Lecture notes 10: Stellar evolution ii

At some point in time the Hydrogen fuel contained in the stellar core will be exhausted. The post main-sequence evolution of stars follows a slightly different route ? even though the general principles are the same ? depending on whether the star is low mass ($< 5M_S$ or so) or high mass.

In the former case temperatures never become high enough to burn elements heavier than Helium, and the end product of evolution is a Carbon or Oxygen white dwarf.

In the latter case elements fuse all the way to Iron in the core, after which a supernova explosion ensues. The end product is either a neutron star or a black hole.

Evolution of low mass stars

Ascending the giant branch

As Hydrogen burning ceases the stars the loss of energy from the stellar surface is no longer balanced by nuclear fusion. The energy losses must be replaced somehow and the only available energy source for the star is gravitational contraction. Thus, upon having exhausted its Hydrogen fuel, a stars core will contract.

The contracting core will raise the gravitational accelertion at the core?s boundary and the pressure needed to support the weight of the overlying layers must increase. This implies both increasing temperatures and densities, high enough to force Hydrogen to fuse in the boundary layers. The star has entered a shell burning phase. The shell burning increases in energy productionas the core continues to collapse and the stars energy production increases. Since a star in which the energy transport occurs by radiative diffusion has, for a given mass, a more or less given luminosity ($L \quad M^4$) the contraction of the core and the initiation of shell burning occurs with a constant luminosity. However, the increased energy production and higher temperature at the boundary of the core leads to an expansion of the entire star: With the stellar radius increasing and the stellar luminosity remaining the same the effective temperature of the star must decrease. The star moves directly to the right in the HR-diagram, becoming in the process a so-called **sub-giant**, luminosity class iv.

Onset of convection; the Hayashi track

The continual decrease in temperature at the star?s surface cannot continue indefinately. A lower limit of approximately 2 500 K is found to exist ? due to the extreme temperature sensitivity of the surface opacity (continuum opacity due the H^- ion) ? which forces convective energy transport to eventually take over in order to carry the required luminosity. The star, now with a more or less constant surface temperature of 2 500 K, continues to contract, but with convective energy tranport the luminosity increases dramatically and the star moves directly upward in the HR-diagram along the so-called **Hayashi track**, continually increasing radius. This leads the star towards the giant branch, luminosity class iii. At the top of the giant branch the star has acheived a radius of some 10 ? $100R_S$ and a luminosity of some 100 ? $1000L_S$.

The Helium flash and descent to the horizontal branch

At the top of the giant branch a $1M_S$ star will have a core that resembles a low mass, $\approx 0.4M_S$, white dwarf, surrounded by a shell of Hydrogen fusing to Helium. Eventually the temperature and the density of the contracting core become high enough ($\approx 10^8$ K) to ignite Helium fusion to Carbon through the triple-α process. The further fate of the star depends on whether this occurs before the star?s core is degenerate or not.

If the core is degenerate the increased temperature due nuclear energy generated by Helium fusion does **not** lead to core expansion. This because the pressure is set by $P_g \quad \rho^{5/3}$ which does not depend on the temperature. The nuclear generation rate of the triple-α process is extremely temperature sensitive and thus a higher temperature lead to a greatly increased fusion rate; leading to yet higer temperatures. This is a *runaway* process which leads the star to devour a large portion of its Helium fuel within a few seconds: **the Helium flash**. Finally the temperature of the gas becomes high enough to ease the degeneracy of the core; the gas pressure in the core becomes dependent on the temperature $P_g \quad \rho T$, the core expands and the explosive Helium burning ceases.

In both stars which experience a Helium flash and stars in which Helium burning ensues more gradually the energy production in the core eventually causes the core to expand. This expansion has the effect of reducing the gravity at the boundary between the core and the stellar envelope. A reduced gravity means that the pressure needed to balance the weigth of the overlying material also is reduced leading to lower temperature, lower densities and thus a greatly reduced shell burning. The net effect of Helium ignition is then that the luminosity of the star is *reduced*, as is the stellar radius and the star moves down and to the left in the HR-diagram to the **horizontal branch**. (The exact location in the HR-diagram a star will end up on while burning Helium depends on the magnitude of mass loss, through a stellar wind, the star has experienced while in its giant phase).

Ascending the asymptotic giant branch (AGB)

When the Helium fuel is exhausted and essentially all Helium has been converted to Carbon and Oxygen nuclear energy generation ceases. The star then responds in the same manner as when the Hydrogen core was exhausted: The core contracts and a shell burning at the Carbon/Helium boundary ensues. This means that the star now has *two* shell sources, including the outer Hydrogen burning shell.

As the Carbon/Oxygen core continues to contract the intensity of the shell burning increases and the star?s luminosity and radius increases yet again and the star moves to the right and up in the HR-diagram as it acends the **asymptotic giant branch** and becomes a bright giant, luminosity class ii or a supergiant, luminosity class i.

The strucure of such a star is that of a increasingly degenerate hot Carbon/Oxygen white dwarf like core, surrounded by a Helium burning shell, which in turn is surrounded by a Hydrogen burning shell. All of this is embedded in an extremely tenuous envelope or atmosphere stretching out to $1000R_S$ or so. This situation, with two shell sources, is not stable and stars of this type experience thermal instabilities, exensive convective mixing and large mass loss through a stellar wind (on the order M_S^{-4} per year).

Eventually the entire envelope is thrown off leaving a **planetary nebula** and a extremely hot but rapidly cooling **white dwarf**.

Evolution of high mass stars

The evolution of high mass stars is in many ways similar to that of low mass stars. The major exeption is that high mass stars do not become degenerate in their core before these stars have fused elements all the way to iron; at which point no more exothermic processes are available to the star.

In short: all stars are on their way from a condition of high entropy to a condition of low entropy with steadily increasing temperatures, densities and degree of degeneracy in their cores. The evolution of any star is determined by whether or not sufficient temperatures and densities are acheived before the degeneracy becomes great enough to halt the increasing temperature that an ideal gas would experience. High mass stars will, in turn, fuse steadily heavier elements in the core under non-degenerate conditions.

Another difference is that high mass stars do not develop (significant) convection during their evolution: thus the luminosity of such stars is more or less constant as described by the luminosity-mass relations developed in the last lecuture, $L \quad M$ or $L \quad M^3$. These stars, **supergiants** luminosity class i, then move directely right or left in the HR-diagram. To the right and expanding when one nuclear fuel is expended and the core contracts towards the densities and temperatures required to ignite the next stage of burning, accompanied by shell burning at the core boundaries; to the left after the next stage of burning has ignited. This evolution continues until the inner core contains iron and iron-like elements.

An example: SK 69^o202

Let us take as an example the blue giant that exploded as a supernove of type ii in the Large Magellenic Clound in 1987; the star SK 69^o202, later known as SN 1987a. This originally $20 M_S$ star?s life may be summarized as follows:

1. H → He fusion for a period of roughly 10^7 yr with a core temperature $T_c \approx 40 ? 10^6$ K, a central density $\rho_c \approx 5 ? 10^3$ kg/m^3, and a radius $\approx 6\mathrm{R}_S$.

2. He → C, 0 fusion for a period of roughly 10^6 yr with a core temperature $T_c \approx 170 ? 10^6$ K, a central density $\rho_c \approx 9 ? 10^5$ kg/m^3, and a radius $\approx 500\mathrm{R}_S$. The core mass is $6\mathrm{M}_S$. The star is in this phase a red supergiant.

3. C → Ne, Na, Mg fusion for a period of roughly 10^3 yr with a core temperature $T_c \approx 700 ? 10^6$ K, a central density $\rho_c \approx 1.5 ? 10^8$ kg/m^3, and a radius $\approx 50\mathrm{R}_S$. The core mass is $4\mathrm{M}_S$. From this stage and onward the star loses more energy through the emission of neutrinos than from the emission of photons. In addition from this point onwards the evolution of

the core is very rapid and the outer layers do not have time to adjust to the changes happening below: the stars radius remains unchanged.

4. Ne → O, Mg fusion for a period of some few years with a core temperature $T_c \approx 1.5 ? 10^9$ K, a central density $\rho_c \approx 10^{10}$ kg/m^3.

5. O → S, Si fusion for a period of some few years with a core temperature $T_c \approx 2.1 ? 10^9$ K. The neutrino luminosity is at this stage 10^5 greater than the photon luminosity.

6. S, Si → ?Fe? (actually a mix of Fe, Ni, Co) fusion for a period of a few days with a core temperature $T_c \approx 3.5 ? 10^9$ K, a central density $\rho_c \approx 10^{11}$ kg/m^3. Si ?melts? into α-particles, neutrons and protons which again are built into ?Fe? nuclei. The core mass is now roughly 1 .4M$_S$.

The structure of the star at the end of Si burning is shown in ?gure 1.

Supernova of type ii

Having burnt Si to Fe a star has no more exothermic processes again and nothing can prevent the star from collapsing under its own gravity. This collapse leads to a supernove expolosion of type ii.

A supernova explosion is a phenomena of incredible energy release. During the ?rst 10 s of such an explosion the star loses on the order of 10^{46} J of which 99% is in the form of neutrinos, 1% in the form of photons. A comparison may be in order: During its *entire* lifetime on the main sequence the Sun produces roughly $4 ? 10^{26}$ W for $10^{10} ? 3 ? 10^7$ s or roughly 10^{44} J. *I.e.* a supernove loses in ten seconds what the Sun produces during its entire lifetime. And as a ?nal reminder, the energy contained in all the nuclear weapons on Earth can maintain the Sun?s energy losses for 10^{-6} s.

During the last 1000 yr there have been ?ve supernovae visible to the naked eye; SN 1006 of type ii was bright enough (approximately 1/4 moon) to read by, the last one before SN 1987a, ?Keplers Star?, was a type sc i supernova that exploded in 1604 only four years before the discovery of the telescope.

Type i supernovea are Carbon/Oxygen white dwarfs that explode after having accreted sufficient mass from some neighboring star to tip over the Chandrasekhar mass $1.4 M_S$. This leads to the explosive nuclear burning of the Carbon and Oxygen under degenerate conditions, much as in the Helium ?ash, but without any stellar envelope to ?contain? the explosion. It is calculated that there are roughly one such supernova per 36 years in the Milky Way.

Type ii supernovae are caused by the implosion of an Iron core built up by a high mass star as that core becomes heavier than the Chandrasekhar mass and the degenerate electron gas pressure no longer can resist gravity. The explosion is a result of the hydrodynamic shock that arises when the core material reaches nuclear density. It is calculated that there are roughly one such supernova per 44 years in the Milky Way.

The disparity between calculated and observed supernovae is due the fact that the Sun resides in the disk of the Milky Way and is protected from supernovae by the vast amounts of interstellar gas and dust that lie in the disk.

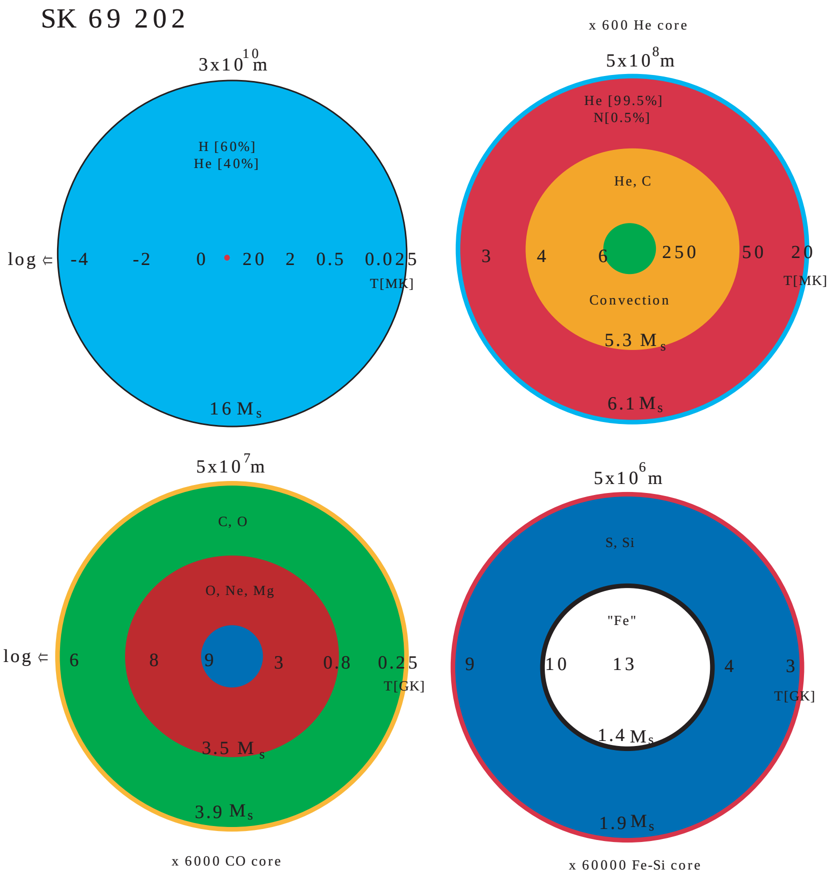

Figure 1: The structure of SK 69^{o}202 immediately before core collapse.

As the Iron core of a fully evolved high mass star contracts the gas becomes degenerate ($P_g \propto \rho^{5/3}$) and then relativistically degenerate ($P_g \propto \rho^{4/3}$). The pressure in the gas can no longer resist gravity and the core collapses. Two processes hasten this effect

1. Photodisintigration of Fe: The energy of the photons in the core becomes high enough to destroy the Iron nuclei that the star has built up.

$$^{56}\mathrm{Fe} \rightarrow 13\,^{4}_{2}\mathrm{He} + 4\,^{1}_{0}\mathrm{n} \qquad (1)$$

This is an endothermic process, sucking up energy that otherwise could be used in resisting gravity.

2. Electron capture and the neutronization of matter: The energy of electrons become great enough to force them into the protons of the nuclei.

$$^{0}_{-1}e + A \rightarrow A^{-1} + ^{0}_{0}? \qquad (2)$$

   This both removes energy from the core in the form of neutrinos and removes the very electrons that are responsible for maintaining the pressure gradient force against gravity.

The net sum of these effects is that the core collapses from something with a radius of some few thousand kilometers (the size of Mars) to something with a radius of some ten kilometers in the timespan of < 1 s. The infall velocity reaches a significant fraction of the speed of light. The collapse is only halted when the density approaches nuclear densities 10^{17} kg/m^3. At this point the strong interaction becomes important and the stellar core material becomes very ?stiff?.

A hydrodynamic shock, containing roughly $5 ? 10^{44}$ J, is formed which starts propagating out through the star. It is this shock that upon reaching the surface is thought to produce the supernova explosion. However, this scenario is fraught with some difficulties: The shock distintigrates ?Fe? as it moves through the shock. This costs quite a bit of energy, $\approx 1.5 ? 10^{44}$ J per 0.1M$_S$. In addition the core medium becomes optically thin for neutrino emission at some point, which costs on the order of 10^{44} J. Taken together these losses make it extremely difficult for the shock to reach the stellar surface, models show instead that the shock stagnates leaving nothing but a black hole.

The solution to this dilema lies in tapping into the gravitational binding energy released from newly formed neutron star in the core; GM_{NS}^2/R_{NS}. This energy is converted to a thermal gas of neutrinos, electrons, positrons and photons with an staggering temperature $3 ? 10^{11}$ K. The neutrinoes will diffuse out of the extremely high density core to the region of the stagnating shock over a period of roughly 1 s leaving there enough energy to re-energize the shock.

As the shock reaches the surface we can estimate its effect: The energy contained in the shock $E \approx 10^{44} J$ heats the gas in the volume V of the star such that $E \quad V ? aT^4$ giving a temperture of some $5 ? 10^9$ K. This temperature is high enough to fuse ?everything? to ^{56}Ni.

The veracity of this scenario may be checked. One indication is from observations of the light curve of the supernova since ^{56}Ni will decay with a half life of 7.7 days to ^{56}Co which in turn decays with a half life of 70 days to ^{56}Fe. The radiactivity from this decay is what powers the later stages of the supernova remnant which are observed to decrease in luminosity with a timescale of 70 days.

In addition it is now possible to observe (some few!) of the neutrinos produced in the core directly, as was done for the first time with SN 1987a. This star was located in the Large Magellenic Cloud some 160 000 ly away, yet 10^{46} J in neutrino emission still gives a flux of some 50 ? 10^9 neutrino/cm^2 at the Earth. Of these 11 were detected by Kamiokande ii in Japan over a period of 12 s and 8 were detected by the IMB detector in Cleveland USA over a period of 6 s. The neutrinos were that were detected arrived three hours before any visible manifestation of the explosion was observed from the star; the three hours accounting for the time it took for the shock wave to traverse the stellar interior.

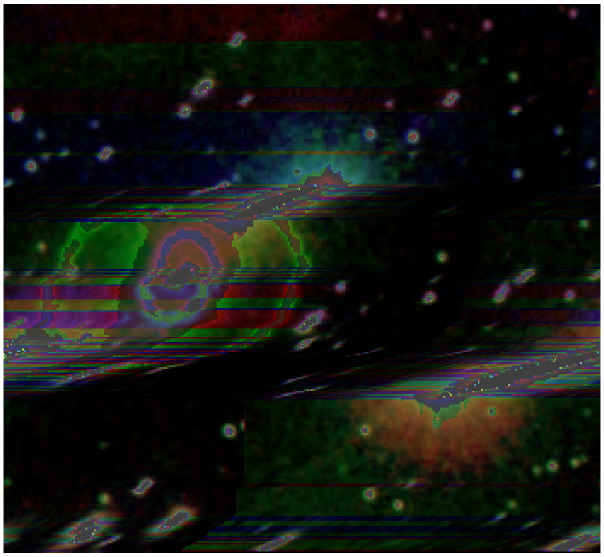

Figure 2: Three rings in the vicinity of SN 1987a. These rings consist of material ejected from the star as a stellar wind during SK69^{o}202?s lifetime and are heated and lit up by radiation (photons) from the explosion of the star. The inner ring has a diameter 0.4 pc in this image. In 2001 the shockwave from the explosion hit the inner ring, an event that had a signature in the X-ray, ultraviolet and visble parts of the spectrum.

A supernova of type ii leaves behind it a neutron star and an shock front that expands into the interstellar medium; an interstellar medium that has previously been enhanced by the stellar wind from the stages of the stars life where the stellar wind mass loss was copious.