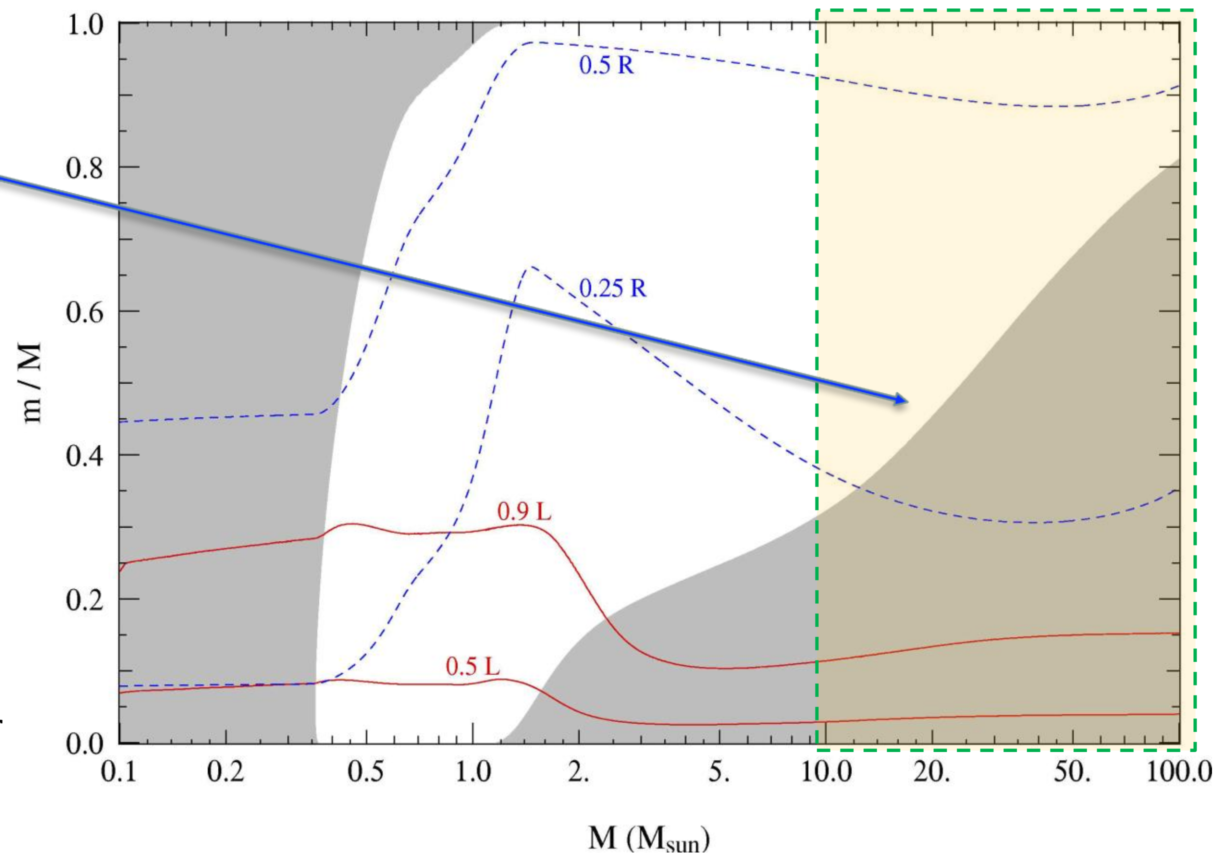
The evolution of massive stars

Convective regions on the ZAMS

The cores of **massive** stars on the ZAMS are convective.



Occurrence of convective regions (gray shading) on the ZAMS in terms of fractional mass coordinate m/M as a function of stellar mass, for detailed stellar models with a composition $X = 0.70$, $Z = 0.02$.

The solid (red) lines show the mass shells inside which 50% and 90% of the total luminosity are produced.

The dashed (blue) lines show the mass coordinate where the radius r is 25% and 50% of the stellar radius R.

(After Kippenhahn & Weigert)

From the main-sequence to He burning

1. The cores of massive stars are convective, hence newly formed He is evenly mixed in the core.
2. As the hydrogen is consumed, the core contracts and also shrinks in mass.
3. The convective core becomes exhausted of hydrogen homogeneously, while it contracts to a smaller volume and becomes hotter.
4. The star also develops a H-burning shell around the He dominated core.
5. The temperature at the bottom of the hydrogen envelope is too high to sustain hydrostatic equilibrium. The envelope expands and the star becomes cooler, moving to the red region of the HRD. It becomes a red supergiant star.
6. Due to the rapid drop in temperature throughout the outer atmosphere, the criterion for convection is reached in this region and a convection zone develops, reaching deep into the star.
7. It dredges up some of the material from the original convective core.
   This core material can appear at the stellar surface in the atmosphere of the red supergiants.

High-mass stars create heavy elements in their cores

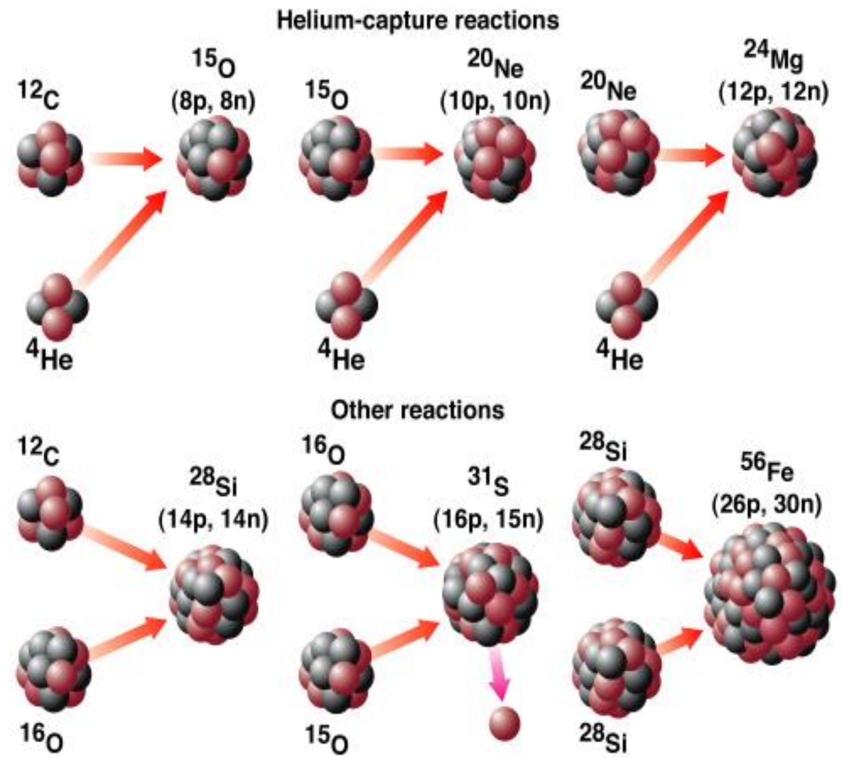
- Unlike low-mass stars, **massive** stars ($M > 8\ M_\odot$) can go through all phases of nuclear fusion, up to the Fe-core.
- The internal evolution goes by a series of successive fusion-phases, ending with a shell-like structure, consisting of shells of different compositions.
- Massive stars of course spend most of their lives on the main-sequence, and illustrative timescales for $25\ M_\odot$ - stars given below.

Evolutionary Stages of a 25-$M_\odot$ Star

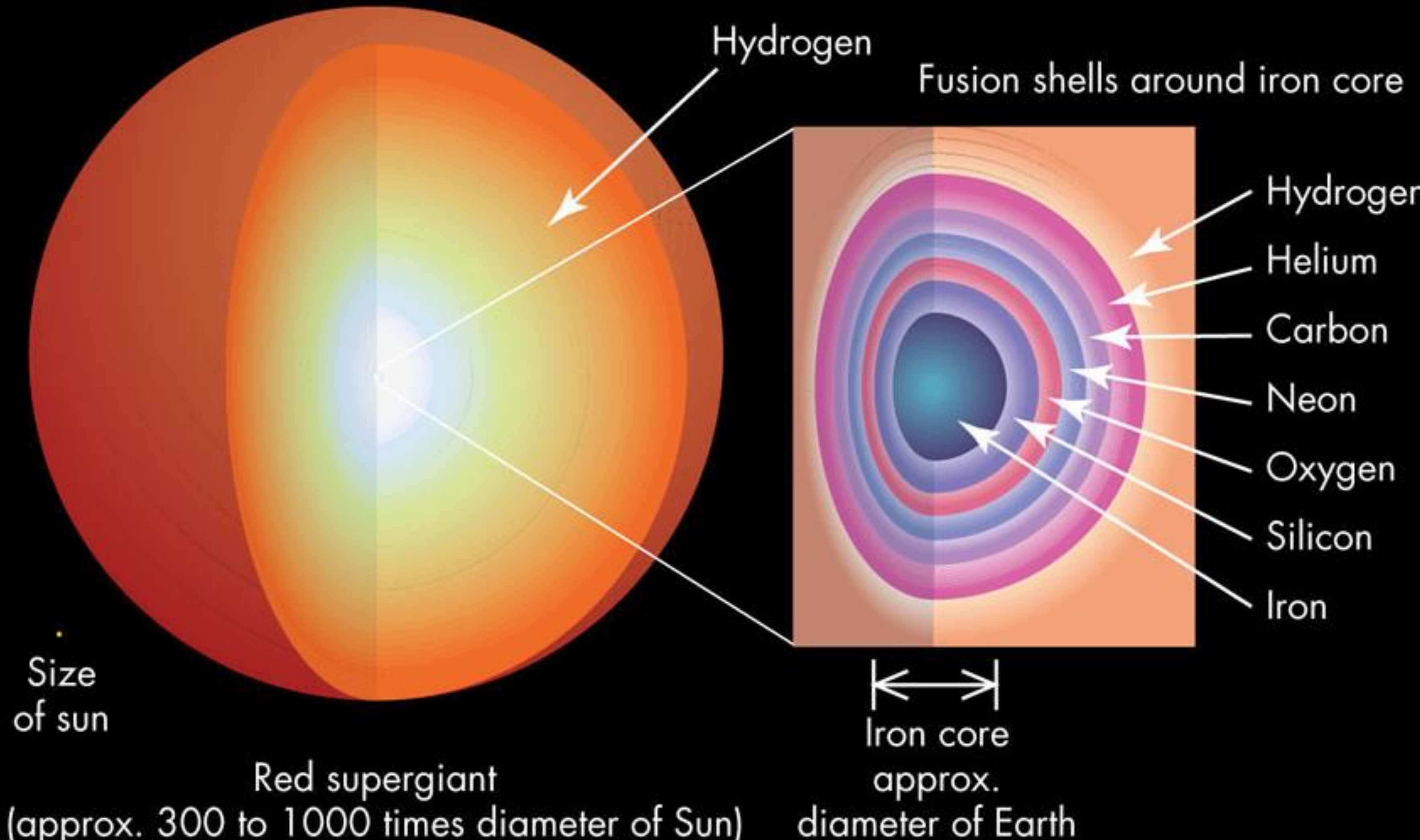
Stage	Core temperature (K)	Core density (kg/m^3)	Duration of stage
Hydrogen fusion	4×10^7	5×10^3	7×10^6 years
Helium fusion	2×10^8	7×10^5	7×10^5 years
Carbon fusion	6×10^8	2×10^8	600 years
Neon fusion	1.2×10^9	4×10^9	1 year
Oxygen fusion	1.5×10^9	10^{10}	6 months
Silicon fusion	2.7×10^9	3×10^{10}	1 day
Core collapse	5.4×10^9	3×10^{12}	¼ second
Core bounce	2.3×10^{10}	4×10^{15}	milliseconds
Explosive (supernova)	about 10^9	varies	10 seconds

From He burning to core-collapse

1. The He burning core is surrounded by a H-burning shell.
2. The triple-α process liberates less energy per unit mass than for H-burning (~10%). Hence the lifetime is shorter, again around 10%.
3. There is **no** He-flash as densities in the He-core are not high enough for electron degeneracy.
4. We have now core of ^{12}C and ^{16}O, surrounded by He and H burning shells.
5. The core will again contract and the temperature will rise (~0.5-1.5 billion K), allowing C and O burning to Mg, Ne, Si.
6. Neutrinos from pair annihilation contribute a substantial amount to the luminosity (energy loss), even more than the nuclear burning.
7. So, the star contracts to make up the loss with gravitational energy.
8. The photons released in above reactions have such high energies that they can photo-disassociate surrounding nuclei.
9. Silicon burning sets in through interactions with alpha particles.
10. This process continues, with increasing Z, building up heavier and heavier elements until the iron group of elements of Ni, Fe and Co are formed.



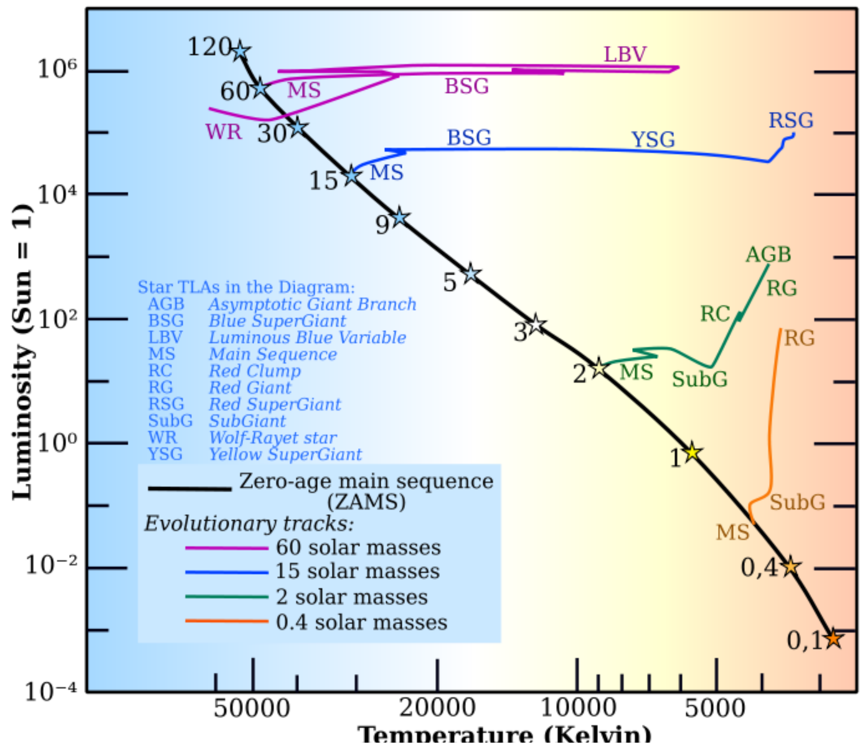
The core is surrounded by a series of shells at lower T, and lower ρ.



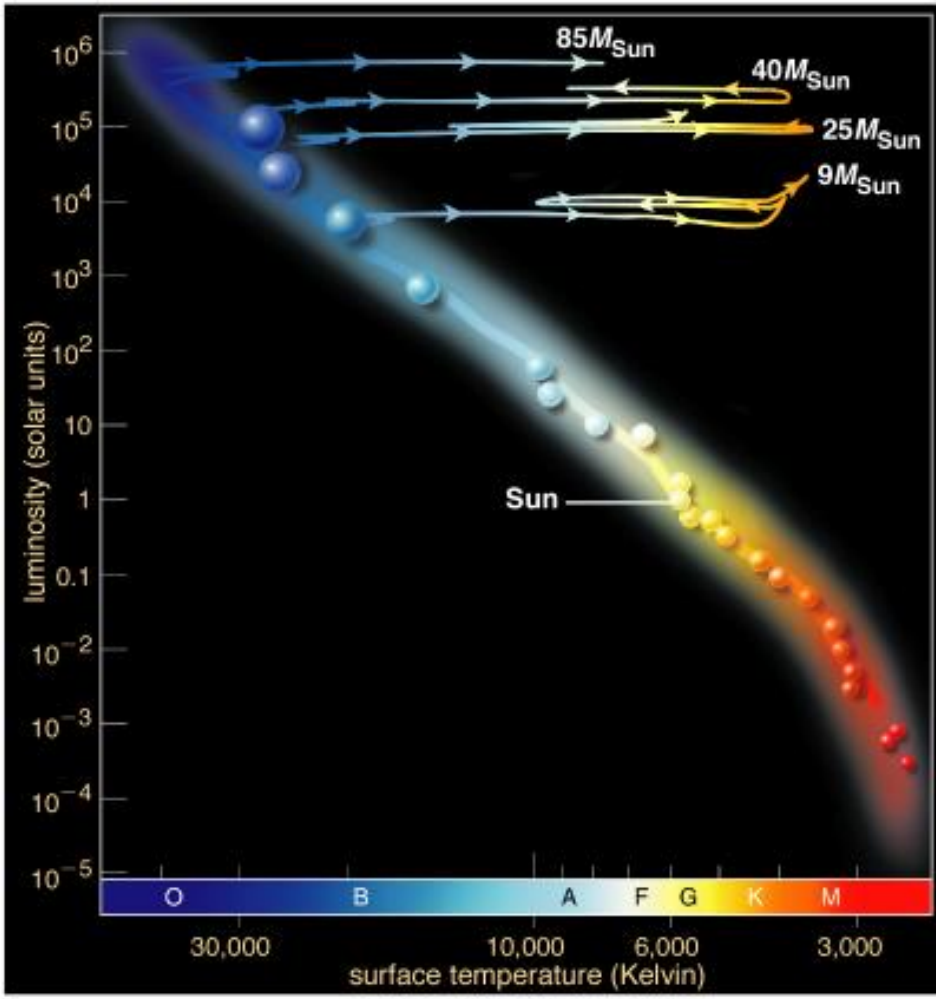
Schematic description of the evolution of massive stars

The evolution of massive stars have the following general characteristics and differences to lower mass evolution:

1. The electrons in their cores do **not** become degenerate until the final burning stages, when iron core is reached.
2. The external evolution of massive stars proceeds mostly along horizontal lines in the HRD, i.e. about constant luminosity, because the star does not develop a degenerate core and most of the mass is in radiative equilibrium.
3. Mass-loss plays an important role in the entire evolution. Stars above 30 $M_\odot$ typically lose about 15 percent of their mass during the main sequence phase so the products of nuclear fusion appear at the surface right after the MS phase. The mass-loss time-scale can be shorter than the main sequence timescale.
4. The luminosity remains approximately constant in spite of internal changes. The track on the HRD is therefore horizontal. For a 15-25 $M_\odot$ star there is a gradual red-wards movement. But for higher mass (or stars with different initial compositions) the star moves back and forth between low and high effective temperatures.



Supergiants on the H-R Diagram



- As the shells of fusion around the core increase in number:
  - thermal pressure overbalances the lower gravity in the outer layers
  - the surface of the star expands
  - the surface of the star cools
- The star moves toward the upper right of H-R Diagram
  - it becomes a red supergiant
- For the most massive stars:
  - the core evolves too quickly for the outer layers to respond
  - they explode before even becoming a red supergiant

The evolution proceeds differently in three distinct mass ranges

1) The stars with $8 < M < 25\ M_{\odot}$ become **red supergiants** (RSG) in their H-shell fusion phase. (This is similar to the RGB (Red Giant Brunch) of lower mass stars, but their He-core is not degenerate). During their He-core fusion phase they make a leftward loop in the HRD and temporarily become yellow supergiants. (This is similar to the HB – Horizontal Brunch – of low mass stars). The later fusion phases are all spend as a RSG (Hayashi limit). In the end these RSGs explode as supernova (SN).
   So their evolution track in the HRD is quite similar to those of stars of M>4 $M_{\odot}$ but they never develop a degenerate core.
2) The stars with $25 < M < 50\ M_{\odot}$ also become RSG, but their mass loss rate is so high that after a short time at the Hayashi limit they have lost most of their envelope and move to the left of the HRD. (This is similar to the post AGB evolution of lower mass stars, but they do not become WDs). When they are in the left of the HRD they have a very high mass loss rate and their atmospheres are dominated by He, N and C. These are Wolf-Rayet stars (WR-stars). They explode as SN in the WR phase.
3) Stars with $M > 50\ M_{\odot}$ become unstable due to radiation pressure in their envelope immediately after the MS, because they are very close to the photospheric Eddington limit. They become Luminous Blue Variables with high mass loss rates and occasional eruptions. They stay on the blue side in the HRD where they become Wolf-Rayet stars and explode as SN.

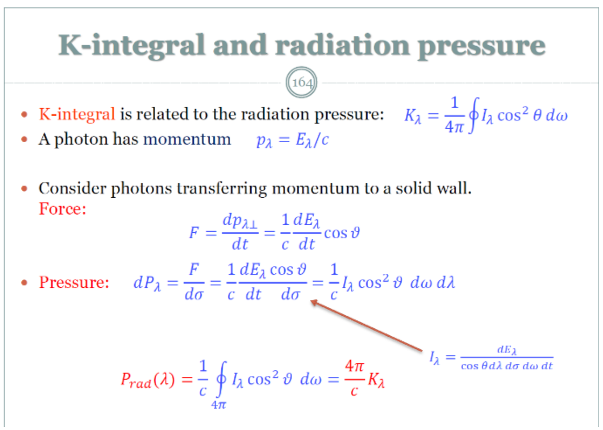
The importance of Radiation Pressure

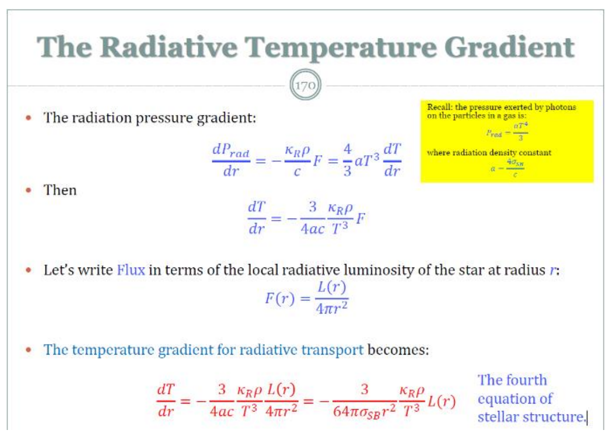
Radiation is important:

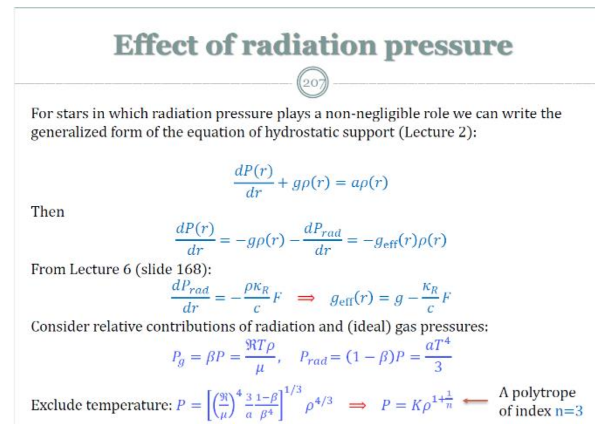
- inside stars, as a source of energy transport
- outside stars and other sources, from its effect on surrounding gas.

Radiation is an inefficient carrier of momentum (velocities have the highest possible value), but when a photon is absorbed or scattered by matter, it imparts not only its energy to that matter, but also its momentum hν/c.

We already discussed the importance of radiation pressure several times (e.g., slides 164, 168-170, 207):







Let's now shortly repeat it again and introduce the Eddington limit on Luminosity.

Radiation vs Gravity

We already discussed the importance of radiation pressure several times (e.g., slides 164, 168-170, 207):

$$\frac{dP_{rad,\lambda}}{dr} = -\frac{\kappa_\lambda \rho}{c} F_\lambda$$

$$dI_\lambda / I_\lambda = -\kappa_\lambda \times \underbrace{\rho ds}_{\text{column density of gas}}$$

Can therefore interpret κ_λ as being the fraction of radiation absorbed by unit column density of gas.

$$\boxed{F(r) = \frac{L(r)}{4\pi r^2}}$$

Force exerted by radiation on that gas (of unit mass) is then:

outward force $$F_{rad,\lambda} = \frac{\kappa_\lambda L}{4\pi c r^2} dm$$

$$\alpha_\lambda = \kappa_\lambda \rho = n\sigma_\lambda$$

Force due to gravity on that gas (unit mass):

inward, toward star of mass M $$F_{grav} = \frac{GM}{r^2} dm$$

The Eddington limit

Radiation pressure balances gravity when:

$$F_{grav} = F_{rad}$$

$$\frac{\kappa_\lambda L}{4\pi c r^2} dm = \frac{GM}{r^2} dm$$

$$L_{edd} = L = \frac{4\pi c G M}{\kappa_\lambda}$$

If L is larger than this value, then the pressure due to radiation exceeds the gravitational force at all radii, and gas will be blown away.

Critical luminosity is called **the Eddington limit**.
Depends upon:

- the mass of the star
- the opacity of the gas surrounding the star / source

How large is the opacity?

$$L_{edd} = \frac{4\pi c G M}{\kappa}$$

Opacity depends upon temperature, density, and composition.

In the outer regions of massive stars, it is generally ionized hydrogen; scattering is due to the electrons with Thomson cross-section σ_T , while the mass is set by protons, so $\kappa = \sigma_T / m_p$. In that case,

$$L_{edd} = 6.3 \times 10^4 (M/\text{gram})\ \text{erg/s}$$

$$L_{edd} = 1.25 \times 10^{38} \left(M/M_\odot\right)\ \text{erg/s}$$

$$L_{edd} = 3.2 \times 10^4 \left(M/M_\odot\right)\ L_\odot$$

Only important for sources that are much more luminous that the Sun.

Remember?
Main sequence stars obey a mass-luminosity relation, with $L \propto M^\eta$.
The slope η changes slightly over the range of masses; between 1 and $10M_\odot$, $\eta \approx 3.88$.

So… why is there a Solar wind?

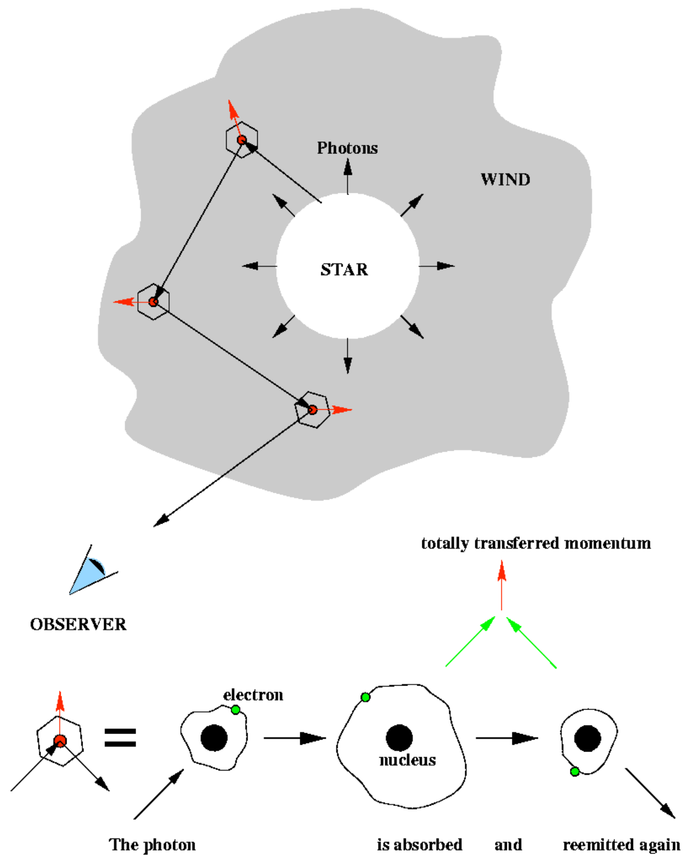
Mass-loss from high mass stars

Large amount of evidence now that high mass stars loose mass through a strong stellar wind.

- The winds are driven by radiation pressure - UV photons from a hot, very luminous star absorbed by the optically thick outer atmosphere layers.
- atmosphere is optically thick at the wavelength of many strong UV transitions (resonance transitions) of lines of Fe, O, Si, C (and others).
- photons absorbed, imparting momentum to the gas and driving an outward wind.
- It leads to wind velocities of up to 4000 km/s and mass-loss rates of up to $5 \times 10^{-5}\ M_{\odot}\ \mathrm{yr}^{-1}$.
- Huge effect on massive stellar evolution - the outer layers are effectively stripped off the star.

$$L_{edd} = \frac{4\pi c G M}{\kappa_{\lambda}}$$

The principle of radiatively driven winds



Stellar Winds

Hot Stars possess dense outflows, or stellar winds, which are produced via radiation pressure which influence their subsequent evolution – e.g. Wolf-Rayet Star 124.

Wolf-Rayet Stars

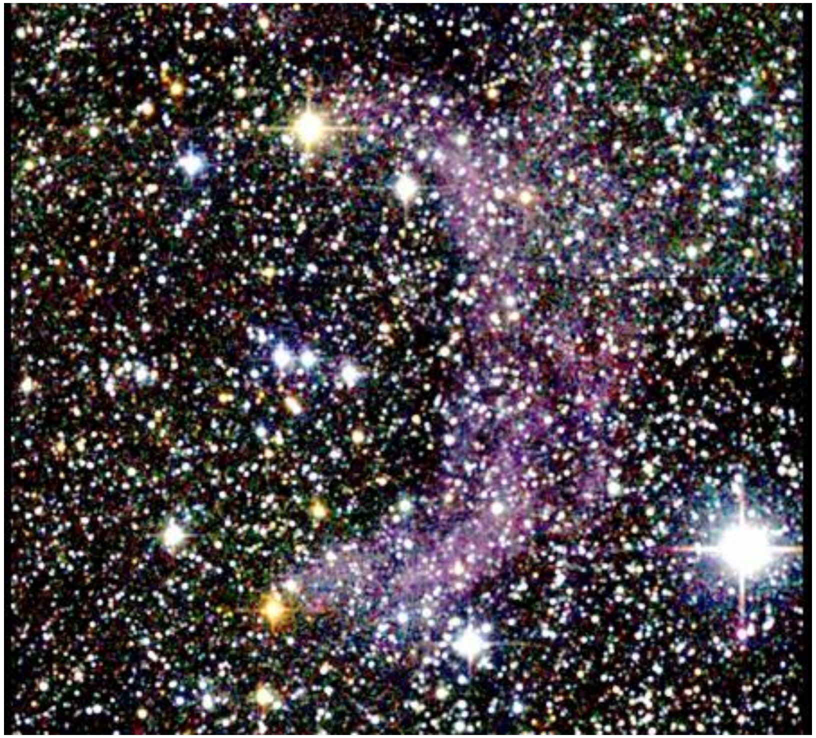
H-deficient massive stars. Spectra show either high abundances of He+N or C+O.

These are products of H-burning (CNO cycle) and He burning. Likely there is a relation between initial mass and final WR star produced.

Possible evolution scenario:

main-sequence star →
blue supergiant →
red supergiant →
lost of the envelope and WR star.

On the right: NGC 3199, in the constellation Carina, which is the wind-blown partial "ring“ around the WR star WR 18 (= HD 89358), the easternmost (leftmost) of the three bright blue stars near the center of the 2MASS image. NGC 3199 and WR 18 are at a distance of about 3.6 kpc from us.



The death of a high-mass star: supernova explosions

- Nuclear reactions in a high-mass star stop at the iron group, and the last reaction is ^{52}Fe capturing an alpha particle to make nickel.
- Further reactions would require energy to proceed.
- The star dies in a violent cataclysm in which its core collapses and most of its matter is ejected into space at high speeds.
- The luminosity of the star increases suddenly by a factor of around 10^8 during this explosion, producing a supernova.
- The matter ejected from the supernova, moving at supersonic speeds through interstellar gases and dust, glows as a nebula called a supernova remnant.
- Leaves either a neutron star or black hole behind.

In 1987 a nearby supernova gave us a close-up look at the death of a massive star

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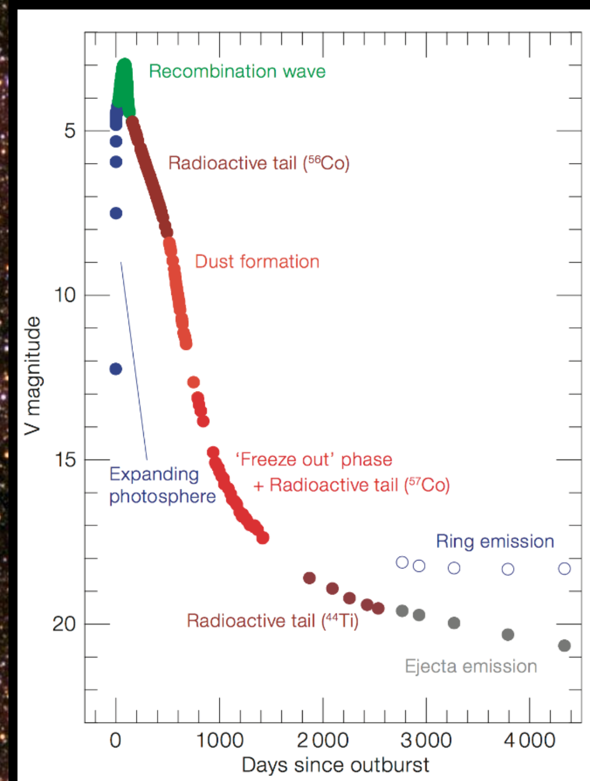
After the star exploded

Before the star exploded



Light curve

The evolution of SN 1987A

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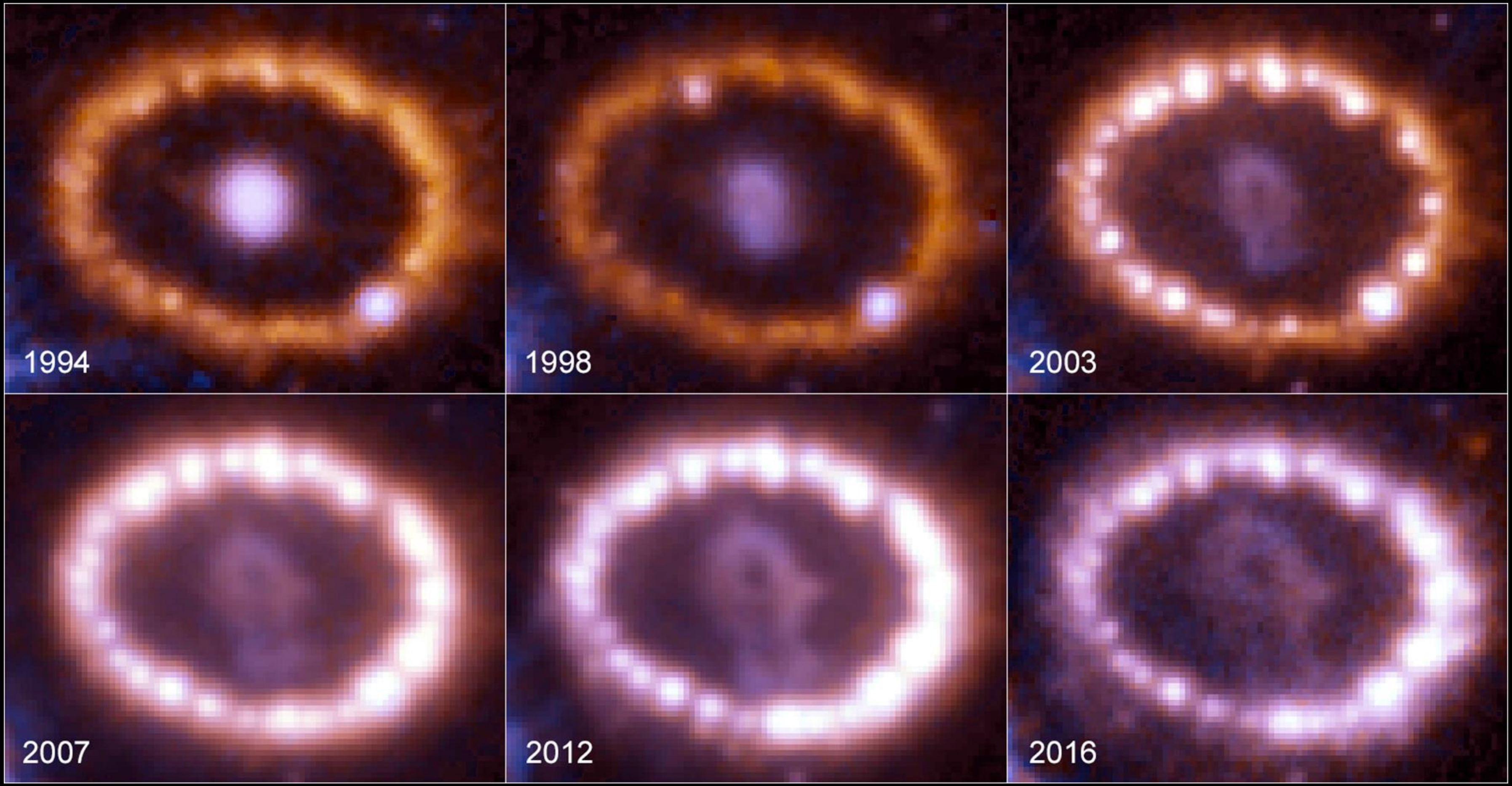


Summary of the differences between high- and low-mass stars

Compared to low-mass stars, **high-mass stars**:

- live much shorter lives.
- fuse Hydrogen via the CNO cycle instead of the p-p chain.
- die as a supernova.
  - low-mass stars die as a planetary nebula.
- can fuse elements heavier than Carbon.
- may leave either a neutron star or black hole behind.
  - low-mass stars leave a white dwarf behind.
- are far less numerous.

The initial mass function

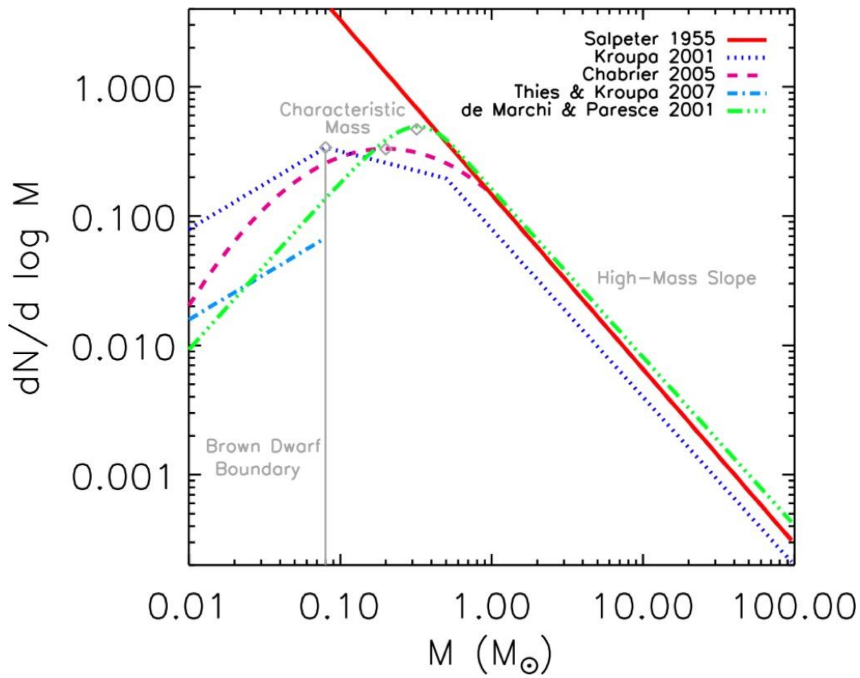
The initial mass function (IMF)

How many stars are formed at each mass in a star cluster, or a star forming region?
Is it always the same distribution ?
Is it constant across environments and galaxies?

Define the number of stars formed at a given time within a given volume, with masses in the range (M, M+dM) as a function solely of M:

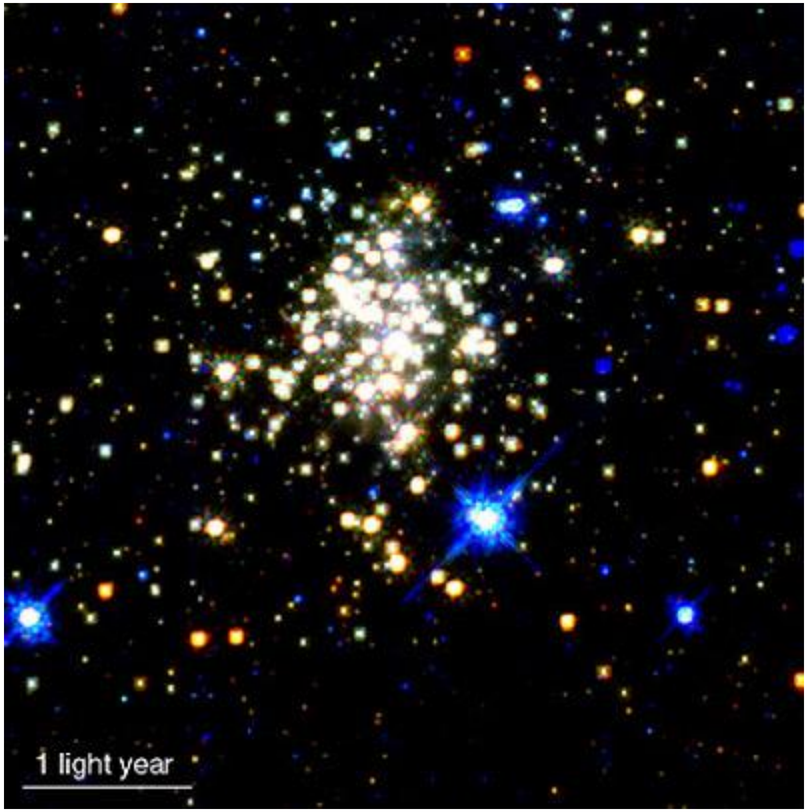
$$dN \propto M^{-\alpha} dM$$

This was the form originally adopted by Salpeter (1955), who determined α = 2.35 by fitting observational data. Over 65 years later, this value is still considered the standard for stars above 1 $M_\odot$.
However, this function diverges as it approaches zero.



Upper mass limit for stars

- How big do stars get?
  Is there an upper mass cut-off?
  What are the masses of the most massive stars?
- The most luminous stars in the Galaxy have inferred masses of ~150-300 $M_\odot$ but this value depends on estimate of $\log L/L_\odot$ and T_{eff}.
  The former requires distance, reddening, bolometric correction and the later requires reliable model atmosphere.
  Probably uncertain within a factor 2.



- The IMF was determined for the very massive Arches cluster (Figer 2005, Nature, 434, 152), which is massive enough that there is a reasonable probability that stars of masses >500 $M_\odot$ could exist in cluster, if they form.
- Most of the bright white stars near the centre of the image have M~120 $M_\odot$.

IMF is constant at different Z

- Solar neighbourhood composition: $X=0.70$, $Y=0.28$, $Z=0.02$.
- The Large Magellanic Cloud (LMC): $Z=0.5Z_{\odot}$
- The Small Magellanic Cloud (SMC): $Z=0.2Z_{\odot}$.
- Star formation of massive stars proceeds independently of metallicity.
- Local Group galaxies SMC and LMC are excellent laboratories to study massive star populations.

No evidence for environment influence

- Whatever the star-formation rate, the IMF seems constant,
- Starburst regions, "normal" young clusters, low mass clusters in Milky Way, LMC, SMC, all similar.
- IMF not measured well beyond the Magellanic Clouds.

Summary

- We have covered qualitative description of the evolution of star from modern calculations.
- The theoretical HRD in general, and $1M_\odot$ and $25M_\odot$ stars in detail.
- Time-scales for evolutionary stages: 90% of massive star's life is on main-sequence. Final stages of C-burning and beyond last few hundred years.
- Massive stars loose mass - most massive become WR stars, with final masses significantly less than birth mass.
- The main-sequence stars should have upper mass limit.
- The initial mass function (IMF) implies significantly less massive stars than low mass stars born - implications for galactic evolution.