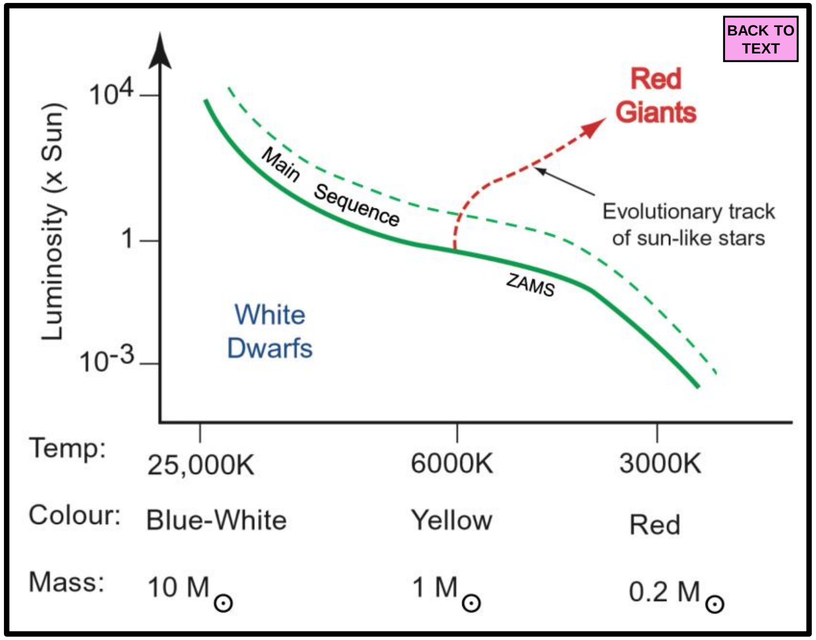


Fig. 5 (above). Schematic Hertzsprung-Russell (HR) diagram showing the relationship between stellar luminosity and surface temperature and (main sequence) mass; ZAMS marks the 'zero-age' main sequence on which stars first form. The evolutionary track of a solar-type star once it leaves the main sequence is also shown.

Fig. 6 (right). The three steps of the nuclear p-p chain. Here, ^1H represents a proton (hydrogen nucleus); ^2H is a deuteron (heavy hydrogen consisting of one proton and one neutron); ^3He is a helium-3 nucleus (2 protons and 1 neutron); ^4He is a 'normal' helium nucleus (2 protons and 2 neutrons); e+ is a positron; ν is a neutrino; and γ is a gamma ray. The first two stages must occur twice for the third to occur.

BACK TO TEXT

$$(1)\quad {}^1H + {}^1H \rightarrow {}^2H + e^+ + \nu$$

$$(2)\quad {}^2H + {}^1H \rightarrow {}^3He + \gamma$$

$$(3)\quad {}^3He + {}^3He \rightarrow {}^4He + {}^1H + {}^1H$$

Every second a star like the Sun converts 600 million tonnes of hydrogen into helium, of which about 4 million tonnes (0.7%) is actually converted into energy in accordance with Einstein's formula: $E = mc^2$. Clearly, this rate of fuel consumption cannot continue indefinitely, although fortunately the Sun was formed with sufficient reserves to last for about 11 billion years – as it is now 4.6 billion years old, it is just less than halfway through its hydrogen-burning ('main sequence') lifetime.

Stars remain on the main sequence for as long as the reserves of hydrogen in their cores are not exhausted, although (as discussed in Foundations of Astronomy) main-sequence stars do slowly brighten with time as helium accumulates in their cores (Fig. 5) – the Sun is now about 30% brighter than it was 4.5 billion years ago, which has astrobiologically important consequences (discussed in Lecture 2).

Once core hydrogen is exhausted, hydrogen fusion continues in a thin shell surrounding a core that is now made mostly of helium. This 'shell-burning' phase is more efficient at heating the overlying layers of the star, which expands as a consequence (Fig. 7).

As the star expands it gets more luminous (because of its larger surface area), but its surface temperature becomes cooler and its colour redder – causing it to move to the upper-right of the HR diagram (Fig. 5). Such a star is said to be a 'red giant'. When the Sun becomes a red giant, in about 7 billion years time, its radius will be ~170 times its present value (engulfing Mercury), and it will be ~2300 times brighter than at present; life on Earth will have become impossible.

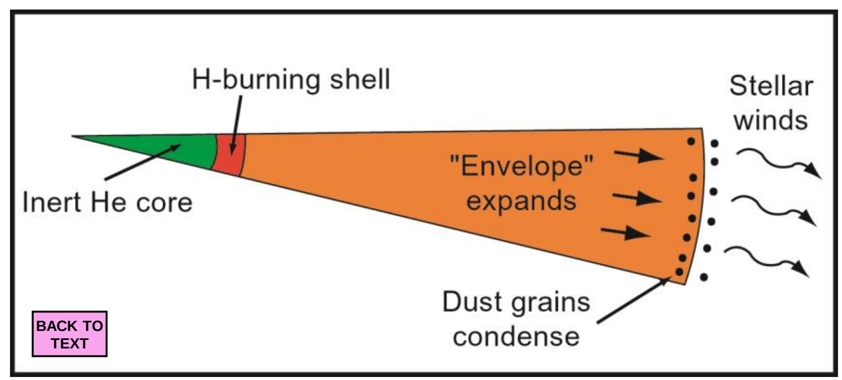


Fig. 7. A sketch of the interior of a red giant star (see text for details).

Red giants also have a positive role in the cosmic scheme of things: if they contain elements heavier than hydrogen and helium (which wasn't the case for the first stars to form but has been true of all subsequent stellar generations, as discussed below) these elements condense in the cool outer layers ('atmospheres') of red giant stars to form small (~0.1μm) solid silicate and oxide grains. As these are blown away from the red giants by powerful stellar winds (shown schematically in Fig. 7) they add a solid component to the interstellar medium, which will aid in the formation of planets around later generations of stars.

Recall that solar type stars become red giants twice. The Sun will spend about 600 million years as a red giant the first time around. This stage ends when the inert helium core, which is not supported by nuclear fusion reactions, starts to collapse under its own gravity causing its temperature to rise to the 100 million degrees necessary to fuse three helium nuclei to form carbon:

$$^{4}He + ^{4}He + ^{4}He \rightarrow ^{12}C$$

This reaction first introduces the biologically crucial atom, carbon, into the Universe. However, it is still buried in a stellar core, and understanding how it gets out into the wider universe requires some further discussion of stellar evolution.

Red giants contract somewhat during core He-burning, but this stage lasts for only about 100 million years, and is followed by He-burning in a shell surrounding a mostly carbon core (Fig. 8). This once again causes the star to swell in size to become a red giant for a second time. Such stars are called 'asymptotic giant branch' (AGB) stars after their evolutionary tracks in a HR diagram.

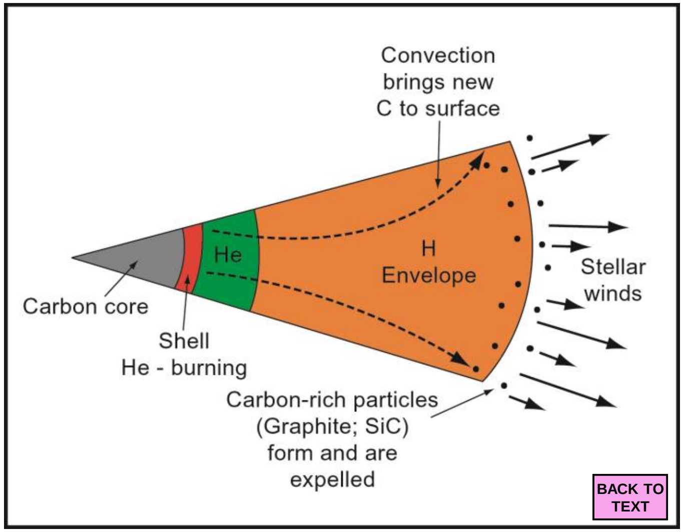


Fig. 8. A sketch of the interior of an asymptotic giant branch (AGB) star (see text for details).

During the later stages of AGB evolution the outer layers of the star become convective, and newly synthesised carbon from the He-burning shell is transported to the surface (Fig. 8). Here it may condense into small carbon-rich particles (e.g. graphite), which are then carried out into the interstellar medium by stellar winds. Stars at this stage of their evolution are often called 'carbon stars' and are important producers and distributors of carbon in the Universe.

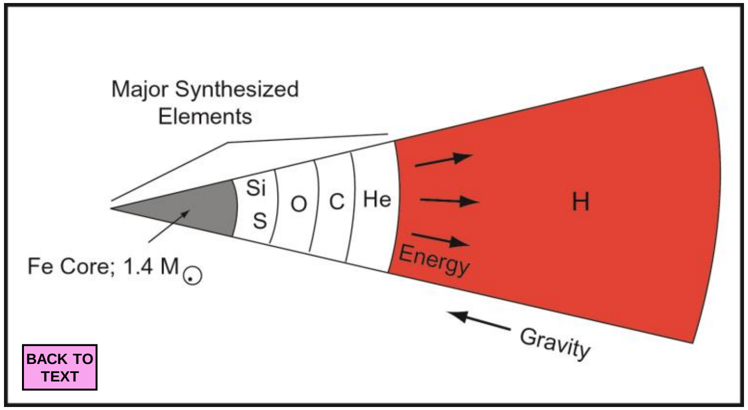
The Sun will spend about 20 million years as an AGB star, when it will have ~213 times its present diameter, and ~5200 times its present luminosity. By this time, the Earth, already made uninhabitable during the first red giant phase, may have been destroyed by falling into the Sun's AGB photosphere.

Eventually, the outer layers of these giant stars drift away leaving behind the exposed, very hot and mostly carbon, core as a white dwarf star (Fig. 5), surrounded by an expanding cloud of ionized gas known as a 'planetary nebula' (Figs. 1, 9). As planetary nebulae drift out into space, they add some of the products of the star's earlier life to the interstellar medium from which future stars and planets will form. These include He (produced by H-fusion), C (produced by He-fusion), some N and O (derived from nuclear reactions involving C), elements heavier than Sr produced by the addition of neutrons to pre-existing nuclei in the shell-burning zones of red giant and AGB stars; discussed below), and carbonaceous dust particles. If the star contained some heavy elements to begin with, its earlier red giant phase will already have added silicate dust to the interstellar medium.

Fig. 9. Hubble Space Telescope image of the 'Cat's Eye' nebula (NGC 6543), a planetary nebula 3000 light-years away in the constellation of Draco; red: ionized H; blue: neutral oxygen; green: ionized N (NASA).

4.2 High-mass stars and supernovae

Although the contributions of red giants and AGB stars are important, it is apparent that we have yet to discuss the origins of the heavy chemical elements, such as silicon (which a red giant star must already have if it is to produce silicate dust), or iron, or all the other elements up to uranium. These elements are mostly produced by the evolution of hotter, more massive stars (typically more than ten times the mass of the Sun), which end their relatively short lives in spectacular explosions known as supernovae.



BACK TO TEXT

Fig. 10. Sketch of the interior structure of a 20 solar-mass star shortly before the core implodes and triggers a supernova explosion (see text for details).

Higher temperatures in more massive stars permit production of heavier elements by nuclear fusion. Fig. 10 shows the structure of a star with 20 times the mass of the Sun near the end of its life (only a few million years after it formed). The star has an iron core, surrounded by shells of heavier elements that have been produced by nuclear fusion at earlier stages of its life.

Unfortunately for the star, nuclear fusion beyond iron does not produce energy but instead absorbs it. This means that the core is no longer supported, and it implodes into a very dense, exotic object called a neutron star. This collapse of the core releases a vast amount of gravitational potential energy which causes the rest of the star to explode as a so-called `core-collapse' (or 'Type II') supernova. Not only does this expel the chemical elements produced by the star during its lifetime, but the energy is sufficient to synthesise and eject many elements up to and heavier than iron. Some of these elements also condense into dust in the expanding cloud of debris. Examples of supernovae remnants of different ages are shown in Fig. 11.

A supernova occurs on average every hundred years in the Galaxy today, but they were more frequent billions of years ago. Because the lifetimes of the progenitor stars are so short, heavy elements probably accumulated rapidly in the Galaxy, especially towards the centre where the density of stars is higher.

Table 1 shows the yields of newly synthesised elements measured in given in Earth masses – a single supernova produces enough raw material to make tens of thousands of Earth-like planets!

Table 1. The typical heavy element yield of a single core-collapse (Type II) supernova resulting from the explosion of a 20 solar-mass star.

Element	Yield (Earth-masses)
C	26,000
N	500
O	600,000
Mg	40,000
Al	5,000
Si	35,000
Ca	2,000
Fe	28,000

BACK TO TEXT

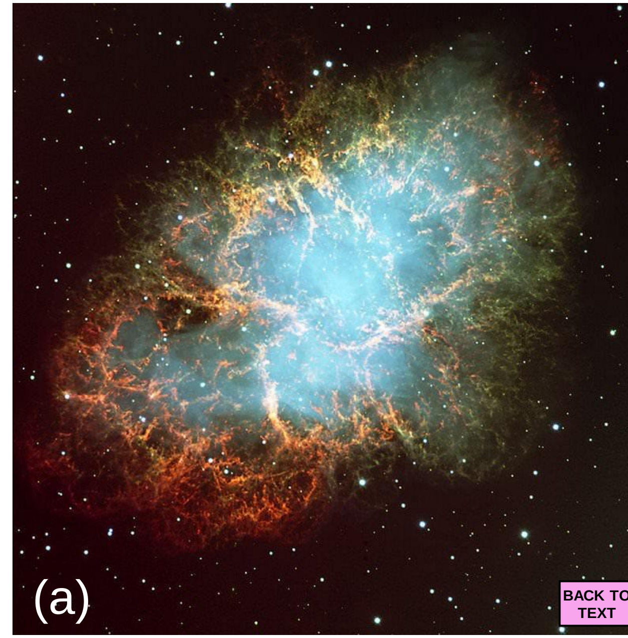


Fig. 11. Supernova remnants. (a) The Crab Nebula, ~7000 light-years away, is the remnant of a supernova observed on Earth in 1054. (b) The Vela supernova remnant, ~800 light-years away, is ~12,000 years old (NASA images).

5. Chemical enrichment of the Galaxy

Type II supernovae are not the only astrophysical environments where heavy elements are produced. Some elements (e.g. Fe, Ni, Co) are produced more efficiently in exploding white dwarf stars (i.e. ‘Type Ia’ supernovae; Fig 12).

Moreover, most elements heavier than strontium (atomic number 38) are not generally produced by nuclear fusion, but by the continuous addition of neutrons to pre-existing atomic nuclei. The are two main types of these ‘neutron capture’ reactions: ‘slow’ and ‘fast’, where the timescale is with respect to the radioactive decay of intermediate nuclei being constructed. Slow neutron capture occurs in or around the shell-burning layers within red giant or AGB stars, whereas fast neutron capture is thought to occur mostly in the collision of neutron stars (most commonly when the orbits of binary neutron stars decay owing to the radiation of gravitational waves – a remarkable connection between general relativity and the synthesis of chemical elements!). Figure 13 shows current thinking on the origins of the chemical elements.

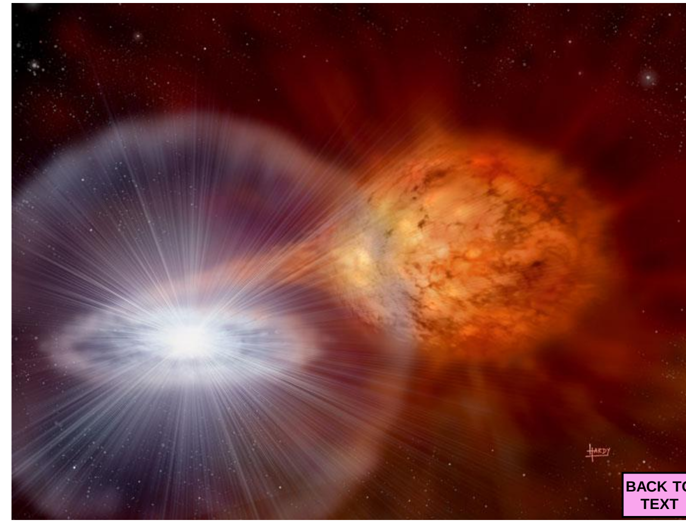


Fig. 12. Matter being transferred gravitationally from the outer layers of a red giant to the surface of a white dwarf, which can cause novae and Type Ia supernovae (David Hardy/STFC).

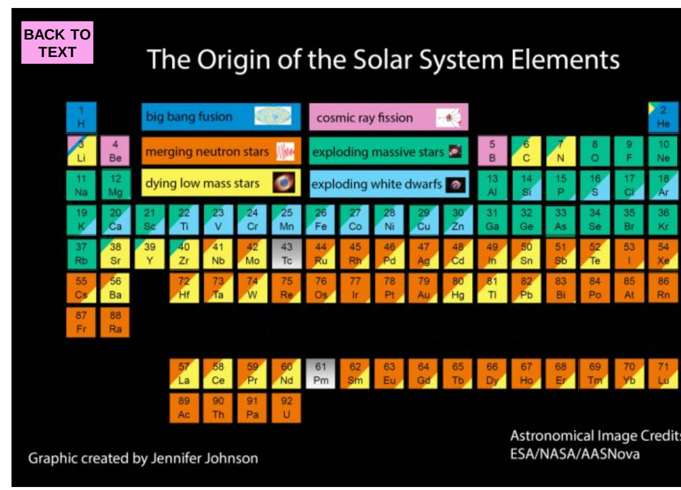
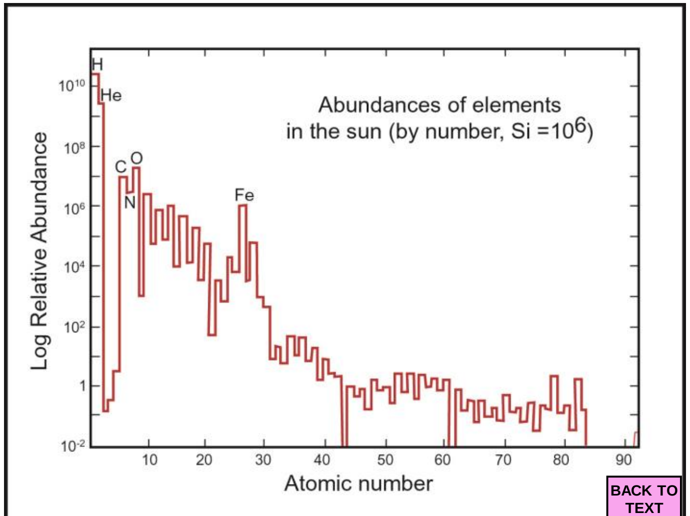


Fig. 13. Summary of the astrophysical origins of the chemical elements. Blue: Big Bang; Pink: spallation by cosmic rays; Green: SN Type II; Blue: SN Type Ia; Yellow: slow neutron capture in red giant and AGB stars; Orange: fast neutron capture in colliding neutron stars. (credits: Jennifer Johnson/ESA/NASA).

Eventually, all the material created in, and ejected from, red giants, AGB stars, supernovae and colliding neutron stars will be swept up into the cold, dark interstellar clouds such as that shown in Fig. 2. It is from this material that new stars will form, and so the cycle continues – all the time enriching the interstellar medium in heavy elements and dust grains.

By the time the Sun formed, 4.6 billion years ago, about 2% of the mass of its parent interstellar cloud consisted of elements heavier than hydrogen and helium, all of which had been created in earlier generations of stars. Studies of interstellar grains preserved in meteorites suggest that about 35 to 40 AGB stars, and at least one supernova, contributed solid material to the interstellar cloud which formed the Sun. The relative abundances of the elements at this time (i.e. those of the present solar system) are shown in Fig. 14.



BACK TO TEXT

Fig. 14. The abundances of the chemical elements in the outer layers of the Sun, and therefore in the interstellar cloud from which the sun formed 4.5 billion years ago (note that helium produced by the Sun itself over this time hasn't yet appeared at the surface and so isn't included). Both the absolute and relative abundances of the elements in the interstellar medium as a whole change with time and place in response to stellar evolution (see text).

Note, that both the overall concentration of heavy elements will increase, and their relative abundances change, with time and place. In general, abundances of heavy elements will increase with time, although as we shall see in Lecture 10, sufficient heavy elements appear to have built up to allow the formation of Earth-mass planets within a few billion years of the Big Bang (see, e.g., Zackrisson et al., *Astrophysical Journal*, 833, 214, 2016). We would also expect the carbon/oxygen ratio to increase with as the supernova rate (which produces most of the oxygen) declines, but more old low-mass stars leave the main sequence to become AGB stars (which produce most of the carbon).

Once these heavier chemical elements accumulate in cold interstellar clouds, chemical reactions can produce a wide assortment of molecules. These are detected by radio astronomers as many of them emit radiation at radio wavelengths. Many are simple molecules containing only two or three atoms (e.g. CO, CH, CN, H_2O, HCN). The volatile molecules condense onto cold interstellar grains, forming icy mantles which are locations for the formation of more complex molecules, some of which are of astro-biological significance. Examples include formaldehyde (H_2CO), methanol (CH_3OH), formic acid (CHOOH), and long carbon chains (e.g. $HC_{11}N$). More complex molecules, such as amino acids, may also form and some of this organic material may be inherited by forming planetary systems and play a role in the origin of life.

Fig. 15 is a sketch of the pre-history of the Solar System, showing the build up of the heavy elements from the Big Bang (hydrogen and helium only) to the collapse of the particular interstellar cloud which formed the Sun and Solar System 4.6 billion years ago. This contained $\sim$2% by mass of elements heavier than hydrogen and helium, many of them in the form of solid dust particles and possibly complex organic molecules.

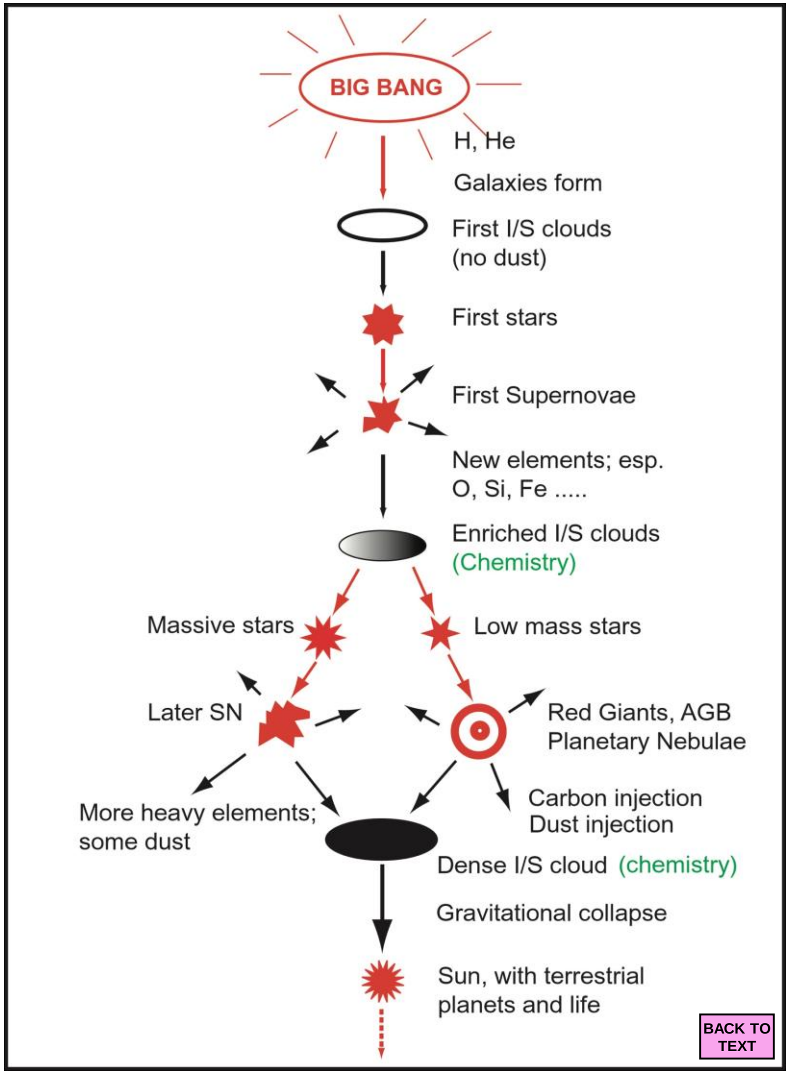


Fig. 15. A sketch showing the chemical pre-history of the Solar System.