Tema 2

Conceptos generales sobre estructura y evolución estelar

Asignatura de Astrofísica Nuclear

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General properties of stars

1.1 Luminosity

Luminosity is defined as the total power of the star to sustain the energy flux cross a large surface surrounding the star. This energy flux is of three types of radiation: photons, neutrinos and mass loss.

$$L = L_\gamma + L_\nu + L_m$$

Photon luminosity can be determined from the apparent brightness measured by a telescope or detector corrected by the distance to the star, the energy absorption in the inter-stellar medium or in the Earth's atmosphera and the detection efficiency.

Considering F_λ as the net outgoing energy flux at wavelength λ and R the radious of a surface surrounding the star, the photon luminosity can be obtained as:

$$I_\gamma = 4\pi R \int_0^\infty F_\lambda d\lambda$$

If the Earths is a distance r from the star, the incident flux on Earth will be:

$$f_\lambda = \left(\frac{R}{r}\right)^2 F_\lambda$$

Defining a as the collecting area of the telescope/detector, A_λ the transmission probabilty through the inter-stellar medium and Earth's atmosphera, and R_λ the recording efficiency, the apparent brightness can be obtained as:

$$b = \pi a^2 \int_0^\infty f_\lambda A_\lambda R_\lambda d\lambda$$

The magnitude (m) of the difference in apparent brightness between two stars in defined using a logaritmic scale according to the equation:

$$m_2 - m_1 = 2.5 \log \frac{b_1}{b_2}$$

General properties of stars

1.1 Luminosity

Neutrino luminosity is defined as the energy lost by the star by radiating neutrinos.

- ✓ Because neutrinos interact so weakly with matter, in general, those produced in the stellar interior scape from the star without further interaction. Therefore, neutrino emission provides a heat loss directly from the stellar interior. The only exception occurs for matter at extremely high density and temperature as may be found in the imploded core of a supernova.
- ✓ Neutrino luminosity is unobserved, therefore can only be determined from model calculations. The correctness of the neutrino luminosity estimates are to be found in the effects it has upon the observable evolution of the stars.

Mass-loss luminosity is due to loss mass from the stellar surface.

- ✓ Supernovas explosively eject a large amount of matter, comparables to the solar mass, at velocities of the order of thoudands kilometers per hour.
- ✓ In binary stellar systems one of the stars acretes matter from the companion.
- ✓ Main sequence stars as our sun eject matter from their surface due to hydromagnetic shock waves produced at their outer layers.

General properties of stars

1.2 Temperature

A star is defined as a mechanical system in **themal equilibrium** and therefore characterised by a temperature.

✓ A gas system like a star with internal energy *E*, has many configurations corresponding to the different distributions of its energy among the gas particules. The most probable configuration is known as the equilibrium configuration.

✓ Statistical mechanics allows us allow to calculate the most probable configuration. The number of gas particles of energy ε, $n(\varepsilon)$, can be obtained as the product between the number of possible particle states of energy ε, $g(\varepsilon)$, and the ocupation probability of those states that depends on the nature of the gas particles:

- in the classical limit, identical but distinguishable particles: (**Maxwell-Boltzmann statistics**)

$$n(\varepsilon) = \frac{g(\varepsilon)}{e^{\alpha+\varepsilon/kT} + 0}$$

- identical but distinguishable particles of half-integral spin: (**Fermi-Dirac statistics** for fermions)

$$n(\varepsilon) = \frac{g(\varepsilon)}{e^{\alpha+\varepsilon/kT} + 1}$$

- identical but indistinguishable particles of integral spin: (**Einstein-Bose statistics** for bosons)

$$n(\varepsilon) = \frac{g(\varepsilon)}{e^{\alpha+\varepsilon/kT} - 1}$$

1.2 Temperature

- ✓ In previous expressions, *k* is the Boltzmann constant, *T* is temperature and α is a real number whose value depends upon the density of particles. For small density, α is a large positive number, whereas for very high density, α is a large negative number.

- ✓ Photons are a particular case. Since they do not have mass it costs little energy to create photons with small frecuency. Therefore, only the total energy of the photon gas and not the number of photons must be conserved in establishing the most probable configuration (α=0).

$$n(\varepsilon) = \frac{g(\varepsilon)}{e^{\varepsilon/kT} - 1}$$

- ✓ The intrinsic probability that a state of energy ε is occupied can be obtained as P(ε)=n(ε)/g(ε), known as occupation index.

- ✓ The density of states for a given energy ε can be calculated as:

- for fermions (electrons) $$g_{e^-}(\varepsilon) = \frac{4\pi V}{h^3}\left(2m_{e^-}\right)^{3/2}\varepsilon^{1/2}$$

- for bosons (He gas) $$g_{He}(\varepsilon) = \frac{2\pi V}{h^3}\left(2m_{He}\right)^{3/2}\varepsilon^{1/2}$$

- for photons (ε=hν) $$g_{\gamma}(\nu) = \frac{8\pi h \nu^3}{c^3}$$

General properties of stars

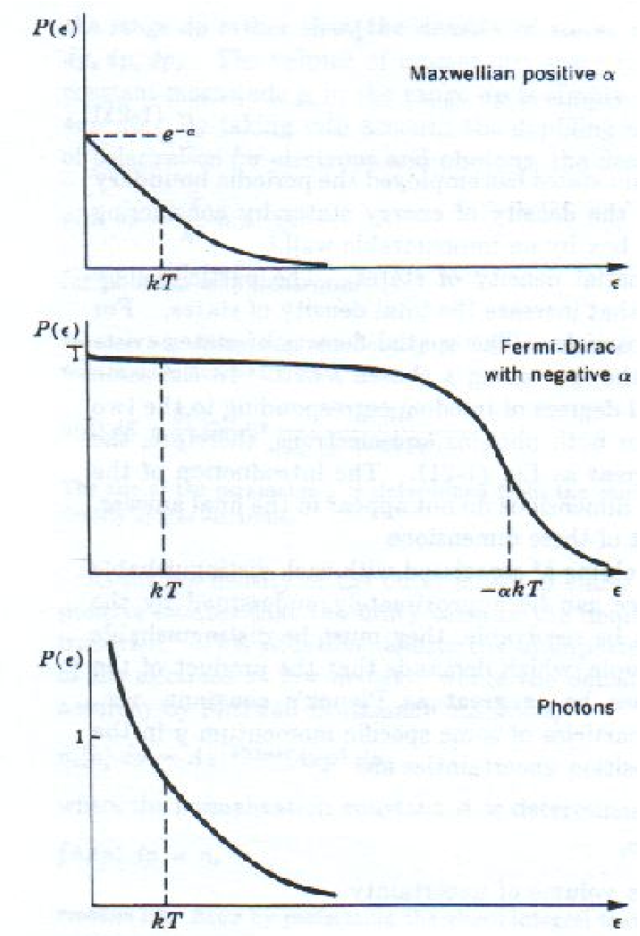
1.2 Temperature

✓ The analysis of the energy dependence of the occupation index for the different statistical distributions of gas particles yields the following conclusions:

- The Maxwell-Boltzmann distribution presents a pure exponential dependence with energy. This distribution is only valid when α is a large positive number, i.e., when the occupation is much smaller than unity.

- The occupation index of the Fermi-Dirac distribution never exceeds unity. This limit is an expresion of the Pauli exclusion principle for fermions. If the temperature and density fall into a domain for which α is a large positive number (low density), the Fermi-Dirac statistics reduces to Maxwelll-Boltzmann statistics.

- For a gas of Einstein-Bose particles there is a tendency for large occupation indices at low energies. For the special case of photons (α=0), P(ε) increases without bound at zero.



General properties of stars

1.2 Temperature

✓ The single greatest simplification of the physics of stellar interior results from the fact that the stellar interior is very nearly in the state of thermodynamic equilibrium. Therefore, one method for determining the stellar photosphere temperature is fitting the total power radiated by the star according to the following expressions where the temperature is a free parameter.

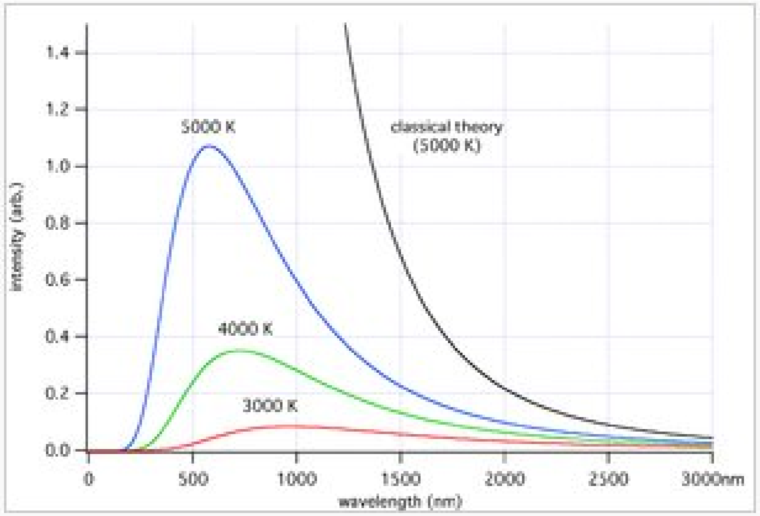
- From previous expressions one can determine the power radiated per unit area and wavelength interval by a blackbody (Planck's law) as:

$$I_\lambda = \frac{2\pi c^2 h}{\lambda^5} \frac{1}{e^{ch/\lambda kT} - 1}$$

and the total power radiated per unit area (Stefan-Boltzmann law) as:

$$I = \int_0^\infty I_\lambda d\lambda = \sigma T^4$$

where $\sigma = 5.67\ 10^{-5}$ erg cm^{-2} s^{-1} deg^{-4}



General properties of stars

1.2 Temperature

- ✓ The **color temperature** is obtained not from the total emitted power but fitting the the energy spectra of photons leaving the start with per unit area and wavelength interval (color) to the corresponding Einstein-Bose with the temperature the free parameter.

$$I_\lambda = \frac{2\pi c^2 h}{\lambda^5} \frac{1}{e^{ch/\lambda kT} - 1}$$

  - The above expression corresponds to a black body emission, therefore, corrections due to spectral absortion (ionization frecuencies) or stellar opacity should be applied.

- ✓ Since the temperature of a true black body is completely determined by the intensity at two distinct wave lenghts, the **color index** (B-V) is defined as the difference in the star luminosity measured with a blue-sensitive photographic plate (blue luminosity: B) and a yellow-sensitive plate and a yellow filter (visual luminosity: V).

  - B-V is greatest for cool stars and smallest for very hot ones

General properties of stars

1.3 Mass

✓ The masses of stars can be measured only when they occur in a binary system and the orbital motion of the pair can be measured, separation and relative motion about their center of mass. The difference of the Doppler shift of spectral lines from the two stars also provided their orbital velocity. Then the masses M_1 and M_2 can be obtained using Kepler's third law:

$$\frac{M_1 + M_2}{M_O + M_{earth}} = \frac{A^2}{P^2}$$

where A is the distance between the two stars (semimajor axis) in astronomical units (1 AU = 1.496 10^{13} cm) and P is the period of the binary system in years. In addition, the ratio of the masses can be determined in those cases where the center of mass of the pair can be found. In those cases is then possible to determine the individual masses.

✓ The only single star whose mass is known with precision is the sun. In this case the mass in obtained from the accurately known orbits of the planets.

$$M_O = 1.989 \pm 0.002\,10^{33}\ \mathrm{g}$$

✓ An interesting feature is that most stars with known masses show a proportional relation between their mass and luminosity. Exceptions are found for white dwarfs and giant stars.

$$L = k \cdot M$$

General properties of stars

1.4 Radius

✓ Despite the importance of this quantity for the theory of stellar evolution, his measurement is still a challenge for astronomers.

- Intensity interferometry has been succesfully applied only to a reduced number of stars.

- More general but uncertain method is based on the Planck's emission law

$$L = 4\pi R^2 \sigma T_e^4$$

the problem in this case is that one needs to know the effective temperature of the star T_e. This effective temperature is defined as the temperature of a black body having the same radiated power per unit area as the star under consideration. As we have previously seen luminosity can be determined from the apparent brightness of the star while temperature can be obtained fitting the energy spectra of the emitted photons.

Stellar classification

2.1 Spectral types

✓ The emission spectrum of stars shows absorption lines corresponding to the ionization of the different chemical elements on his composition and temperature.

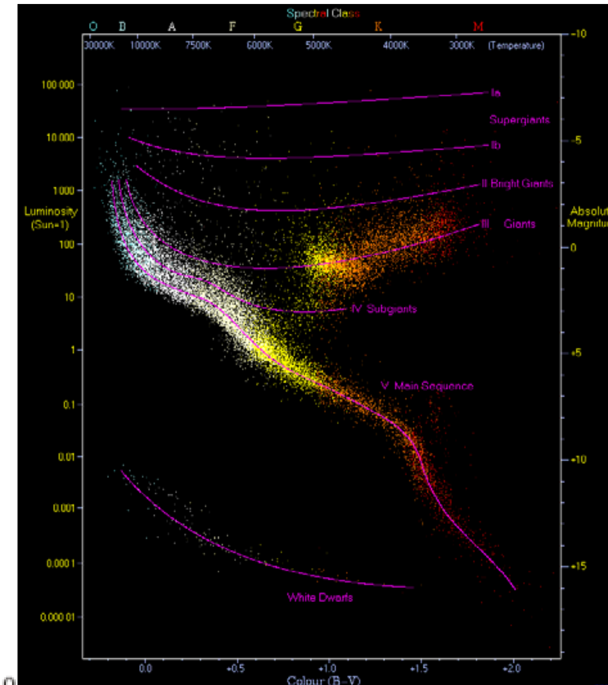
✓ The relation between temperature and the appearance of characteristic absorption lines has been historically used by the astronomers to clasify the stars.

✓ Persently, stars are sorted according to seven spectral types that because of historical reasons are labelled *O, B, A, F, G, K* and *M*.

Class	Temperature	Sample star
O	33,000 K or more	Zeta Ophiuchi
B	10,500–30,000 K	Rigel
A	7,500–10,000 K	Altair
F	6,000–7,200 K	Procyon A
G	5,500–6,000 K	Sun
K	4,000–5,250 K	Epsilon Indi
M	2,600–3,850 K	Proxima Centauri

Stellar classification

2.2 Herzsprung-Russell diagram

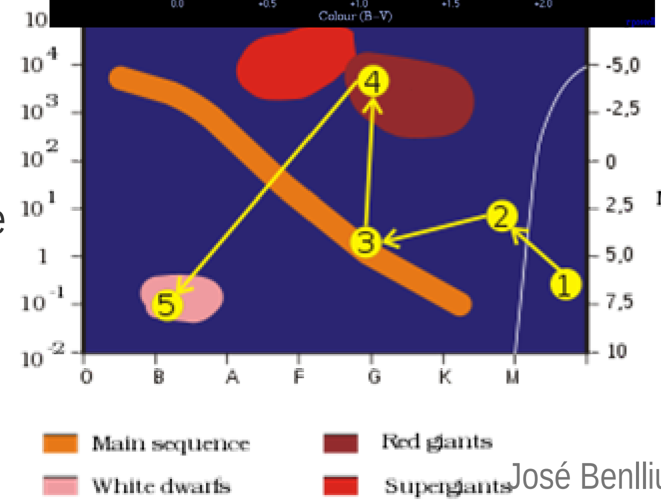


- ✓ The Herzsprung-Russell diagram clasifies the stars according to their luminosity and effective temperature (color index B-V or spectral class). The analysis of this diagram provide important conclusions on the characteristics and evolution of stars.

  - A large percentage of stars (80%-90%) fall on a heavy diagonal curve call **main sequence**. This curve is such that the brightest objects in the sky are those with the highest surface temperatures and are blue in color . The dimmest objects in the sky are red and lie in the lower righ-hand end of the main sequence.

  - Another important group of stars is located above and to the right of the main sequence. These stars call **red giants** are very luminous but they are red in comparison to the main sequence. These stars are powered by the helium burning in their interior.

  - A small number of stars are locates from the lower main sequence upward to the giant region, these are **subgiant** stars. These are belived to be stars whose hydrogen envelopes are expanding while their helium cores contract to a point where the helium ignition begins.

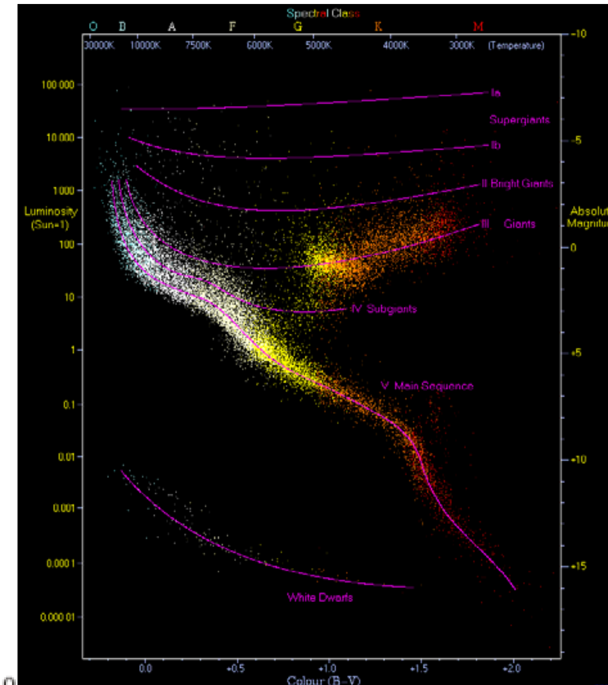


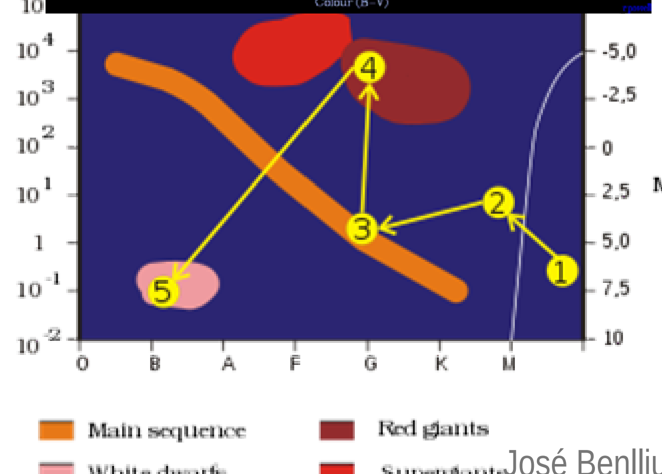
Stellar classification

2.2 Herzsprung-Russell diagram

- There is also a class of very luminous stars of all colors that spreads horizontally across the top of the H-R diagram. These stars called **supergiants** are probably in advanced stages of the stellar evolution and are perhaps approaching the end of their energy-generating lifetime.

- In the lower left-hand of the H-R diagram lies another important class of stars, the **white dwarfs**. These stars are much smaller than the sun although many of them have comparable masses to the sun. Because of their small surface, their surface temperature is quite high, making them blue or white. This class represents around 10% of the observed stars. They represent the end products of the stellar evolution. They consist of degenerate matter having such a high density that the electrons fill all the available cells n momentum space. This situation results in a large internal pressure capable of suporting the start structures despite all internal energy sources are left.





Stellar structure

2.1 Model of stellar structure

A star is a massive , luminous ball of gaseous plasma composed mainly of hydrogen and helium that is held together by gravity and powered by nuclear reactions. Since the vast majority of stars reveal no change in their properties over long time intervals, they are supposed to be in hydrostatic and thermal equilibrium.

Models describing the structure of stars are based on the following assumptions:

✓ Stars are spherically symmetric systems.

✓ Its structure is described by four basic first-order differential equations:
- Radial variation of pressure: hydrostatic equilibrium
- Radial variation of matter density: mass continuity equation
- Radial variation of luminosity: thermal equilibrium
- Radial variation of temperature: energy transport mechanisms.

✓ Relations between pressure, temperature and density are governed by an equation of state that should account for:
- possible degenerancy
- chemical composition

2.1 Equation of state

Equation of state for an ideal gas:

An equation of state is a relation between the pressure, temperature and density of the matter under consideration. In most of the stars (main sequence), the hot gaseous material of the star is described fairly well by the equation of state of an ideal gas:

$$P(r) = \frac{k}{m}\rho(r)T(r) \qquad \text{(Eq. 2.1)}$$

where $k=1.38\ 10^{-16}$ *ergs* K^{-1} is the Boltzmann constant and m is the mean molecular weight.

This equation indicates that since the temperature decreases toward the stellar surface, so does the preasure. The typical values for density and temperature in the interior of the sun and of many other stars are $\rho(r=0)=150$ g cm^{-3} and $T(r=0)=1.1\ 10^7$ K. A normal gas at that density (exciding the one of solid lead) could not be considered as an ideal gas. However, in the very hot interior of a star, matter is nearly completely ionized and the ions and free electrons occupy only a small fraction of the available phase space.

The gas pressure at any point inside the star is produced by the motion of the gas particles (ions and electrons). Additional pressure is generated by the outward fow of radiation being proportional to the Stefan's law.

$$P_{tot}(r) = P_{gas}(r) + P_{rad}(r) = P_{gas}(r) + \frac{1}{3}aT^4$$

where $a=7.565\ 10^{-15}$ ergs cm^{-3} K^{-4}

Stellar structure

2.1 Equation of state

Effects of the chemical composition of stars:

In using equation 2.1 one must take into account that the mean molecular weight *m* of the gas particles in a star change as a function of distance *r* from center. This change occurs because near the surface of the star most of the atoms are f ully recombined, whereas in the interior they are completely ionized.. Furthermore, nucleosynthesis in the stellar interior also changes the chemical composition of the star.

As more and more electrons are stripper off the ions, the mean molecular weigth in the interior decreases, since the same amount of mass is divided among more particles. For completely ionized hydrogen $m=1/2\ m_H$, for helium, $m=4/3\ m_H$ and for metals (ions heavier than helium) $m=2\ m_H$. Using the mass fraction X(H), Y(He) and Z(metals), the mean molecular weight can be obtained as:

$$m = \left[\frac{1}{2X + 3/4Y + 1/2Z} \right] m_H$$

The chemical composition of the sun at its surface is (X=0.73, Y=0.25, Z=0.02), while at its interior is (X=0.42, Y=0.56, Z=0.02)

Exercise 1. Considering two stars with the same size and density distibution but the first one mainly composed of iron and the second one composed by hydrogen, determine their difference in temperature and brightness.

2.1 Equation of state

Equation of state for degenerate matter:

Hot gaseous matter in low-mass main-sequence stars can be described by the ideal gas law. However, in advanced stages of stellar evolution high densities are reached in the stellar interior and the energy distribution of electrons is altered for quantum-mechanical reasons associated with Fermi-Dirac statistics.

In a gravitational collapse, the number of states in a unit energy interval is progressively reduced as the material shrinks and its volume decreases. Since the Pauli principle allows for a single occupation of the states, electrons must occupy states at high energies until all states are filled up to the Fermi level. Under these circumstances, the electrons form a degenerate gas, and the pressure they exert, because of their rapid motion, is much higher than in an electron gas governed by the Maxwell-Boltzmann statistics. This strong resistance to compression produced by a degenerate electron gas is the mechanism that stabilizes certain stars, like white dwarfs, where the rate of nuclear reactions is low because most of the fuel has been used.

Unlike an ideal gas, whose pressure is proportional to temperature, the pressure exerted by a completely degenerate gas does not depend on temperature. If the temperature reaches a sufficiently high value, the degeneracy is lifted and the properties of the gas are again described by the ones of an ideal gas.

There exist an upper limit to the pressure provided by a degenerate gas. If gravity exceeds this pressure, the star will collapse. This limit in mass is called **Chandrasekhar limit** and its value depends on the composition of the star. For an electron degenerate gas and matter composed by two nucleons per electron (e.g. ^{4}He, ^{12}C or ^{16}O) the limiting value amount to 1.44 M_O.

Stellar structure

2.2 Hydrostatic equilibrium

At any point in the interior of a star, the internal pressure must be high enough to support the weigth of the outer layers. Hence, the difference in pressure between two adjacent points in the stellar interior (pressure gradient) will be given by the weight of the material lying between these two points.

$$\frac{dP(r)}{dr} = -\frac{GM(r)\rho(r)}{r^2} \qquad \text{(Eq. 2.2)}$$

P(r) is the total gas pressure at a radial distance *r*, *G* is the gravitational constant, $\rho(r)$ the density at *r* and *M(r)* the mass contained inside the sphere of radius *r*.

The cumulative mass increase with radius is given by the continuity equation:

$$\frac{dM(r)}{dr} = 4\pi r^2 \rho(r) \qquad \text{(Eq. 2.3)}$$

Exercise 2. Using equations 2.1 and 2.2, and the boundary condition P(R)=0, being R the radius of the sun, determine the sun pressure and temperature at r=0.

Stellar structure

2.3 Energy stored and thermal equilibrium

Despite the role of gravitational and thermic energy, the energy flux emitted by stars must be continuosly supplied by an internal source of energy, nuclear reactions. Therefore, we identify three sources of energy in stars.

✓ **Thermal energy,** given by the integral over the star of the thermal energy per unit mass of an ideal gas.

$$E_T = \int_0^R \left[\frac{3}{2}\frac{k}{m}T\right]\rho(r)4\pi r^2 dr \approx \left[\frac{3}{2}\frac{k}{m}T\right]M$$

(see section equation of state for details)

✓ **Gravitational energy**, determined by integrating over the entire star the energy needed to move 1 gram of stellar matter from its surface to infinity.

$$E_G = \int_0^R \left[-G\frac{M(r)}{r}\right]\rho(r)4\pi r^2 dr \approx -\left[G\frac{M(r)}{r}\right]M$$

Using equations 2.1 and 2.3 one obtains $2E_T=-E_G$. This relations is known as the **virial theorem** of classical mechanics. According to this theorem, in a non rotating star, the internal energy stored in the form of heat E_T, is one-half of the gravitational potential energy. The other half will be lost by radiation. Then the energy available for radiation from the stellar surface would just be equal to the thermal energy, but this is known to be insufficient to account for the radiation losses over the whole life o a star.

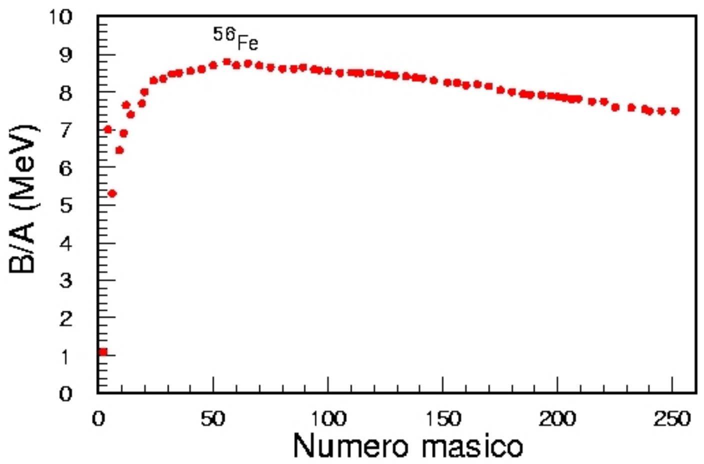
Stellar structure

2.3 Energy stored and thermal equilibrium

Exercise 3. Using numerical values for the mass, radius, temperature and mean molecular weight for the sun, determine the time t over which the thermal energy will cover the radiative loss of the sun.

✓ **Nuclear energy** provides the additional energy to cover the radiative losses of stars from the energy excess in fusion reactions.

Since the original composition of stars is mostly hydrogen and helium the only possible reactions powering stars are fusion reactions. These reactions produced heavier nuclei but also energy. Taken into consieration the evolution of the nucler binding energies the fussion of hydrogen produces the larger amount of energy. This mechanism stops with the production of nuclei as heavy as iron since the synthesis of heavier elements requires energy.



Stellar structure

2.3 Energy stored and thermal equilibrium

Gravitational energy contraction, although it does not provide the long-range energy source, is nevertheless of Importance since it provides the energy youthful stars need to heat up to the point where their supply of nuclear energy can be released. Since stelar evolution is governed by the buring of different nuclear fuels at different temperatures, gravitational compresion provides the additional heating needed is each phase change.

Thermal equilibrium is obtained within a system when all parts of the system have reached the same temperature and there is no further flow of energy. This definition can not apply to stars where the thermal equilibrium is assured from energy conservation between the energy lost at the surface and the energy generated by nuclear reactions. This condition may be expressed by the equation:

$$\frac{dL(r)}{dr} = 4\pi r^2 \rho(r)(\varepsilon - \varepsilon_\nu) \qquad \text{(Eq. 2.3)}$$

where L(r) is the energy flux radiated by the star, ε is the energy released from nuclear reactions and ε_ν is the energy lost by neutrino emission.

2.4 Energy transport

The energy flux in stars is determined by the temperature gradient and energy transport mechanisms: conduction, convection and radiation.

✓ **Thermal conduction** provides energy transport through electrons. This mechanism plays a role in stellar mediums where the mean free path of electrons is relatively large, as it happens when electrons form a degenerate gas. In this case energy transport can be described by the following equation:

$$\frac{dT}{dr} = -\frac{1}{k}\frac{L}{4\pi r^2}$$

(Eq. 2.3.a) where *k* is the thermal conductivity.

✓ **Radiative transfer** is the dominant mechanism leading to the emission of gamma radiation according to the Stephans law. Due to the density is the stellar interior the mean free path of photons is of the order of 1 cm. Under such conditions, only the temperature gradient inside the star produces an effective outward flow of energy described by the equation:

$$\frac{dT}{dr} = -\frac{3K\rho L}{64\pi r^2 \sigma T^3}$$

(Eq. 2.3.b) where *K* is the opacity of the star and σ is the Stefan-Boltzmann constant.

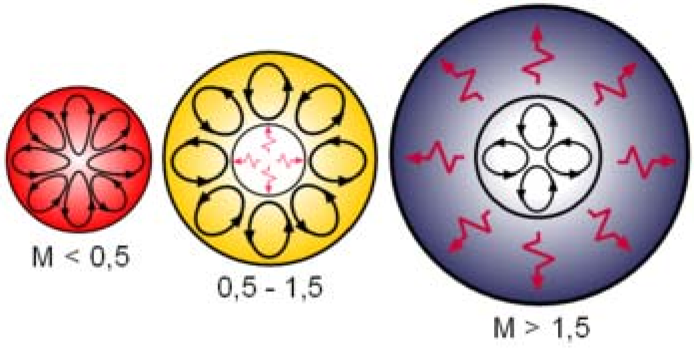
2.4 Energy transport

✓ **Convection** transports energy through the movement of mass, like in boiling water. This mechanism takes place when the opacity of the star is so high that radiation is not effective anymore in transporting energy.

$$\frac{dT}{dr} = \left(1 - \frac{1}{\gamma}\right)\frac{T}{P}\frac{dP}{dr}$$ (Eq. 2.3.d)

where γ=5/3 is the adiabatic index.

The relevance of the different energy transport mechnisms depends on the mass of the star.



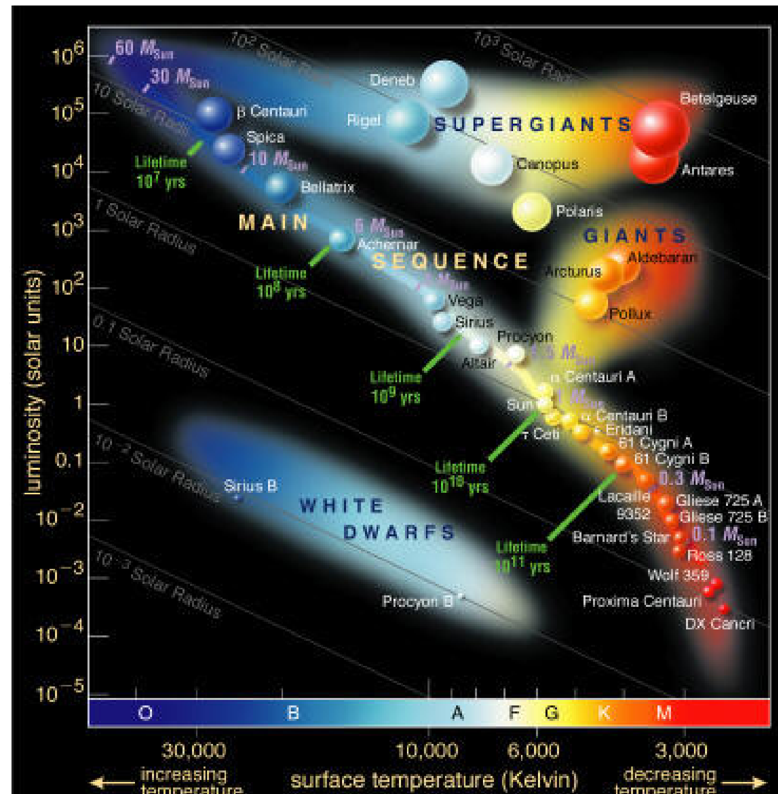
Stellar evolution

Vogt-Russell theorem:

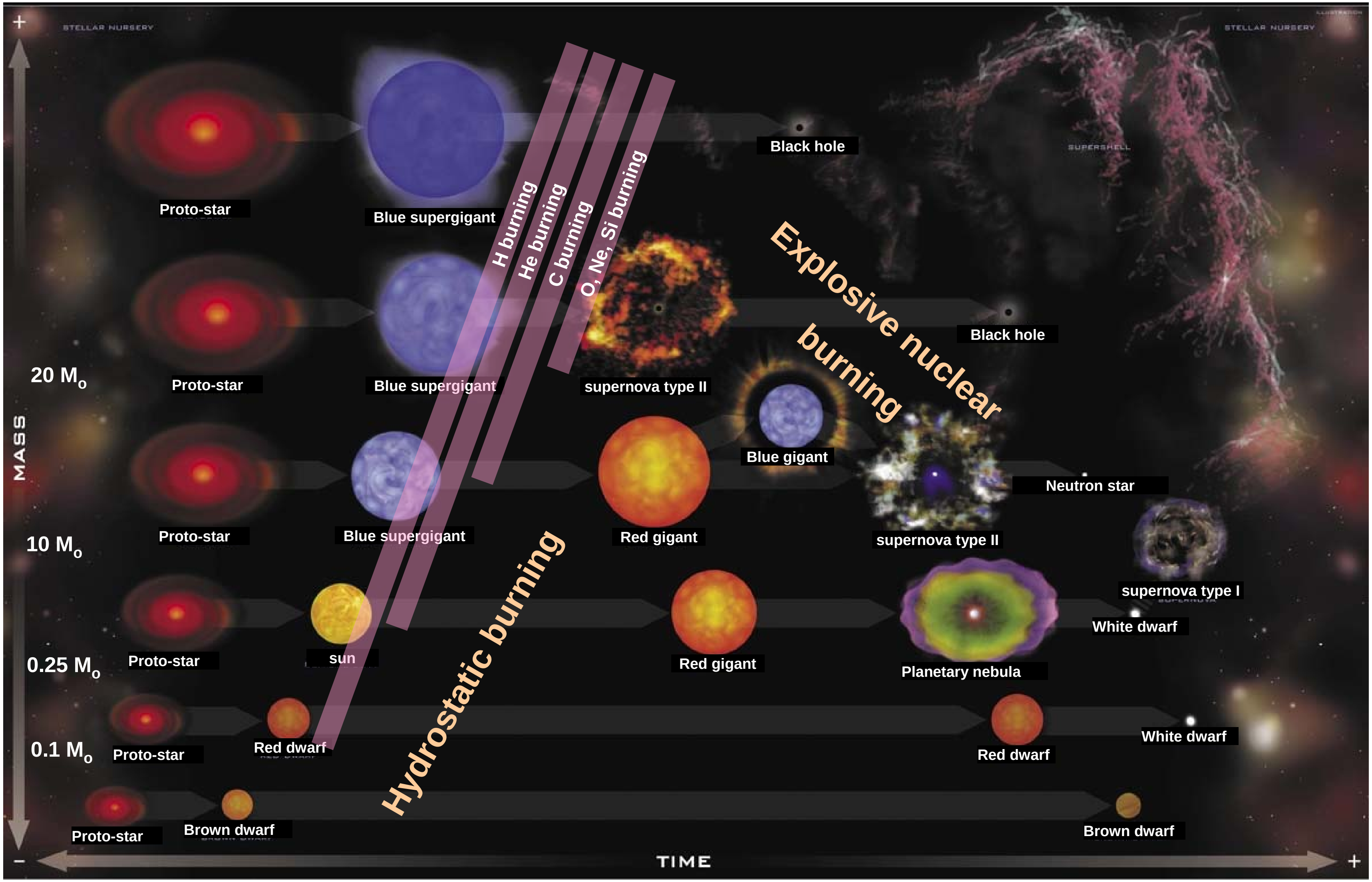
The mass and initial composition of stars determines their radius, luminosity and internal structure, but also their evolution.

The dependence of the stellar evolution with the mass and initial composition is a consequence of the composition changes induced by nuclear reactions.

Stellar models should be able to describe the Hersprung-Russel diagram taking into consideration the mass, initial composition and the nuclear reactions powering stars.



Stellar evolution



Stellar evolution

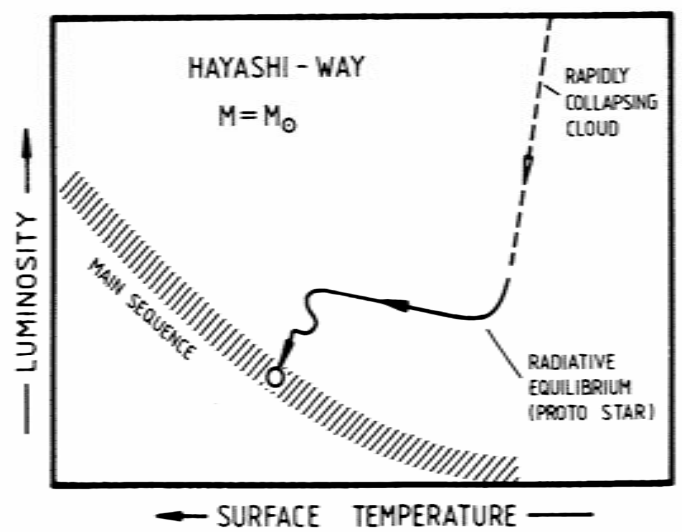
3.1 Stars formation

Star formation begins when a cool cloud of gas in the interstellar medium collapses to a high density. At first, the internal heat resulting from the contraction is readily radiated away because of the high transparency of the gas at such low densities. As the gas becomes denser, its opacity increases and the energy released can be stored in the interior.

✓ The gas settles down to form a star when half of the graviatational energy is stored and the other half radiated (virial theorem) reaching hydrostatic equilibrium (~ 30-100 y).

✓ At his point the star becomes visible, being larger and brighter than it will be when it reaches the main sequence.

✓ As energy is radiated from the surface, the star shrinks just enough to provided the energy that is radiated away and an equal quantity that is stored. Thus the interior of the star shrinks at a rate that is governed by the rate of energy loss from the surface. At this moment the temperature in the star increases with little variations in luminosity until the star reaches the main sequence (~ 10^7-10^8 y).



Stellar evolution

3.2 Very low mass stars ($0.013\ M_O < M < 0.08 M_O$)

This objects known as brown dwarfs were just discovered in the mid-90's and are proposed as for candidates for the baryonic dark matter. Stellar models predict that these stars never reach the central temperature required to sustain hydrogen fusion.

Brown dwrafs are fully convective and their energy source is provided by gravitational contraction.

The outer layer of a brown dwarf can be described by the ideal gas law, vhile the core eventually becomes a degenerate electron gas. As a result, the contraction halts and the brown dwarf slowly cools, at approximately constant radius, by radiating its thermal energy.

In the Hertsprung-Russell diagram, a brown dwarf evolves almost vertically downward and straight past the main sequence.

Stellar evolution

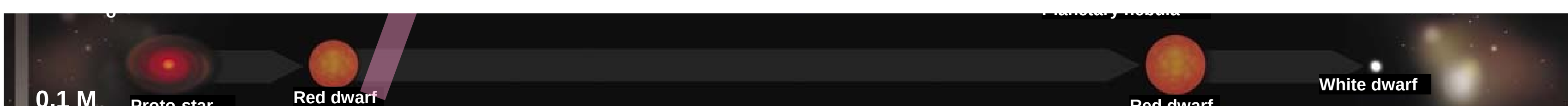
3.2 Low mass stars (0.08 M_O<M<0.4M_O)

Stars in this mass range are known as red dwarfs. They are the most common type of star in the neighborhood of the Sun. They have sufficient mass to fuse hydrogen into helium via the pp chain.

Starting from zero age main sequence, red dwarfs evolve toward higher luminosity and increasing surface temperature.

They are fully convective, which implies that its entire hydrogen content is available as nuclear fuel.

Red dwarfs do not have enough mass to produce the higher temperatures required to fuse helium nuclei. Thus they contract until electron degeneracy sets in. Finally they become helium white dwarfs that cool slowly by radiating away their thermal energy.

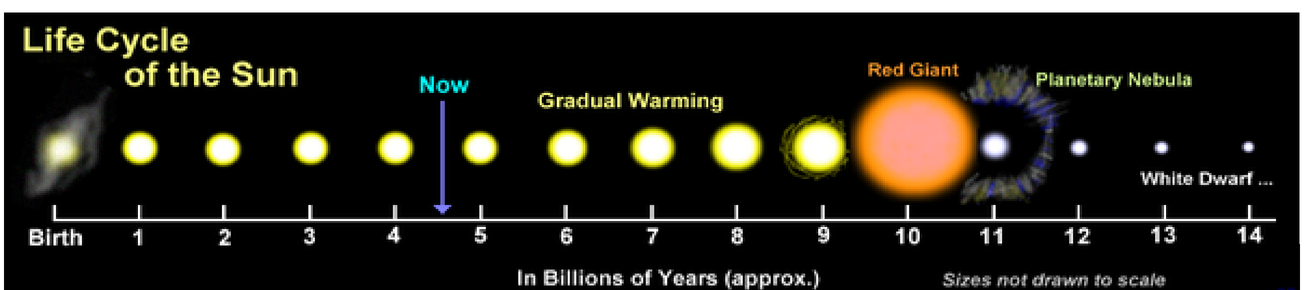


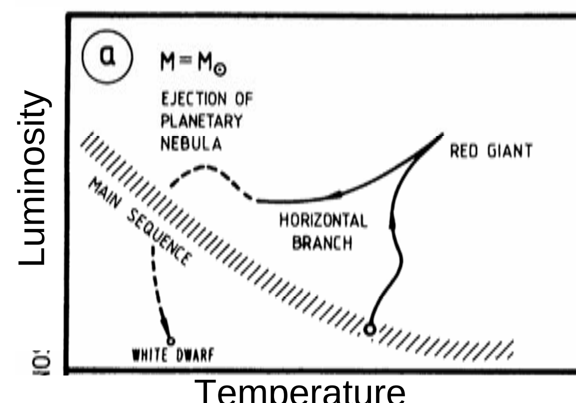
3.3 Sun-like mass stars (0.4 M_O<M<2M_O)

Stars up to 1.5M_O fuse hydrogen through the pp chain and energy is transported by radiation. Heavier stars fuse hydrogen via de CNO cycle concentrating the energy production in the center being convection the dominat energy transport mechanism.

The Sun started central hydrogen burning via de pp chain about 4.5 Gy ago. At present the central temperature and density amount to T~15 MK and ρ~150 g/cm^3. About 4.8 Gy from now, the hydrogen in the core will be exhausted. The Sun will be then located at the bluest and hottest point in the main sequence, call the *turn-off point*. At this point, hydrogen burning will continue in the outer shells while the helium core will contract increasing temperature.

Once the envelope becomes convective, the extra energy output from the hydrogen burning shell results in a dramatic surface expansion, becoming a *red giant star*. During this period its luminosity will increase. The contraction of the core during the red giant phase increases the central temperature and density and matter becomes electron degenerate.

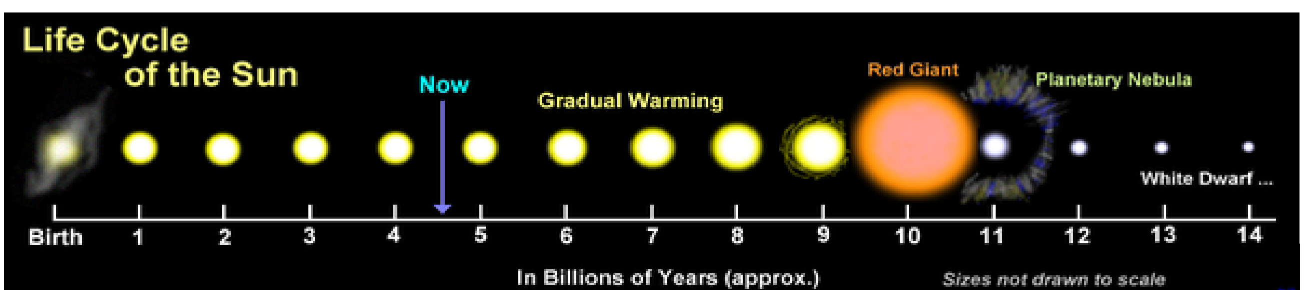


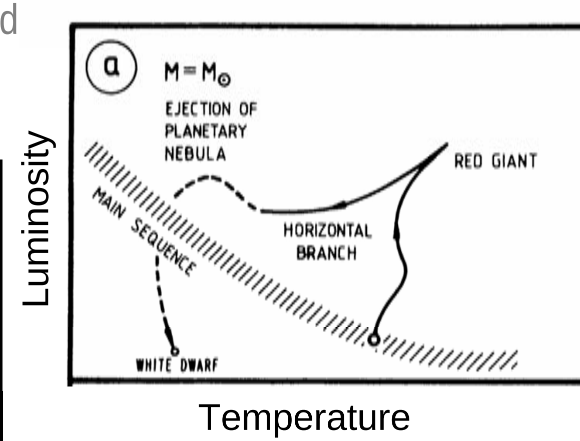


3.3 Sun-like mass stars (0.4 M_O<M<2M_O)

When the temperature reaches 0.1 GK, the helium in the core stars to fuse to carbon and oxygen. Since matter is degenerate, the extra energy do not produce an expansion but a temperature increase with an even higher energy generation rate. At some moment the energy produced is large enough to lift electron degeneracy producing violent detonations or *helium flash*es. This expansion of the core cools the sourronding hydrogen shell, decreasing also the luminosity of the star. At this moment the Sun would enter the so call *horizontal branch* where the loss of mass, hydrogen from the outer shells, produced an increase of the temperature of the star since hotter layers occupy the outer shell.

When the surfase of the star becomes hot enough, the intense ultraviolet radiation ionizes the expanding outer shell, which begins to fluoresce brightly as a planetary nebula. At this moment there is no more hydrogen envelope left and the hydrogen burning shell extinguishes. The luminosity decreases rapidly causing the evolutionary track to turn downward ans slightly to the right. The Sun will become then a *white dwarf* with a mass about 0.5 M_O cosisting mainly of carbon and oxygen. The electron degeneracy pressure will support the star that will cool slowly by radiating away its thermal energy.



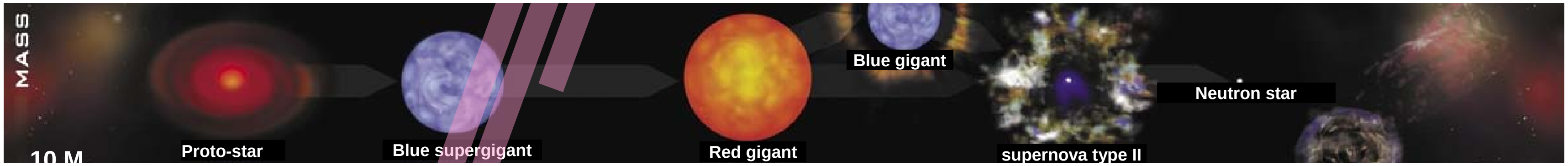


3.4 Massive stars ($2M_O<M<11M_O$)

Since the mass of these stars exceeds the *Chandrasekhar limit* ($1.4\ M_O$), a violent adjustment must take place since in this case degenerate objects cannot support collapsing masses greater than this limit.

Stars with moderate mass ($M<8M_O$), are thought to shed their excess masses rather gently, throwing off their external envelop as a planetary nebula. Other may shed their excess material into space via de novae phenomenon. Mass loss through high-velocity winds (*type O* and *Wolf-Rayet* stars) or low-velocity winds (*M supergiants*). In all these cases the stars reaches the Chandrasekhar limit and finally becomes a *white dwarf*.

Heavier stars ($8M_O<M<11M_O$) become red giants after during a not degenerrate helium burning phase producing an electron-degenerate carbon-oxygen core. Eventually the temperature of the core becomes sufficient for carbon burning, entering the star a *super giant phase* when hydrogen in the outer layers stars burning. Once carbon is exhausted the stellar core is composed mainly by oxygen and neon, leading to a *oxygen-neon white dwarf*.

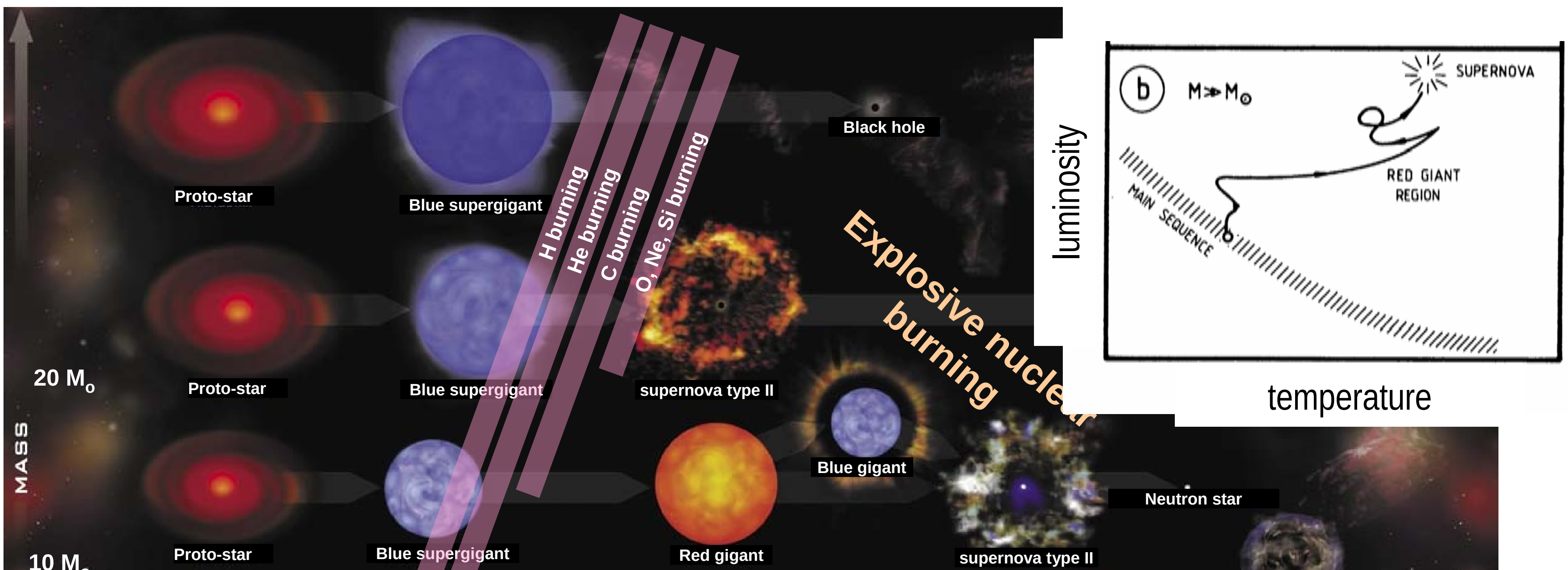


Stellar evolution

3.4 Very massive stars ($M > 11 M_O$)

If we consider a 25 M_O star with initial solar composition, their total life will be about 7 My. The star will spends 90% of this time on the main sequence burning hydrogen and helium via the CNO cycle. As in previous cases, the star becomes a red supergiant when hydrogen in the outer shell is burned.

During the helium burning (~0.8 My), some of the elements heavier thant A~60 are produced via neutron capture reactions (s-process).

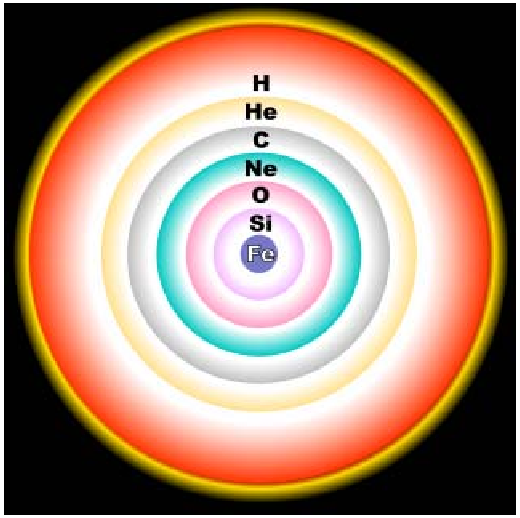


Stellar evolution

3.4 Very massive stars ($M>11M_O$)

Stars with initial masses exceeding ~11 M_O are capable of igniting successive burning stages in their cores using the ashes of the previous core burning stage as a fuel. Three distinct burning stages follow carbon burning, neon, oxygen and silicon burning. During hydrogen and helium burning, nuclear energy is almost exclusively converted to light. During the advanced burning stages energy is almost enterely radiated as neutrino-anti-neutrino pairs.

After the silicon has been exhausted in the core, the star become an onion-like structure with several layers of different composition separated by thin nuclear burning shells, with the heavier and most stable nuclei in the core composed by electron-degenerate matter.



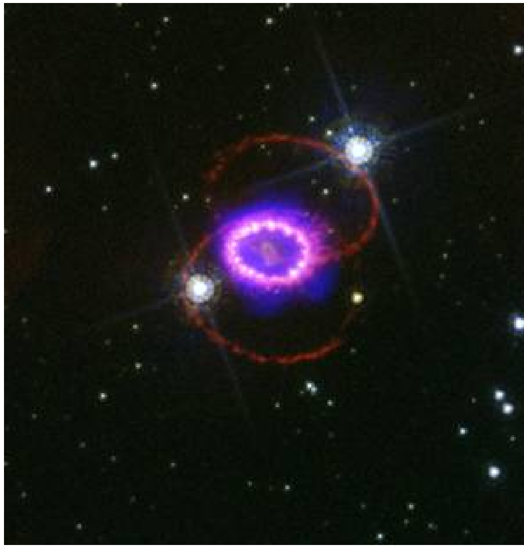
When the mass of the core exceeds the Chandrasekhar limit (~$1.4M_O$), the electron degeneracy preassure is unable to counteract gravity, and the core collapses photodisintegrating the iron peak nuclei into lighter and less stable elements. When the density reaches values of the order of the nuclear density (~10^{14} g/cm^3), nuclei and nucleons feel the short range nuclear force. Then, the nuclear potential will store energy until it rebounds giving rise to an outward moving shock wave while the very hot and dense inner core becomes a proto-neutron star with a mass of around 1.5 M_O.

3.4 Very massive stars ($M>11M_O$)

While the sock wave moves outward through the core region loses energy by photodisintegrating iron-peak nuclei and by neutrino emission. It takes about 1 s after the core collapse and 10 ms after the core has bounced, for the shock wave to reach the outer edge of the core and losses all its kinetic energy.

How exactly the shock is revived and how it will ultimate propagate through the outer stellar layers leading to the supernova explosion is still unknown, although neutrinos coming from the dense proto-neutron star are though to be the reason.

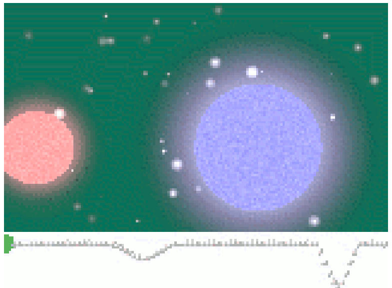
The propagation of the shock wave through the outer stellar layers compresses and heat them leading to other nucleosynthesis processes called *explosive nuclear burning* characterized by the aundance of neutrons present in the stellar medium. These possibly give rise to the nucleosynthesis of many Heavy nuclei in the A>60 mass range via neutron capture known as *r-process.*



This scenario for the core collapse of a massive star is responsible for the *supernovae types II* and *Ib/Ic*. It must be stressed that the explosion mechanism is far from being understood at present. The supernova rate in our Galaxy amounts to about two events per century.

Binary stellar systems

4.1 General considerations

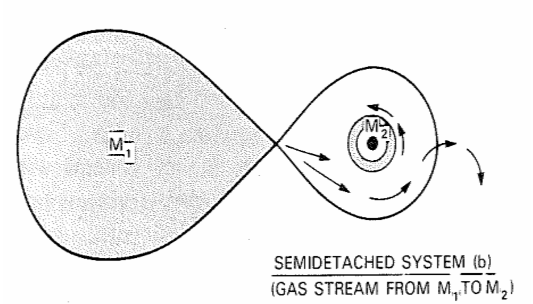


Binary systems are pairs of stars that revolve around a common center of gravity. Probably more than one-half of the stars in our Galaxy are members of binary systems, but only a small percentage are close.

In a close binary system, the evolution of one of the stars can influence the other one. In these cases one can define a point in the line connecting the center of the two stars where matter equally feels the gravitation field of both stars (*inner Lagrangian point*). If now we consider centrifugal acceleration we can find and eight-shape equipotential surface called the *Roche surface*.

If the material of both stars is within the *Roche surface* the system is stable. However, when one of the stars begins to expand as part of its evolution, material exceeding the Roche limit will transferred to the companion star through the *inner Lagrangian point*.

The acretion of material from a companion star can clearly affect the evolution of these stars. The matter falling through the gravitational field of a compact companion star can be a substantial energy source much greater than nuclear burning.



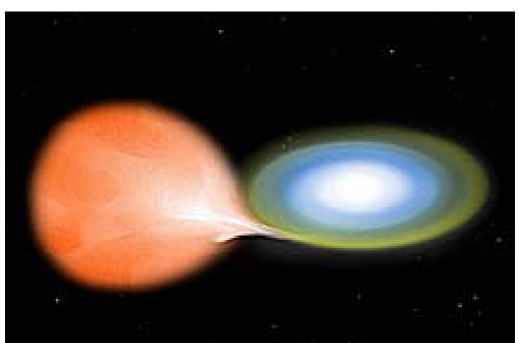
Binary stellar systems

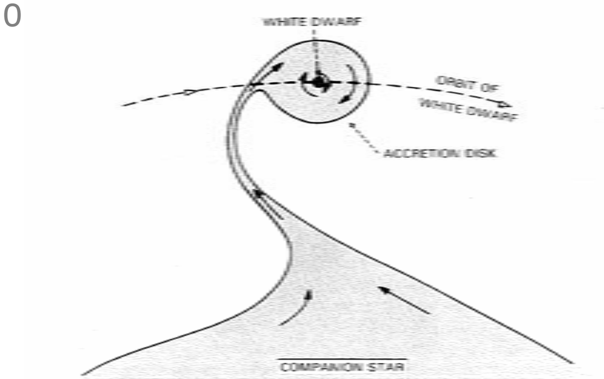
4.2 Classical novae

Nova phenomenon are supposed to happen in close binary systems where one of the stars is a degenerate helium-carbon *whithe dwarf*. When the *white dwafr's* companion expands becoming a *red giant*, its shape is distorted by the gravitational attraction of the *white dwarf*. When Roche's limit is reached, hydrogen gas streaming off the expanding star is swept into an accretion disk that swirls around the *white dwarf*. Finally the gas spirals into the *white dwarf* at extremely high velocity, raising the temperature of the dwarf's surface.

Typically, after thousands of years, the temperature at the *white dwarf's* surface is sufficient to ignite fusion reactions via the typical hygrogen burning reactions that take place in the interior of main-sequence stars.

Since the *white dwarf* is completelly degenerate, reactions are not controlled by expansion, as it happens in an ideal gas. Rather, the reactions proceed at an ever-increasing rate which releases an enormous amount of energy culminating in an explosive o





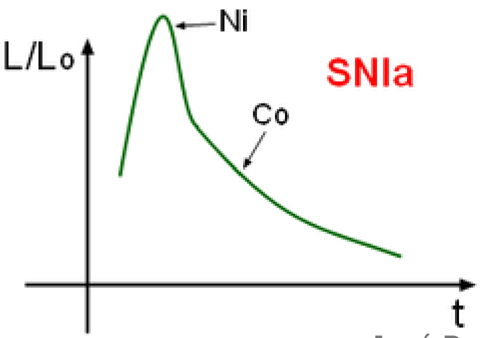
Binary stellar systems

4.1 Type Ia supernovae

In the currently most popular models accreting *carbon-oxygen white dwarfs* in binary systems are assumed to be the progenitors of SNIs. A detailed understanding of SNI is still lacking being one of the most accepted models the following:

The *white dwarf* accreated matter form the *red giant* companion star until it reaches the *Chandrasekhar limit*. Then carbon ignites under degenerate conditions and a thermonuclear runaway occurs. The energy release is so large that it disrupts the *white dwarf* at high velocity in a few seconds. A significant fraction of the initial carbon and oxygen is consumed and, in general, there is no remnant left.

The nucleosynthesis depends on the temperatures and densities achieved in different layers of matter. In the hotest and densest regions, the explosion converts most of the matter to radioactive ^{56}Ni. The decay of this nucleus and its daugther nucleus, ^{56}Co, then gives rise to the observed emission of *type Ia supernovae*. This means that the amount of ^{56}Ni synthesized deternines the absolute brightness of the event. The outer regions that attain smaller temperatures and densities may undergo explosive silicon or oxygen burning giving rise to the production of intermediate-mass nuclei.



Binary stellar systems

4.3 Type I X-ray bursts

These are also close binary systems where the compact star is supposed to be a *neutron star* and even in a few cases a *black hole*. These systems star as a two large-mass main-sequence close binary sistem A and B. A accreates matter from B once the later have arrived to a red giant stage. Then A gets the sufficient mass ($M>11M_O$) to finalize its evolution as a supernova type II leading to a neutron star or a black hole.

During the latter evolution of star B a hydrogen gas streaming off the expanding star is swept into an accretion disk that swirls around the *neutron star.* Because of the strong gravitational effect induced by the dense neutron star, hydrogen gas spirals through the accretion disk and is finally guided to the surface at the nagnetic poles of the neutron star with a kinetic energy higher than 100 MeV. The slowing down process of these high energy protons led to X-ray emission.

Since the magnetic poles usually are not on the axis of rotation of the neutron star, X-ray burst emission seems to pulse with periods of few seconds due to the shadowing effect produced by the rotation of the neutron star.