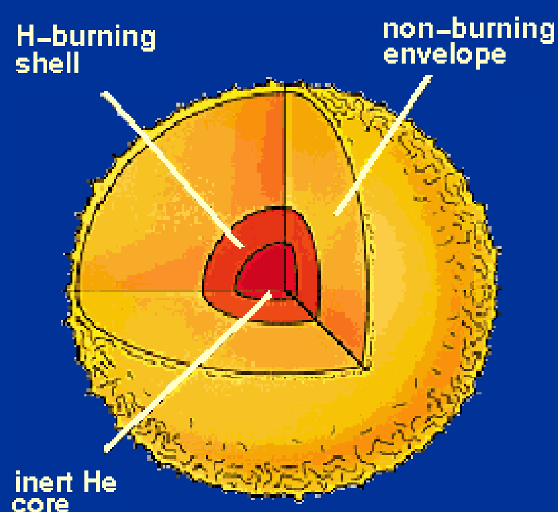
the evolution of low-mass stars

Stars of mass less than 1.1 $M_\odot$ fuse hydrogen using the pp chain. As this has a comparatively weak temperature dependence, energy generation is not sufficiently concentrated at the centre of the star to induce convection, and the core of the star is radiative. This means that the core of the star is not mixed and nuclear reactions can therefore draw only on the fuel that is available locally. The temperature is highest at the centre and so the rate of burning is highest there, forming a concentration gradient with smallest hydrogen content in the centre of the star. Eventually, the centre of the star becomes completely devoid of hydrogen. Immediately outside the centre, however, the temperature is only a little lower and there is still hydrogen left to burn. Nuclear reactions therefore continue, but now in a thick shell rather than throughout a sphere, as shown in figure 14.

Figure 14: The structure of a low-mass star ($M \lesssim 1.1\ M_\odot$) on the sub-giant and red-giant branches of the HR diagram.



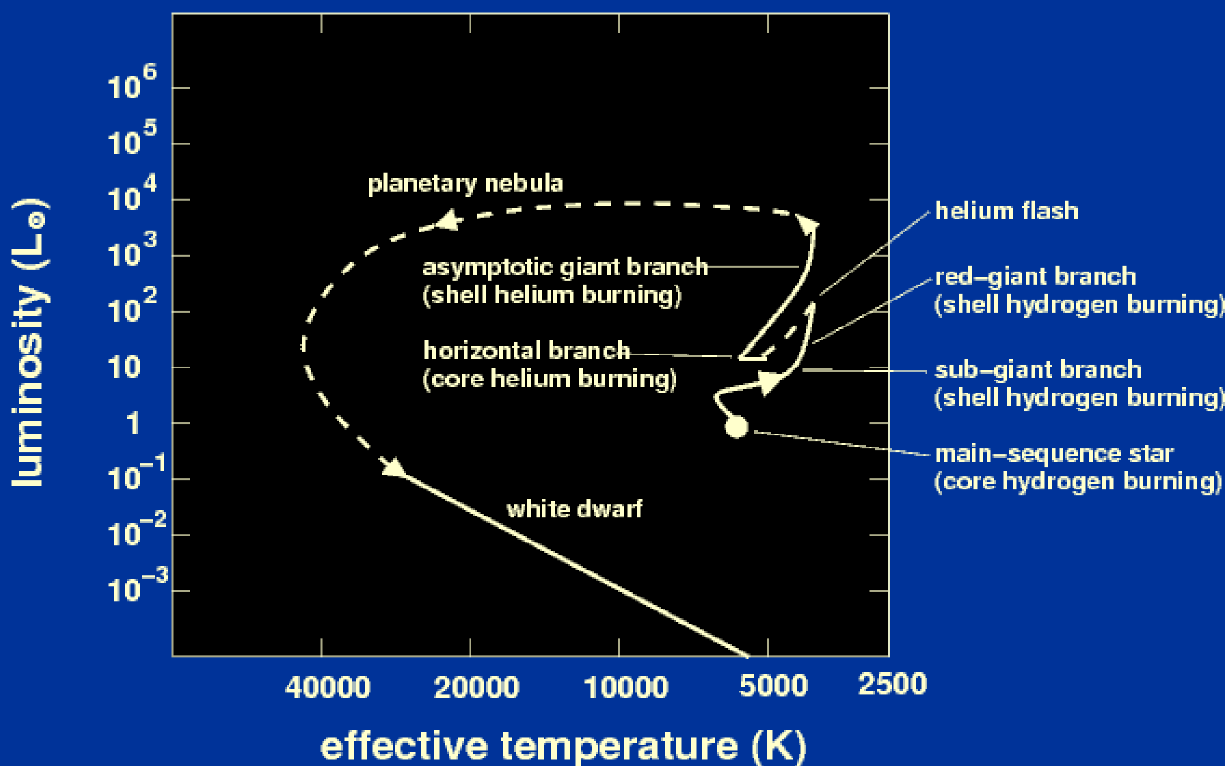
The continuation of nuclear burning in a shell means that there is no need for the whole star to contract. Only in the central regions, where there is no longer any energy production but energy is still leaking outwards in to the rest of the star, is there a need for an additional energy source. The core thus begins to contract, releasing gravitational potential energy and therefore getting hotter. Because the core gets hotter, the temperature of the hydrogen-fusing shell outside the core also increases, increasing the rate of fusion. This heats up the intermediate layers of the star, causing them to expand.

The expansion increases the total radius of the star. Recalling that:

$$L_s = 4\pi r_s^2 \sigma T_e^4,$$

and given that the luminosity a radiative envelope can carry is nearly constant for a star of given mass, there must be a decrease in the effective temperature of the star, causing the star to appear red. The immediate post-main-sequence evolution of a radiative star therefore moves the star's position more-or-less horizontally to the right in to the *sub-giant branch* of the HR diagram, as shown in figure 15.

Figure 15: The complete evolution of a low-mass star ($M \lesssim 1.1\ M_\odot$) from the main sequence to a white dwarf, depicted schematically on an HR diagram.

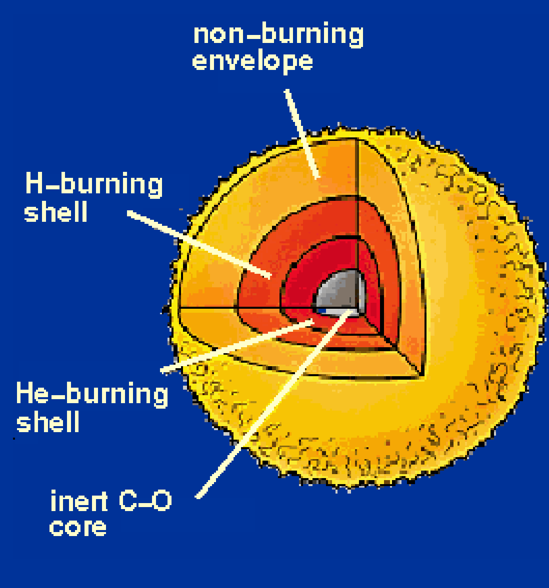


As the star expands, however, the effective temperature cannot continue to fall indefinitely. When the temperature of the outer layers of the star fall below a certain level, they become fully convective. This enables a greater luminosity to be carried by the outer layers and hence abruptly forces the evolutionary tracks of low-mass stars in the HR diagram to travel almost vertically upwards to the *giant branch* (see figure 15). The effective temperature at which this upward excursion in luminosity on the HR diagram occurs is known as the *Hayashi line*. Meanwhile, the helium core continues to contract until it becomes degenerate. The increased gravity at the border of the core and the shell which results from the core contraction raises the density of the hydrogen in the shell. This increases the rate of hydrogen burning in the shell, sending the star quickly up the red giant branch.

The hotter hydrogen-burning shell heats up the degenerate core until it reaches the point where helium fusion to carbon through the triple-alpha process is possible. The onset of this fusion process and the consequent heating of the core would normally increase the core pressure, causing it to expand and cool in response, keeping the temperature just high enough for the nuclear reactions to continue; helium burning would therefore start in a stable fashion. Because the core is degenerate, however, its pressure is independent of the temperature and hence it cannot expand and cool in response to the nuclear energy generation. Hence the core heats up, which increases the rate of helium fusion, which in turn increases the core temperature still further, leading to a *thermonuclear runaway reaction* know as the *helium flash* (see figure 15). The helium flash ends when the temperature has risen sufficiently to make higher-energy electron states available for electrons to move into, lifting the core degeneracy and allowing the core to expand.

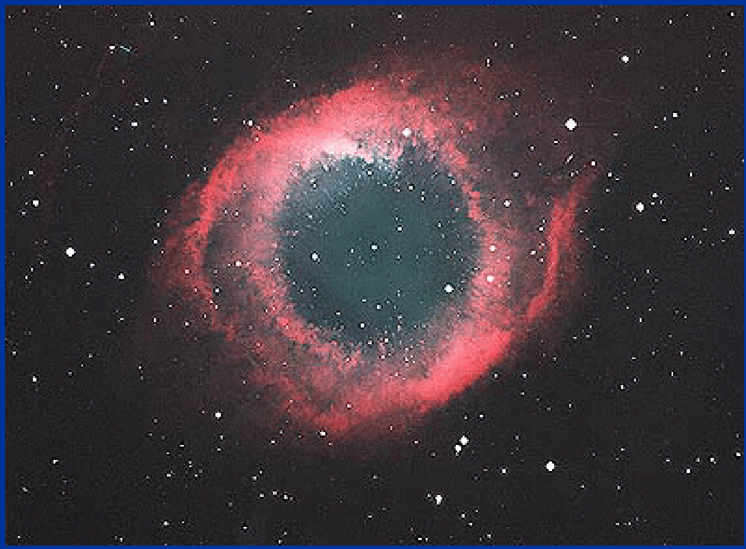
The expansion of the core following the helium flash reduces the gravity at the core/shell boundary, which weakens the hydrogen shell-source. Thus, although the star now has two nuclear energy sources - the helium burning core and the hydrogen-burning shell - the prodigious shell source is now so weakened that the star produces less luminosity than before. The lower total luminosity is too little to keep the star in its distended red-giant state and the star shrinks in size, dims and settles on the *horizontal branch* (see figure figure 15).

Figure 16: The structure of a low-mass star ($M \lesssim 1.1\ M_{\odot}$) on the asymptotic giant branch of the HR diagram.



The history of the helium burning stage is much like the earlier hydrogen burning stage. When the core helium is exhausted, a helium burning shell is established between the inert carbon-oxygen core and the hydrogen-burning shell (see figure 16) and the star evolves up the *asymptotic giant branch*, as shown in figure 15. This stage of stellar evolution is not well understood, involving complex interactions between the helium and hydrogen burning shells. The star becomes increasingly unstable and begins to lose mass in an intense stellar wind, which eventually consumes the whole outer envelope. This lost mass forms an expanding cloud around the star known as a *planetary nebula*, an example of which is shown in figure 17.

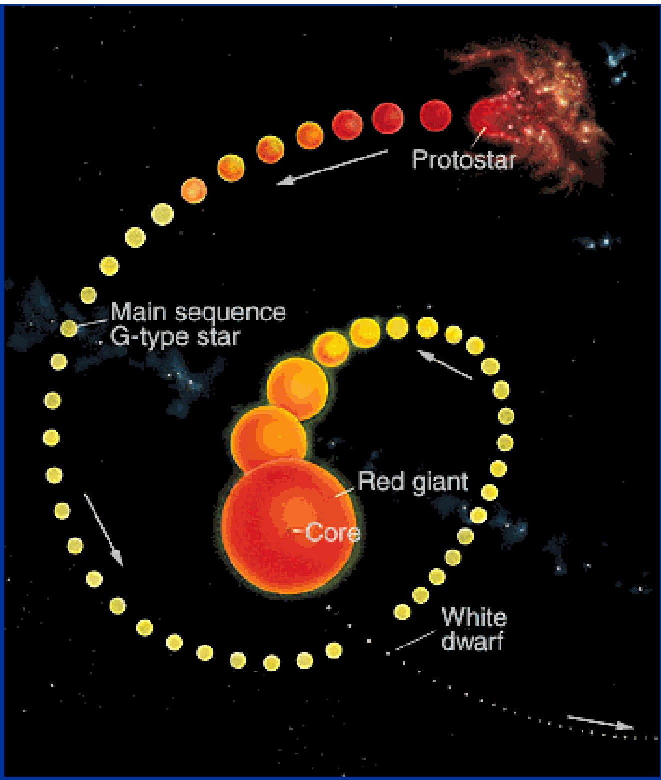
Figure 17: The Helix nebula (©Anglo-Australian Observatory).



The extremely hot, degenerate, carbon-oxygen core of the original star, no longer generating energy, remains as the central star of the planetary nebula and cools slowly as it radiates away its stored heat. When the core has finally burnt its hydrogen and helium shells, lost its extended envelope and descended the HR diagram, it is known as a *white dwarf*. The final approach to a white dwarf from an asymptotic giant star is shown as a dashed line in figure 15 because the theory is incomplete for these late stages of stellar evolution.

Figure 18 summarises the complete evolution of a low-mass star ($M \lesssim 1.1\ M_{\odot}$) from the main sequence to a carbon-oxygen white dwarf in pictorial form.

Figure 18: Pictorial representation of the complete life-cycle of a solar-mass star.



Protostar
Main sequence G-type star
Red giant
Core
White dwarf