Stellar Structure and Evolution

The life of the Stars

From observations of stars and from comparison between observations and theoretical models of stars (huge computer programs written by astronomers in an attempt to understand the physics of the stars), it is now well established that the life of a star is governed almost exclusively by its birth mass. Massive stars burn up their fuel much faster than less massive ones, and the enormous energy production at the centre of the more massive stars makes their inner structure somewhat different from the structure of the less massive ones, as we will come back to in a little while.

Since the heaviest stars are about 1000 times heavier than the lightest, we expect to observe large differences in stellar properties over the entire mass range. Furthermore, the nuclear burning of hydrogen into helium - the very process that makes most stars shine - takes place near the stellar cores, and the process changes the stellar properties over time (see below). We therefore observe differences between stars of different age, even if their mass is about the same. By the way, nuclear burning is not an actual "burning", but just a term astronomers uses for the fusion process of, for example, forming one helium nucleus out of four hydrogen nuclei. This process is described in more detail below.

It is now known that our Universe is approximately 14 billion years old, and that the oldest stars are nearly as old as this. At the same time, new stars are still being born, which means that we can observe stars in all stages of life, as well as we can observe stars with different masses. The result is that we can learn about both the internal structure and the evolution of stars, by studying many stars of different mass and age.

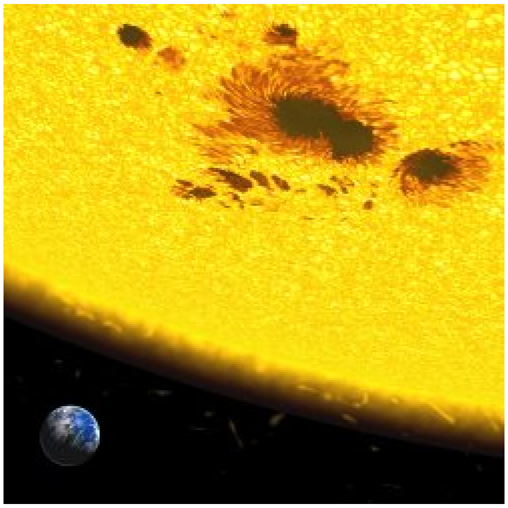
In the following, we will describe the life cycle of a star, but in order to limit the length of our description, we will focus on stars which have masses similar to that of the Sun.

Sun like Stars

The Sun, as other stars, is fuelled by nuclear reactions in the central regions, where the temperature, pressure and density are so high that nuclear fusion of hydrogen into helium can take place. In the Sun, this is happening inside the inner 25% in radius, corresponding to the central 1.5% in volume. However, since stars are much denser in the core compared to the outer regions, this region actually contains about 30% of the total mass of the Sun.

You can read more about the conditions in these central regions of a star like the Sun **here**.

The Sun will spend about 90% of its life in this relatively quite phase, slowly converting hydrogen into helium and shining steadily. Although the nuclear reactions change the chemical composition of the central regions, as the amount of helium gradually increases while the hydrogen content decreases as the star gets older, the star will not change its luminosity and size very much in this phase of life. This stage of evolution is called the "main sequence" and all stars spend most of their lifetime in this phase.

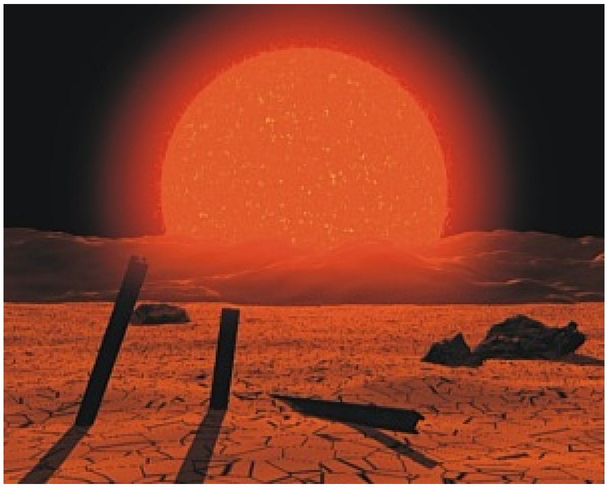


Animation showing the size of the Sun:
MPEG format - (1 MB)
AVI (DivX 5.1) format - (1,7 MB)

In total, the Sun will spend about 10 billion years (of which 5 have already passed) on the main sequence, while a star 10 times as massive will spend only 10 million years in this phase. A star half as massive as the Sun will spend about 140 billion years on the main sequence. The huge differences between these time-scales are due to the rate of nuclear burning - the more massive stars are much more luminous and use up their fuel quicker, underlining that the evolution of stars is indeed governed by the mass.

We will now look into what happens in the central region of the star as time passes by and the star evolves away from the main sequence and into the so-called post-main sequence phases that follow life on the main sequence.

As the star gets older, the amount of hydrogen available for nuclear reactions naturally gets smaller (it is converted into helium). But the core also gets hotter which keeps the energy production up to level. Once hydrogen is completely depleted in the centre, the temperature in the surrounding parts is so high that fusion takes place in a shell around the centre. This marks the end of the main-sequence phase and brings about rapid changes for the star.



Energy is now only being produced in a thin, hot shell around the core, which consists only of helium. But because of the high temperature, the energy production actually increases and so does the luminosity. The surface temperature, on the other hand, is decreased slightly and the diameter of the star grows rapidly: the star becomes a so-called giant. In this phase, the star consists of a very dense core of approximately half the mass of the star, and a huge, but very thin, outer envelope.

Since there is no energy production in the centre, this part of the star contracts and heats up. Ultimately, the temperature in the core gets so high that another nuclear fusion reaction, where helium nuclei are transformed into carbon, sets in. For a star like the Sun, this phase of helium burning will only last for about 100-200 million years.

When all the helium is used up, the star will swell even more, before finally expelling the outer layers completely. This exposes the carbon core, which is now very small (about the size of the Earth), very dense (one cubic centimeter weighs 1000 kg) and very hot: a white dwarf is born.

The white dwarf does not produce energy but shines because it is hot. This means that white dwarfs can be observed from Earth, at least in sufficiently large telescopes, despite the fact that the white dwarf does not produce any energy. Over time, it will radiate its energy away and become cooler and cooler, and less and less luminous. Finally, it will end up in the stellar graveyard, as a dark, but still massive object, which can no longer be seen even with the largest telescopes.

Energy Transport inside a Star

This was a very brief description of the life of a star like the Sun. However, a very important point for understanding both the internal structure as well as the evolution of stars is to understand the way stars transport energy from the hot central regions, where it is created, to the cooler surface, from where it is radiated into space.

Except in very dense objects such as white dwarfs, the energy can be transported up through the star in two well-known ways: by radiation or by convection. In the dense objects, energy can also be transported by conduction, but this can be neglected in "normal" stars.

Energy transportation by both radiation and convection are well-known everyday phenomena. The

Earth receives energy from the Sun in the form of radiation, and the atmosphere is transparent to radiation - we feel a difference between being in the sunlight and being in the shade. Similarly, convection can be seen as the hot air rising over a heater, or over the asphalt on a hot day.

For stars, the preferred way of energy transportation from the interior to the surface depends on many factors, such as temperature, pressure and the detailed chemical composition of the stellar matter. In the outer layers of the Sun, energy is primarily transported by convection, while radiation is the dominant form of energy transport in the interior regions.

Stars with a mass only slightly larger than that of the Sun (~10% larger) have convective cores and only a shallow outer convective layer. These stars have convective cores because the energy production is so large, that all the energy simply cannot be transported by radiation alone. Convection - hot gas rising up in higher, slightly cooler layers and cold gas sinking - must therefore set in.

For stars even more massive, only the core is convective, while stars less massive than the Sun have a very deep outer convection zone. Again, the mass is the dominant factor in a star's life.

These differences are very important for the stellar structure and evolution, but especially energy transport by convection is, in fact, very poorly understood - even in the convection phenomenon we observe here on Earth.

For the theoretical modeling of stars, convection is one of the most difficult processes to describe. In fact, although we understand stars pretty well, there are still many aspects of the physics of stars that are unknown or poorly understood. One of the reasons of this is that we are generally limited to observe only the surfaces of stars, including the sun. But with asteroseismology we can use stellar oscillations - or star quakes - to look beyond the surface and learn about the stellar structure in much more detail. This is the topic of the next chapter.