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Scilla Degl'Innocenti

Physics Department, Pisa University, Largo B. Pontecorvo n.3, I-56127 Pisa
INFN, Sezione di Pisa, Largo B. Pontecorvo n.3, I-56127 Pisa

E-mail: scilla.deglinnocenti@unipi.it

Abstract. This contribution is meant as a first brief introduction to stellar physics. First I shortly describe the main physical processes active in stellar structures then I summarize the most important features during the stellar life-cycle.

1. Introduction

The quantitative study of the physical structures called "stars" developed later with respects of other physical topics, as electromagnetism or thermodynamics. This because to understand the operation of stellar structures one must already be acquainted with fundamental physical mechanisms as photon-matter interactions or energy production through nuclear fusion. Moreover precise evaluations have been made possible only by the development of electronic calculators. At the same time telescopes more and more refined have been developed, also on board of satellites, to observe the whole electromagnetic spectrum without the limitations induced by the terrestrial atmosphere. Now the characteristics of stars of different mass, chemical composition and evolutionary phase are known with a quite good precision; the general scenario is well defined and in agreement with the most of observations of the Sun and of the stars in our Galaxy.

2. Stellar Observables

The main stellar observables are luminosity and color. The luminosity is the energy emitted per unit time, but it is not directly measurable for two main reasons. In general, the adopted detector (telescope) is not sensitive to the whole electromagnetic spectrum, but only to a given spectral range, which depends on its characteristics. Most important, due to the fact that a star isotropically emits its energy in all the directions, what is measured is a flux (energy per unit time and unit surface of the detector) and not a luminosity which, however, is the physical quantity directly linked to the stellar characteristics. In more detail, if L_* is the stellar luminosity, a detector at a distance d from the star measures the flux:

$$\Phi = \frac{L_*}{4\pi d^2} \tag{1}$$

The luminosity can be obtained only if a distance estimate is available; it's thus easy to understand why the problem of distance determination of astrophysical objects is of paramount importance. The color of a star, that is the spectral distribution of the emitted energy, can be directly connected with the temperature of the stellar surface (photosphere). In fact for

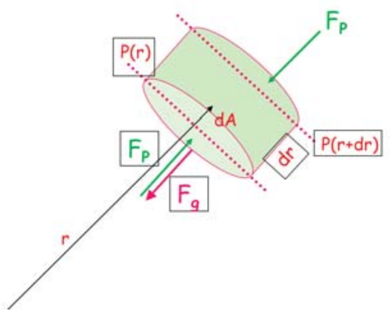

Figure 1. Balance between pressure force (F_P) and gravity force (F_g) on a given infinitesimal element at distance r from the center of the star with tickness dr and base area dA.

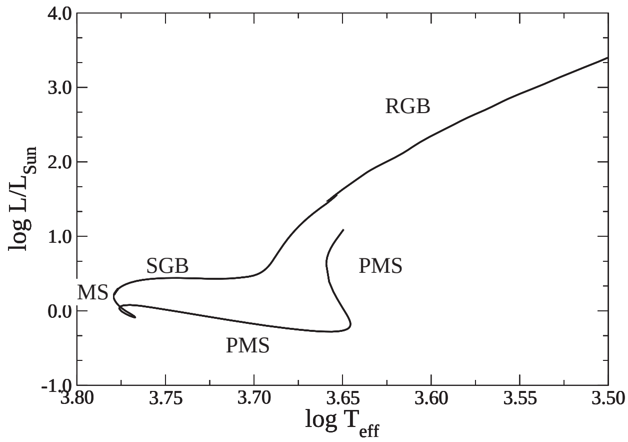

Figure 2. Evolution in the Hertzsprung-Russell diagram of a 1 $M_\odot$ star from the Pre-Main Sequence to the end of the Red Giant Branch phase.

almost the whole stellar structure photon-matter interactions are so efficient that the star can be assumed at thermodynamical equilibrium. In this case the gas particles follow a Maxwell-Boltzmann distribution while the photons a Planck one, with the same temperature for particles and photons. The temperature clearly varies with the position inside the star; in most cases the temperature monotonic decreases from the center to the stellar surface. Under these conditions the energy spectral distribution is the so called "black body distribution". In reality the emission of a star with a given surface temperature slightly differs from the one of a black body of the same temperature, due to emission and absorption phenomena by the atoms/molecules/grains of the stellar atmosphere. For a precise relation between the observed stellar color and the surface temperature one needs so solve the photons transport equation in the stellar atmosphere, taking into account all the possible absorption/emission phenomena. It's easy to understand that these calculations are very complex and they become more and more difficult as the photospheric temperature decreases because, due to the higher presence of molecules and grains, the possible photon-matter interactions increase more an more. These kind of calculations, which are an example of how much computing capacity is fundamental for precise stellar physics evaluations, are performed by few groups in the world and they are still affected by not negligible uncertainties mainly for stars with relatively low photospheric temperature. In absence of high rotation velocities and magnetic fields (which is supposed to be the situation of the most of the stars) the stellar equilibrium configuration is a sphere (as we will better discuss in the following); however, in general, it's not possible to directly measure the stellar radius. Stellar surface temperatures are generally expressed as "effective temperature" , that is the temperature which would have a star if it would exactly emit as a black body. Thus the relation among luminosity (L), radius (R) and effective temperature (T_{eff}) is:

$$L = 4\pi R^2 \sigma T_{eff}^4 \tag{2}$$

where σ is the StefanBoltzmann constant, $\sigma = 5.67 \cdot 10^{-5}$ dyne cm^{-2} K^{-4}. Usually, observed stars are shown in a plane which resumes the main stellar observables: effective temperature (or correspondingly the stellar color) on the abscissa and total luminosity (or correspondingly the luminosity in a given photometric band) on the ordinate, the so called Hertzsprung-Russell (Color-Magnitude) diagram.

3. Stellar structure and evolution equations

To "solve" a stellar structure means to theoretically calculate its physical quantities (temperature, pressure, density, luminosity production etc..) at each point inside the star. To do this one has to solve the so called "stellar equilibrium equations" which reflect the stellar characteristics describing its working principles.

3.1. Stellar gas characteristics

Stars are spheres of photons and plasma, that is ionized gas in which electrons are extracted from the atoms; the plasma is thus constituted by electrons and ions but it is globally neutral. The ionization state of the atoms which constitute the stellar plasma mainly depends on temperature and density (and clearly on the ionization energy of the various electrons of the different atomic species) and thus it varies inside the star. At each point in the stellar interior the ionization state of each specie can be calculated through the Saha equation [see e.g. 1, , cap.3]. The thermodynamical properties of the plasma can be calculated as a function of the chemical composition and of two physical quantities (e.g. pressure and temperature) through the equation of state (EOS) of a system of plasma and photons at thermodynamical equilibrium. For the Sun the law of perfect gas holds with a very good approximation, except for the very central regions in which few percents of the pressure are due to degenerate electrons. For different conditions of temperature and pressure the EOS can be more complicated; at relatively high density electrons became degenerate and under specific conditions coulombian effects among ions are no more negligible. Thus if one knows the chemical composition and two physical quantities (e.g. temperature and pressure) at a given point inside the star, one can obtain through the EOS all the thermodynamical quantities at that point. This can be synthetically written as:

$$\rho(r) = \rho[T(r), P(r), X(r), Y(r), Z(r)], \tag{3}$$

where X(r),Y(r) and Z(r) are, respectively, the fractional abundance in mass of hydrogen, helium and elements heavier than helium, which in astrophysics are called "metals", at a given radial coordinate. Clearly X(r)+Y(r)+Z(r)=1.

3.2. Hydrostatic equilibrium

Stellar lifetimes are orders of magnitude higher than the human ones, thus it's impossible to directly follow a stellar life-cycle. However now one can observe an enormous number of stars at different ages, obtaining in this way information about the characteristics of the stars at different phases of their life. Moreover the Sun has been observed in a scientific way from centuries. In addition the fact that the life is present on the Earth from some millions of years means that the solar characteristics did not change in a relevant way during this period. The evidence that most of the stars do not change their luminosity, effective temperature and thus radius for periods longer than centuries means that they are structures at mechanical equilibrium. The dynamical timescales (that is the time in which a structure out of dynamical equilibrium changes its characteristics) in stars are in fact of the orders of hours, [see e.g. 2, cap.1]. At each point inside a star the gas pressure counteracts the gravity force which would cause the stellar contraction. The gravity is a central force, thus the equilibrium configuration is a sphere. This simplifies very much the calculations: for spherical symmetry all the quantities can be expressed as a function of the radial coordinate. One can imagine a stellar structure composed of several spherical shells so thin that the physical quantities inside each shell can be assumed constant; by solving the stellar structure equations one can obtain the value of the physical quantities in each shell.

The mass, dM, inside a shell of radius dr is then:

$$dM(r) = 4\pi r^2 \rho(r) dr; \tag{4}$$

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where ρ(r) is the corresponding density inside the shell. This is called "continuity equation".

If at each point of the star one equates the pressure force to the gravity force, as shown in Fig.1, one obtain the so called "hydrostatic equilibrium equation":

$$\frac{dP(r)}{dr} = -G\frac{M(r)}{r^2}\rho(r) \tag{5}$$

where P(r) is the pressure and M(r) is the mass inside a sphere of radius r; the above equation holds at each radial coordinate r.

The hydrostatic equilibrium equation also implies that the most internal regions, which must "support" the above layers, have an higher pressure. Thus, in general, the pressure is expected to monotonically decrease from the center to the surface. The two equations written until now, as a function of the radius, contains three unknowns: P(r), ρ(r) and M(r). P(r) and ρ(r) are linked through the equation of state, but, except some particular EOS, in this case, also the temperature (unknown) appears in the EOS. Thus the system is still not resolvable. This is expected, because the energy production and transport, which play an important role in stellar structures have still not taken into account.

3.3. Thermal equilibrium and energy production

Stars are very hot structures and thus they radiate, that is they emit photons, losing energy from the surface. The fact that the stellar effective temperature remains constant for longtime means that the stellar surfaces are at thermal equilibrium, that is the energy losses from the photosphere through photons emission are counterbalanced by an energy flux which reaches the photosphere from the underlying layer. If this would not happen the photosphere would change its temperature in few minutes. Actually the concept of "thermal equilibrium" is more general and it must be applied to the whole star; the energy which enters in each shell is equal to the one which exits from the same shell plus the energy which is possibly produced inside the shell itself.

The stellar photosphere is continuously supplied of energy by the more internal regions. For the majority of the stellar life this energy is produced by nuclear reactions; stellar interiors are so hot that fusion nuclear reactions of nuclei to form heavier elements can happen. The nuclear reactions most important for energy production are among charged nuclei. For these fusion reactions high temperatures (higher than about 10^6K) are needed because the nuclei must reach enough energy to pass the Coulom barrier through tunnel effect, reaching nuclear distances ($\approx 10^{-13}$ cm) in a way that nuclear reaction can happen, [see e.g. 3, cap.3]. The mechanism of nuclear fusion in stars has been described in detail in other talks at this school and thus I will not discuss it here. I only remind that the higher is the charge of reacting nuclei the higher is the threshold temperature for the ignition of the fusion. However the nuclear fusion is not the only possible energy source in stars; stars can produce energy through thermodynamical transformations of the gas linked to contractions and expansions of stellar regions, the so called "gravitational energy". Then stars lose energy also through neutrino production. Neutrinos have a mean free path larger than the stellar radius (except the case of very dense stellar cores of massive stars at the end of their life) and thus they escape from the stars without interacting with the stellar matter, that is without releasing their energy to the stellar structure. During nuclear fusions electron neutrinos are formed; in this case the only effect is that neutrinos take away a relatively small amount of the energy produced by the fusion, which is no more available to the structure. Most important for the stellar energy balance is when neutrinos are produced in regions in which nuclear fusions are not active. Different processes active for different ranges of density and temperature are responsible for this kind of neutrino production: neutrino photoproduction, neutrinos from couple production, plasma neutrinos etc...[see e.g. 4]. In these case the neutrino production constitutes for the stars a net energy loss and thus the

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regions in which these kind of neutrinos are produces cool down. Summarizing, in each region of the star energy production through nuclear fusions and/or thermodynamical transformations and/or neutrino energy losses can happen. Usually we define ε the energy produced/lost per unit time and unit mass due to the mechanisms described above, that is:

$$\varepsilon(r) = \varepsilon_{nuclear}(r) + \varepsilon_{gravitational}(r) - \varepsilon_{neutrinos}(r) \tag{6}$$

Each process of energy production depends on the physical quantities (density/pressure and temperature) and chemical composition which vary at each point of the star. In particular the various nuclear reaction rates can be written as analytical expressions, as a function of temperature, density and reagent abundances [see e.g. 5]. With these information it's possible to write the thermal equilibrium equation in each shell of the star:

$$\frac{dL(r)}{dr} = 4\pi r^2 \rho(r)\varepsilon(r); \tag{7}$$

where L(r) is the luminosity (energy per unit time) which enters in a shell of radius r. Another equation is added to the system but another unknown, i.e L(r), is also added.

3.4. Energy transport

The energy produced in the internal regions must be transferred to the whole star. The only energy transport mechanism which is always active in stars is the radiative transport, that is the totality of processes of photon-matter interaction. The main processes in the stellar interiors are: photon-electron scattering (which, due to the relatively low energies, is mainly a Thompson scattering), photoionization, inverse bremsstrahlung, photon absorption (and further isotropic emission) of photons by atoms ,[see e.g. 1, cap.16]. While for the external parts of the stars, much less dense and with relatively low temperatures, the main opacity sources are scattering and photoionization on H^- ions, absorption on molecules and grains, scattering on molecules and molecules photodissociation. The total amount of photon-matter interaction processes, which remove energy from the outgoing flux, is called "opacity", k, and it is measured as a cross section (of the various processes) per unit mass, that is in cm^2/g. In this sense the induced emission process constitutes a negative contribution to opacity. Clearly, each opacity process depends on the physical quantities (e.g. temperature and density) and on the chemical composition, in a way that not only the total opacity varies with radius but also the photon matter interaction process which dominates the opacity is dependent on the position inside the star. The opacity also depends on photon distribution. By assuming a Planck distribution (which is a valid guess for the whole star, but the atmosphere) one can mediate the opacity over the photon distribution obtaining the so called "Rosseland mean opacity" , $\bar{k}$,[see e.g. 2, cap.4]. It's easy to understand that opacity calculations are very difficult because one must evaluate the efficiency of the described processes for each element of the stellar mixture taking into account all the possible ionization states. Opacity calculations must thus rely on a equation of state too. Few groups in the world are able to perform these calculations; the results are made available to the astrophysical community through tables as a function of temperature, density and chemical composition. By imposing that photons follow the Planck distribution and assuming that the photon-matter interaction is the only active energy transport mechanism, it's easy to find [see e.g. 6, cap.3], at each point inside the star, a relation between the temperature gradient and energy flux to be transported, the so called "energy radiative transport equation":

$$\frac{dT(r)}{dr} = -\frac{3}{4}\frac{\bar{k}(r)\rho(r)}{ac}\frac{1}{T(r)^3}\Phi(r); \tag{8}$$

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where the photon flux Φ at each point of the star is:

$$\Phi(r) = \frac{L(r)}{4\pi r^2}, \tag{9}$$

c is the light speed and a is the radiation pressure constant (a=$7.56 \cdot 10^{-15}$ erg cm^{-3} K^{-4}). Thus one sees that the temperature gradient needed to transport a given flux entirely through photon matter interactions (radiative gradient) is proportional to the flux itself and to the opacity, that is to the "resistance" of the matter to the photon flux. For completeness one has to mention that other energy transport mechanisms are possible. If the temperature gradient required to a stellar structure to transport energy through photon-matter interactions would be too much high, energy transport through convection becomes efficient too, even if radiative transport is still present. Briefly, the convective energy transport is due to mass elements which move from hotter to colder regions releasing their heat similarly to what happens for the water boiling in a pot. In this case the total energy flux is transported through both the radiative and convective mechanisms and the temperature gradient expression is different from the one written in eq.8. A precise treatment of convection is out of the purposes of this talk but it's useful to remind that convection is active in the regions where the radiative gradient of eq.8, which is proportional to the energy flux and to the opacity, is enough high. More precisely, for the convection activation, the radiative gradient must be higher than the adiabatic gradient, a thermodynamical quantity, obtained from the EOS. It's also worth noticing that in very dense stellar regions energy transport due to degenerate electron conduction [see e.g. 2, cap.4] dominates; in this case too eq.8 is no more valid.

If one reminds that pressure is, in general, monotonically decreasing from the center to the surface, taking into account the radiative transport equation and the thermodynamical characteristics of the photon and gas mixture (e.g. for simplicity one can image a perfect gas law) generally speaking one can understand that temperature and density too decreases from the center to the stellar surface.

We have thus written in total four equations as a function of the radius for four unknowns (pressure, temperature, mass, luminosity), whereas the density is related to pressure and temperature through the EOS; thus the system is resolvable, once ε(r) and $\bar{k}$(r) are evaluated. These differential equations can be numerically solved [see e.g. 6, cap.3] finding, once fixed the mass and the stellar original chemical composition, the physical quantities in each point of the star.

As it will be better discuss in the following, the temporal evolution of the stars is generally driven by chemical composition variations, mainly due to nuclear reactions. Once solved the equations set at a given time, t_0, taking into account the variations of the chemical composition after a temporal step Δt, one can integrate again the equations with the new composition at the time $t_0 + \Delta t$ obtaining the stellar characteristics at that time. A similar procedure is applied in the phases in which the nuclear reactions are not active when the stellar changes are mainly driven by the contraction/expansion of the structure. These procedures are iterated for several temporal steps to follow the stellar evolution.

4. Stellar evolution

In the following I will describe the main stellar features during the different evolutionary phases, as obtained by solving the stellar structure and evolution equations; some of the main characteristics can also be roughly obtained by general evaluations discussed above.

4.1. Pre-Main Sequence and Main Sequence stars

Stars born inside a molecular cloud of gas and interstellar dust; the gas is mainly composed by H and He with traces of other elements. These molecular clouds, neglecting, as a first

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approximation, possible effects due to rotation and magnetic fields, are in equilibrium between the gravitational force and the pressure force. However, due to stochastic motions, the colder and more dense regions of the cloud, can start to contract. As soon as the collapse proceeds the region fragments more and more; until each part in which the original region of the cloud has been divided will form a star. The way in which the gas of the original cloud falls onto the star until the achievement of the stellar final mass is still an open problem, because hydrodynamical protostellar models are still largely debated and not yet settled. The duration of the protostellar phase too is not known with precision and it varies with the stellar mass, but it is supposed to range from few 10^5 to about 10^6 years, [see e.g. 7, for details].

Anyhow, at the end of the protostellar phase the radiation pressure of the new born star sweep away the residual gas of the original cloud. The star is now in the "Pre-Main Sequence phase (PMS)". Moreover during the first phases of their life stars are supposed to be fully convective; thus they are completely mixed and possible chemical inhomogeneities of the original cloud are canceled. During the protostellar phase the star contracted and warmed up until the achievement of the hydrostatic equilibrium: the gas force exactly counterbalances the gravity force. The stellar gas pressure is mainly due to its high temperature. However the star is warm and radiates, loosing energy from the surface; thus, after a while, the star cools down and its pressure decreases becoming insufficient to completely sustain the star against the gravity. The star slightly contracts increasing its temperature and reaching again the hydrostatic equilibrium until the radiation losses from the surface cools down again the star. The PMS phase is characterized by these consecutive stellar contractions when the star passes from one "quasi-equilibrium" state to another one, while its internal temperature increases. The timescale of these processes is the one at which the stars cools down, that is the timescale in which a photon produced in the stellar interior can reach the surface. This timescale that can be seen also as the "relaxation time" for departure of a star from the thermal equilibrium (the so called "Kelvin-Helmholtz" time) varies with the stellar mass but it is of the order of 10^6-10^7 years.

While the star contracts its density increases too and the radius significantly decreases, then also the luminosity strongly decreases as shown in Fig.2. During the PMS evolution a star reaches first the temperature for deuterium and light elements (Li, Be, B) burning, then it reaches the temperature for hydrogen burning into helium in its core, which is the warmest region of the star. The hydrogen fusion into helium is the first nuclear reaction able to produce an energy which can replace the radiative losses from the surface. Hydrogen is the first abundant element to be burned because the coulombian barrier for the fusion of two protons is the lowest one and H is the most abundant element in the Universe. When the hydrogen fusion is fully active the star is in equilibrium, with the nuclear reactions which supply to the star the energy lost by photon emission from the photosphere. Sometimes one hears on TV broadcasts that the stellar luminosity depends on the efficiency of the nuclear reactions, but actually the exactly opposite is true. Stars are luminous because are warm and, as all the warm bodies, they irradiate. As a first approximation, the stellar temperature depends from the fact that the stellar gas must be warm to have enough pressure to counteract the gravity force; then the surface temperature also depends on the temperature gradient inside the star (see eq.8). Thus, roughly speaking, the higher is the mass of the star, the higher is its effective temperature and its luminosity. When, at the end of the PMS phase, hydrogen fusion ignites, it adjust its efficiency until the energy losses from the surface, proportional to the effective temperature and the stellar radius, are completely counterbalanced. This because in stars a feedback mechanism is efficient: if the produced energy is lower than radiative losses the star still cools down and contract, even if with a longer timescale. The result is the increase of the temperature of the central regions together with the burning efficiency, which is very sensitive to the temperature. On the contrary if the produced energy is higher than the one lost from the surface, the central regions warm up and expand; this leads to a temperature decrease and thus to a reduction of the burning efficiency. At the end of the process the energy produced by nuclear reactions is adjusted to exactly counterbalance the surface energy losses. Thus, in this phase, the stellar luminosity is mainly due to the stellar mass (with a smaller dependence on the chemical composition) and the nuclear reaction efficiency is tuned to exactly produce the energy needed to the star to irradiate. When nuclear reactions are so efficient to counterbalance the energy losses from the surface, the star leaves the PMS phase starting its Main Sequence (MS) evolution. The name "Main Sequence" is due to the fact that stars in this phase occupy in the Hertzsprung-Russell diagram a mono-parametric sequence (neglecting the secondary effect of the chemical composition) whose parameter is the stellar mass. It's worth noticing that stars with masses lower than about 0.08 $M_\odot$ do not succeed to reach the central temperatures needed to hydrogen ignition. They remain in the Pre-Main Sequence phase continuing to contract while the density increases until the star is sustained by the pressure of the degenerate electrons; these kind of stars are called "brown dwarfs". The star is now in equilibrium thanks to the nuclear energy, but the reaction efficiency decreases according to the reduction of the fuel (hydrogen) abundance. Thus, after a while, the nuclear energy is no more enough to counterbalance the radiative losses and the star contracts again, with the timescale of the fuel abundance reduction, that is of the nuclear burning rate. Thus the temperature of the central regions slightly increases until the energetic equilibrium is reached again, with a slightly different configuration of the stellar structure; that is the star evolves with nuclear timescale.

Nuclear timescales strongly vary with the stellar mass; the higher is the mass, the higher is the luminosity and thus the higher is the rate of the nuclear reactions which counterbalance the energy losses due to the luminosity. Moreover the higher is the fusion rate, the lower is the time in which the fuel is exhausted. To be more precise for the most of the stars the luminosity increases with the mass to a power of $2\div4$, while the H abundance linearly increases with the mass. As an example, the MS time for the Sun is about 10 Gyr while for a 15 $M_\odot$ star of the same chemical composition is about 10^7years.

4.2. Advanced evolutionary phases

The history of a star after the central H exhaustion can be roughly seen as a succession of central burnings of elements with charges more and more high and central regions contractions to possibly reach the temperatures needed for the various burning ignitions. In the phases in which the stellar core contracts nuclear burnings in a shell out of the central regions are often present. One has to remind that the higher is the nuclear charge of the reacting nuclei the higher is the coulombian barrier and thus the higher is the temperature needed for the fusion ignition. But the higher is the stellar mass the higher is its central temperature. The logical consequence is that only the most massive stars (M $\approx$ 10 $M_\odot$) can reach the temperatures needed to ignite all the exoenergetic reactions up to the production of the elements of the iron peak. These stars can thus produce all the elements of the periodic table, through fusions of charged particles and neutrons and protons captures on nuclei. The death of these stars is through an explosion in which the most of the stellar matter is ejected in the space (type II supernova) and thus it will constitute the cradle for the birth of a following stellar generation. Stars with lower masses have different final fates in dependence of their mass.

After the central H burning the stars experience a phase in which H is burned in a shell around a central inert He core. In this phase the stellar envelope expands and cools down and the star moves toward the red in the HR diagram (Sub Giant Branch, SGB, phase), see Fig.2. During the MS evolution the burning core slightly contracted and its temperature increased, so that during the Sub Giant Branch H burning mainly occurs through the CN-NO bi-cycle, much more sensitive to the temperature than the concurrent proton-proton chain [see e.g. 3, cap.6]. When CNO hydrogen burning reaches the equilibrium of secondary elements in the cycle, the stars enter in the Red Gian Branch, RGB, phase (see Fig.2). Stars now have an extended and low density envelope; their luminosity and lifetime are mainly governed by the dense He core and the surrounding H burning shell, while the temperature gradient in the envelope determines the stellar effective temperature. In particular the RGB luminosity increases with the He core mass which grows due to the burning in the H shell which surrounds the He core. The RGB phase ends when the central regions of the star reach the temperature for helium burning into C and O ($\approx 10^8$ K), thanks to the He core contraction due to its mass growth. Stars with masses lower than about 2.3 $M_\odot$ (the so called "RGB transition" mass), whose interiors did not reach very high temperatures, remain longtime in the RGB phase because the reaching of the He burning temperature is more difficult. These stars reaches very high luminosities along the Red Giant Branch and thus the mass losses by stellar winds, driven by the radiation pressure, increase too. At the end stars with masses greater than about 0.5 $M_\odot$ succeed to ignite central He burning. The evolutionary theory predict that lower masses will remain in the RGB phase loosing more and more mass until the only remain will be the dense, degenerate He core, surrounded by a very thin H shell with all the nuclear burnings switched off. A similar structure, called He white dwarf (He WD), is maintained in equilibrium by the pressure of degenerate electrons which counteracts the gravity and it will cools down until it will reach the cosmic background temperature. However the Main Sequence lifetime of stars with $M < 0.5\ M_\odot$ is higher than the present age of the Universe, thus no one of these stars still reached the white dwarf phase. However He white dwarfs are observed; their progenitors are stars of mass higher that $0.5M_\odot$, which during the RGB phase loose so much mass that the H shell switches off and the stars leave the RGB phase ending their life as He WDs. Stars which ignite He in the center but did not explode as supernovae end their life as white dwarfs with a C/O core or with a Ne core if they succeed to ignite carbon too.

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References

[1] Cox J P 1968 *Principles of stellar structure - Vol.1: Physical principles; Vol.2: Applications to stars* (New York: Gordon and Breach)

[2] Hansen C J, Kawaler S D and Trimble V 2004 *Stellar interiors : physical principles, structure, and evolution* (New York: Springer-Verlag)

[3] Rolfs C E and Rodney W S 1988 *Cauldrons in the cosmos: Nuclear astrophysics* (Chicago, IL: University of Chicago Press)

[4] Raffelt G G 1996 *Stars as laboratories for fundamental physics : the astrophysics of neutrinos, axions, and other weakly interacting particles* (Chicago: University of Chicago Press)

[5] Fowler W A, Caughlan G R and Zimmerman B A 1967 *Annual Review of Astronomy and Astrophysics* **5** 525

[6] Salaris M and Cassisi S 2006 *Evolution of Stars and Stellar Populations* (Wiley-VCH)

[7] Stahler S W and Palla F 2005 *The Formation of Stars* (Wiley-VCH)