Lecture 17

Lives and Deaths of Stars

Outline of Lecture 17

- Evolution of stars with $M < 8M_\odot$:
  MS → RG → HB (or CG) → AGB → PN → WD.
- Evolution of stars with $M > 10M_\odot$:
  MS → successive rounds of nuclear burning
  → "onion-skin" interior structure
  → collapse of degenerate iron core +
  expulsion of envelope in SN explosion
  → remnant = NS or BH.
- Nuclear processing inside stars and expulsion of processed material into interstellar space by dying stars leads to gradual enrichment in successive generations of stars born from the interstellar medium in elements heavier than H and He.

Radii, Masses, and Lifetimes on the Main Sequence

Figure 13.9 Stellar radii on H–R diagram

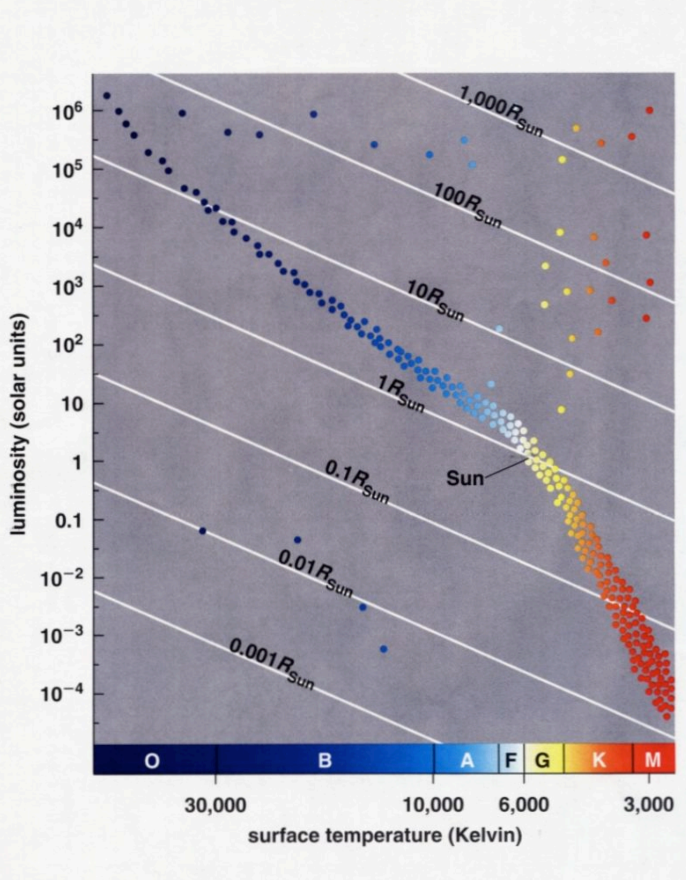
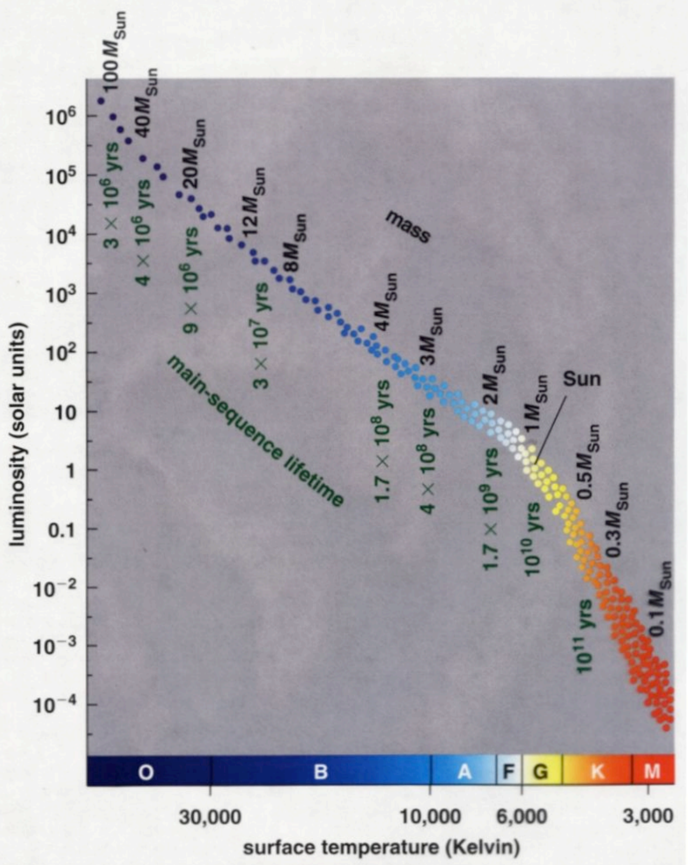
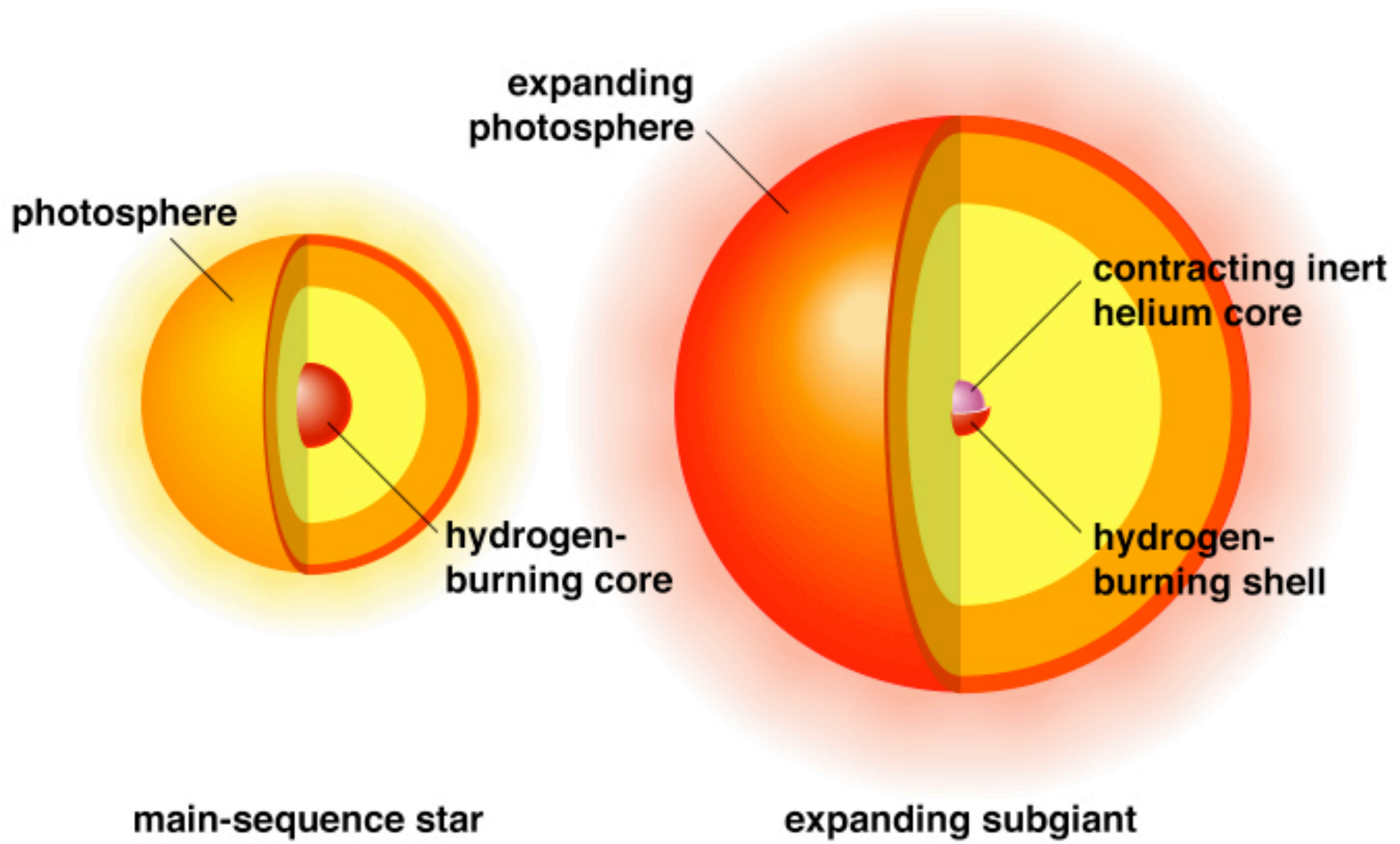


Figure 13.10 Main sequence masses and lifetimes

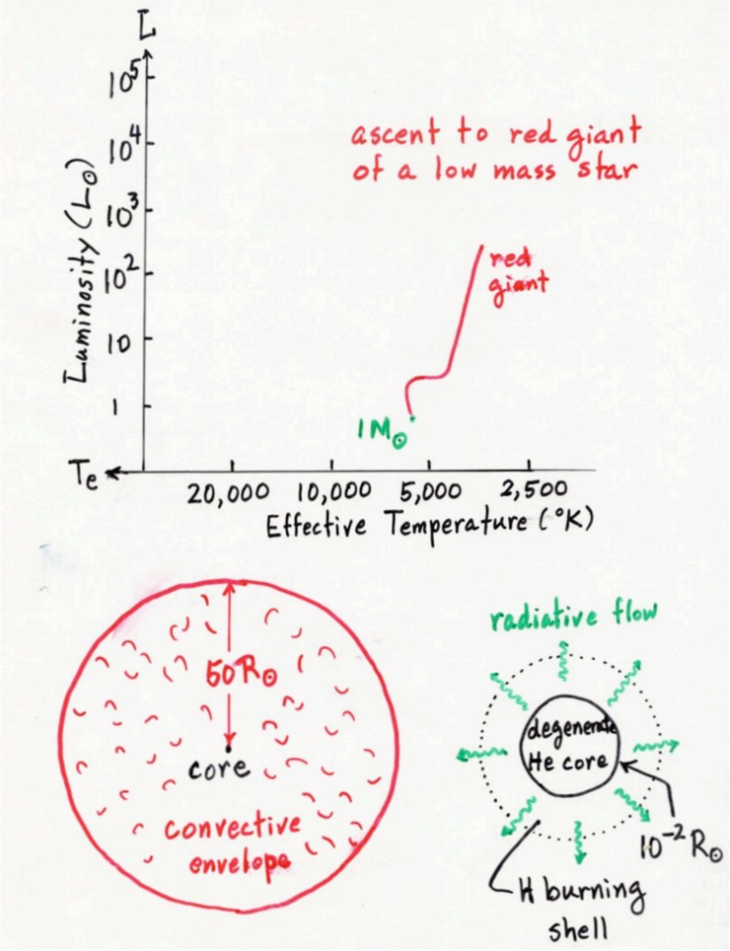


From Main Sequence to Subgiant



Ascent to Red Giant

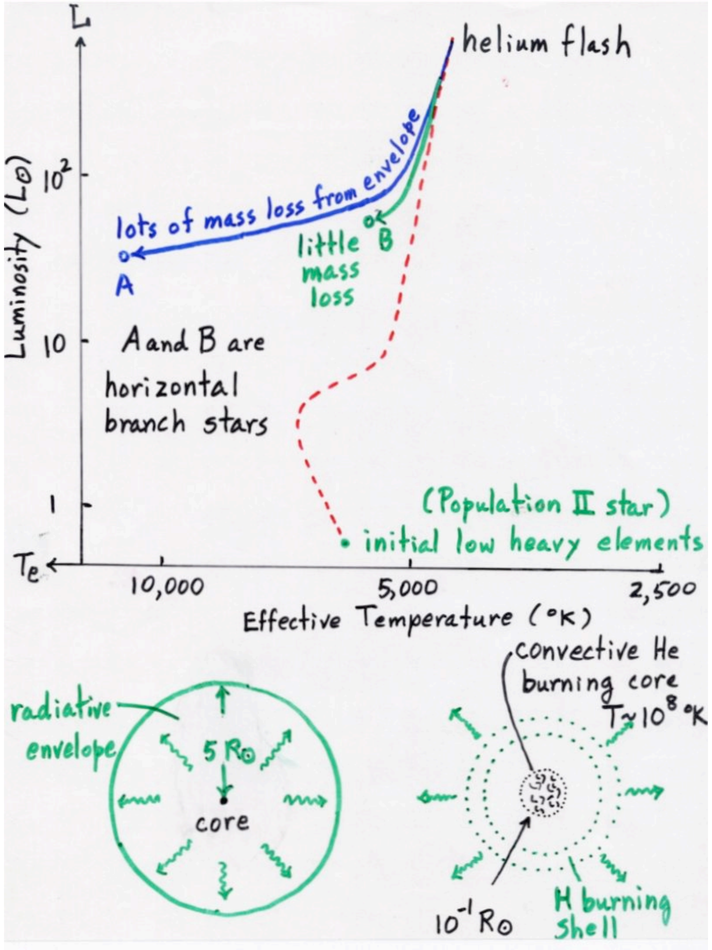
- Core H exhaustion, followed by contraction and heating of core.
- Eventually, shell around core containing H becomes hot enough to ignite H fusion into He.
- Fusion of H drops He “ash” into core, which adds to its gravity and tendency to contract even more.
- Weight and therefore pressure of H-fusing shell becomes greater which makes H fusion occur faster.
- Increased energy released by H-fusing shell compared to what can leave surface expands envelope surrounding inert (contracting core) and H-fusing shell. Star becomes a subgiant then a red giant.
- Increasing radius leads to larger luminosity leaving surface even though effective temperature drops somewhat from its main-sequence values, giving it a red color (like Betelgeuse).
- Meanwhile, contracting core becomes increasingly dense, eventually making electrons in it degenerate. If we could see it, core would look like a white dwarf (i.e., have a size about that of Earth).
- At tip of red-giant branch, core becomes hot enough (about 10^8 K) to ignite He fusion into C in a flash.



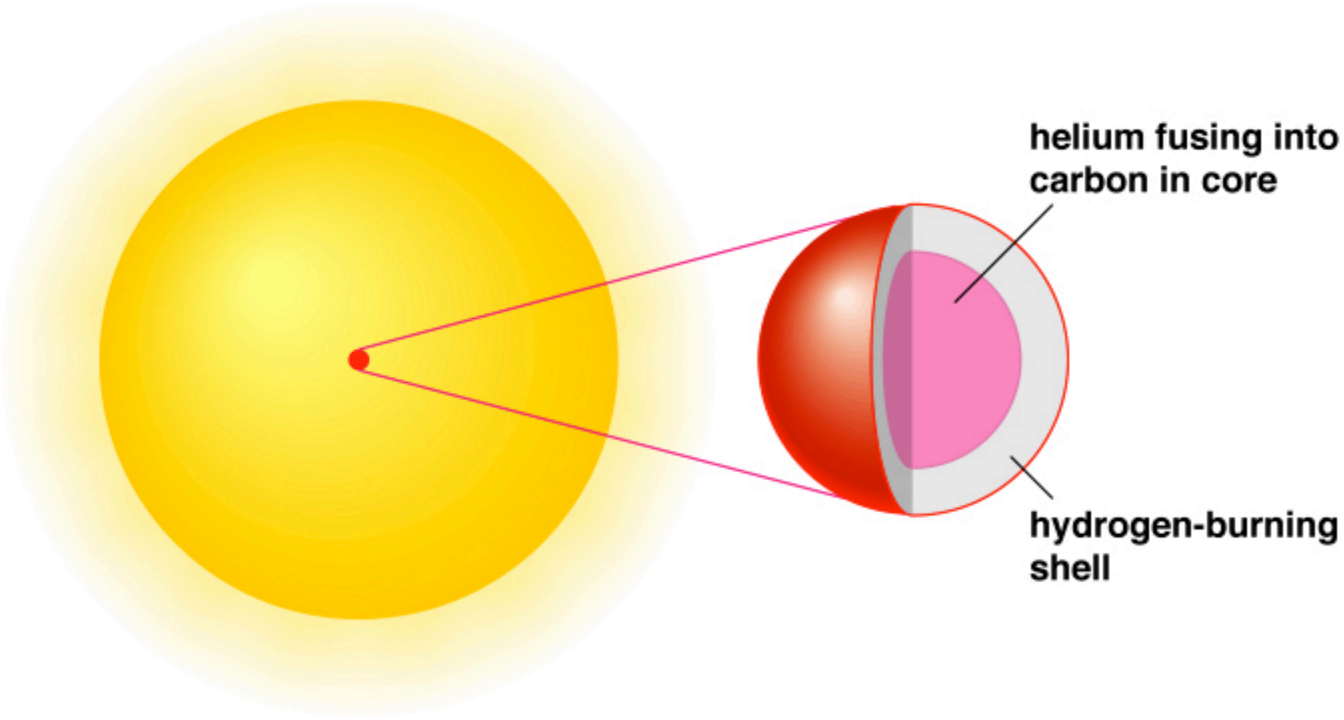
When Sun expands to tip of red-giant branch, its diameter will subtend an angle of about 30° seen from Earth.

Helium Flash to Horizontal Branch

- He-fusion (triple alpha reaction) turns on in a flash because as long as electrons are degenerate, the pressure that they supply the core is insensitive to increases of temperature.
- When the temperature becomes high enough ($T \sim 10^8$ K), heat released by He fusion is enough to "lift the degeneracy" and make the helium-fusing core a normal ideal gas, whose pressure rises with increasing temperature, thereby expanding the core.
- Expansion of the core causes the core and the shell sources to "burn" less vigorously, lowering the luminosity entering the envelope.
- The lowered luminosity supplied the envelope causes the envelope to contract, which makes the star at the tip of the red giant branch descend in the H-R diagram to the "horizontal" branch.

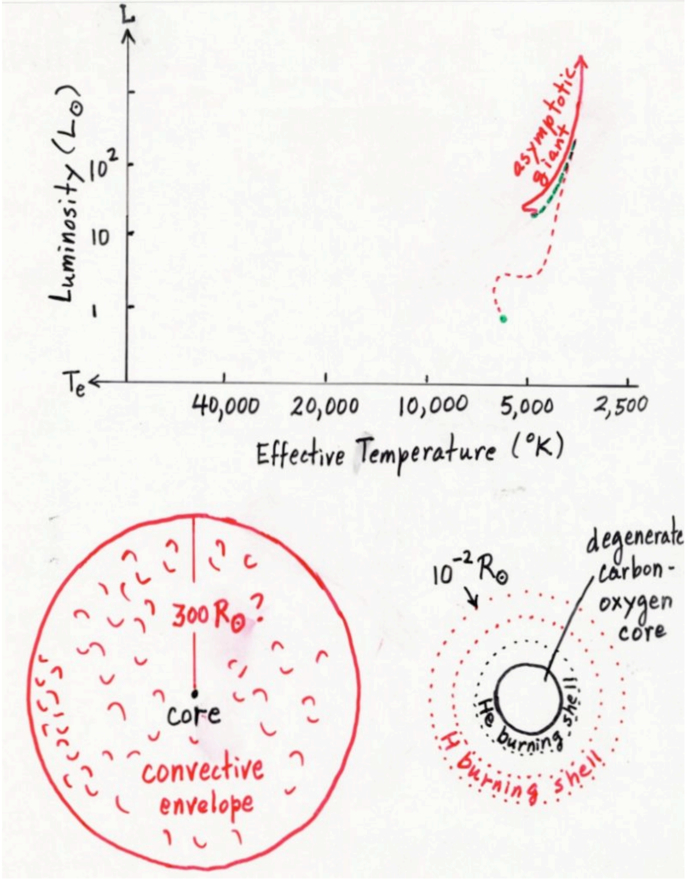


Horizontal Branch Star



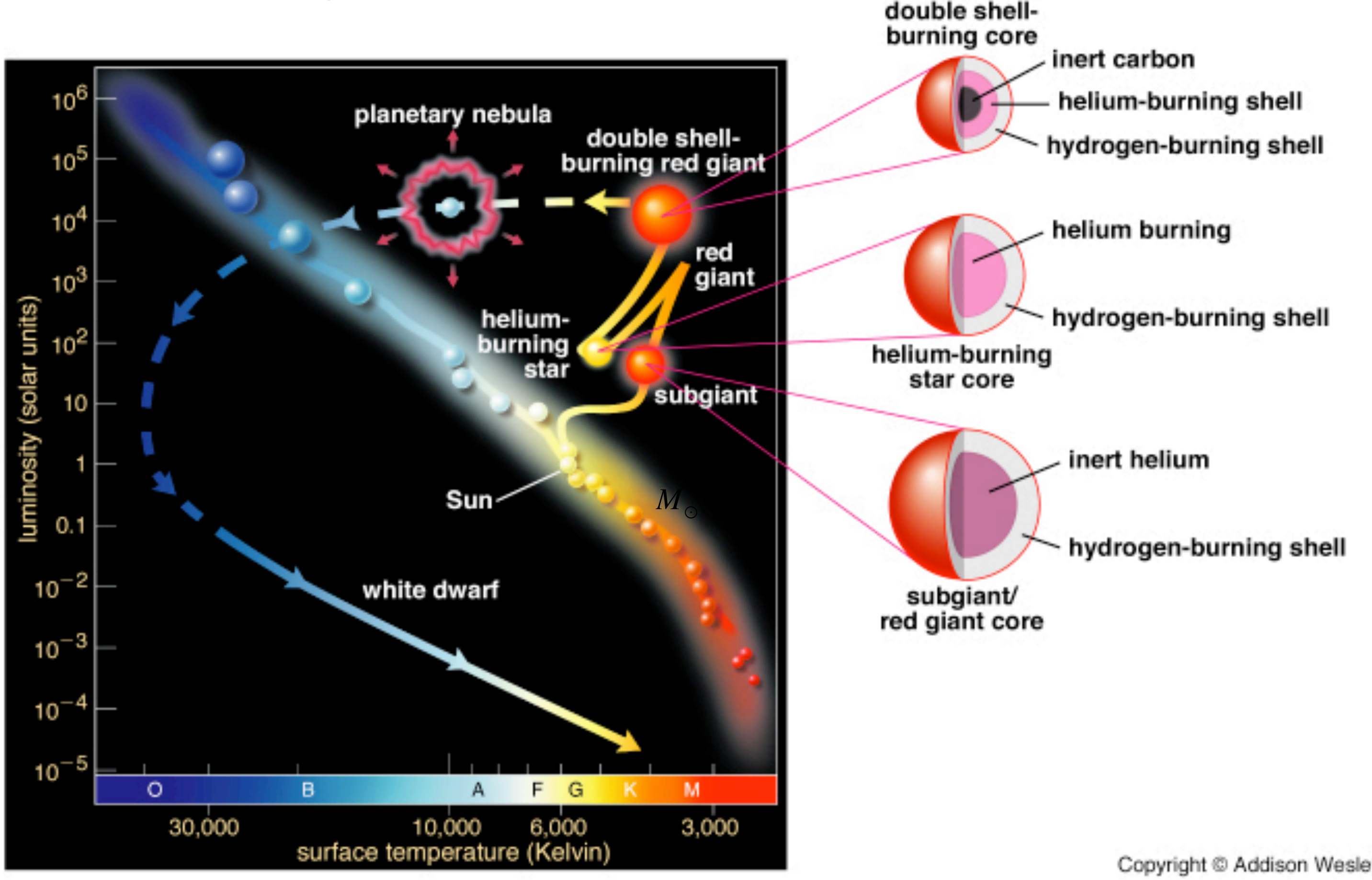
Ascent to Asymptotic Giant Branch

- Eventually, He will be exhausted in core (by alpha captures to make C and O).
- The hot core still loses energy to its surroundings, so the core will again begin to contract.
- The contraction of the core increases the gravity pulling on the envelope, increasing the pressure (density and temperature) of the layers just above it, igniting He-fusion in a shell, which has a H-fusing shell above it.
- The ash dropped through the two shells into the core increases its mass, which accelerates the contraction of the core, increasing the rate of double-shell fusion even more.
- The greater luminosity entering the base of the overlying layers expands the envelope again, causing the star to ascend the asymptotic giant branch.
- Considerable mass-loss occurs from the star's bloated atmosphere, which whittles down the masses of stars that started with less than $8 M_\odot$ to below M_{Ch} (1.4 $M_\odot$).
- With $M < M_{Ch}$, core temperatures never reach the 5×10^8 K needed to ignite carbon fusion.
- Thus, stars that start on the main-sequence below $8 M_\odot$ are destined to end as C-O white dwarfs.



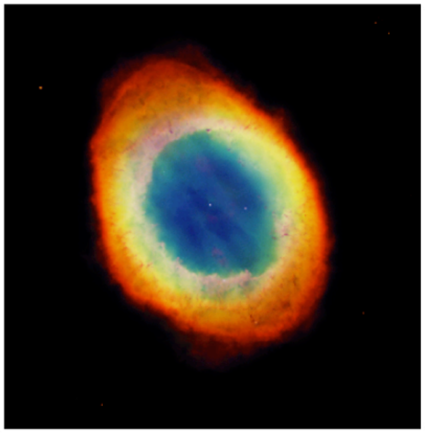
Toward the end of its life as an AGB star, the Sun will have a radius so large as to swallow the Earth.

Planetary Nebula to White Dwarf



On the AGB branch, the outer radius of a star is so large, and its surface gravity is so small, that it has difficulties holding onto its extended outer atmosphere. As a consequence, it loses a prodigious amount of material in a AGB wind, whose rate exceeds that of the present Sun by up to ten orders of magnitude. For stars that start on the main sequence below $8M_\odot$, this mass loss reduces the mass that remains within the star below the Chandrasekhar limit for WDs.

Some Planetary Nebulae



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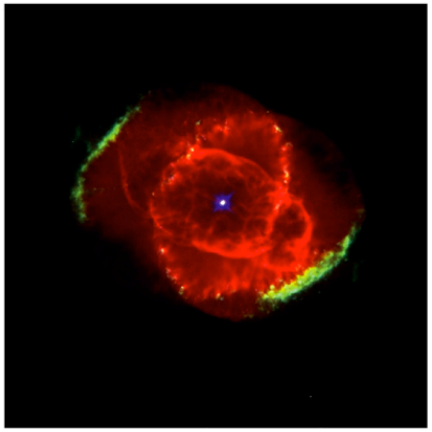

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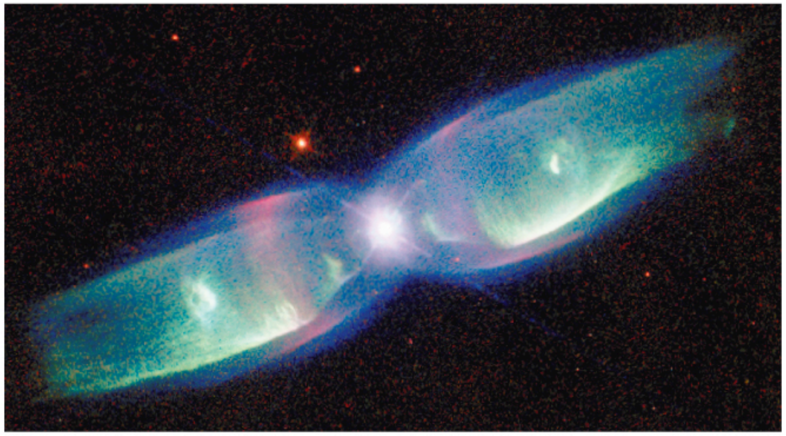


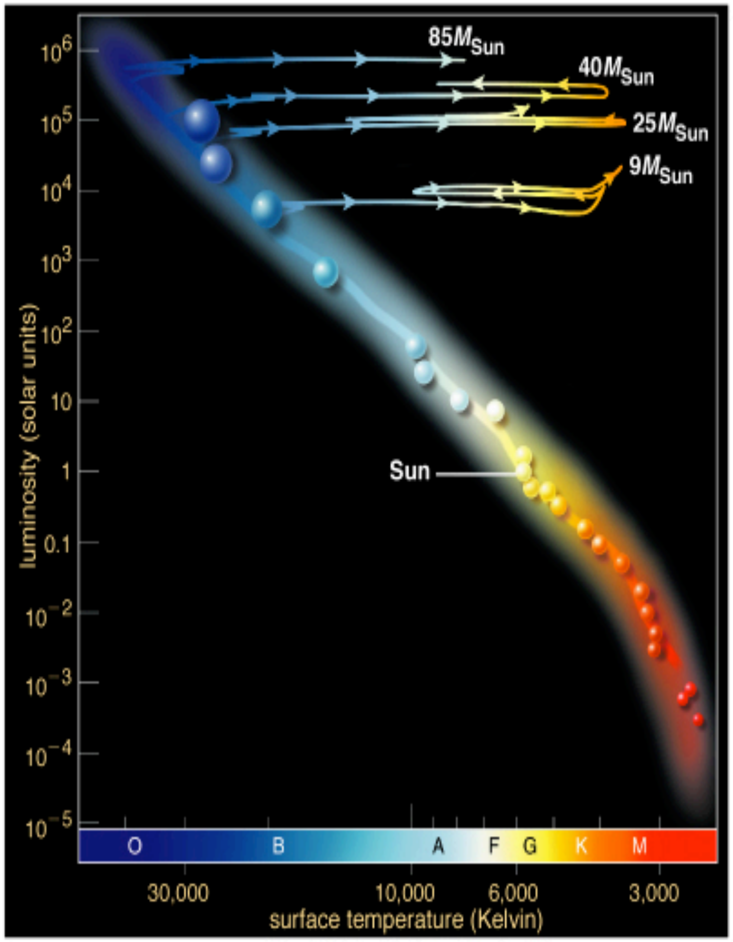
(c)

(d)

Planetary nebulae are the gases expelled in AGB star-winds that are lit up into fluorescence by the ultraviolet light emanating from a blue-white nucleus at the center (an incipient white dwarf born of the hot ashes of the prior advanced stages of nuclear burning).

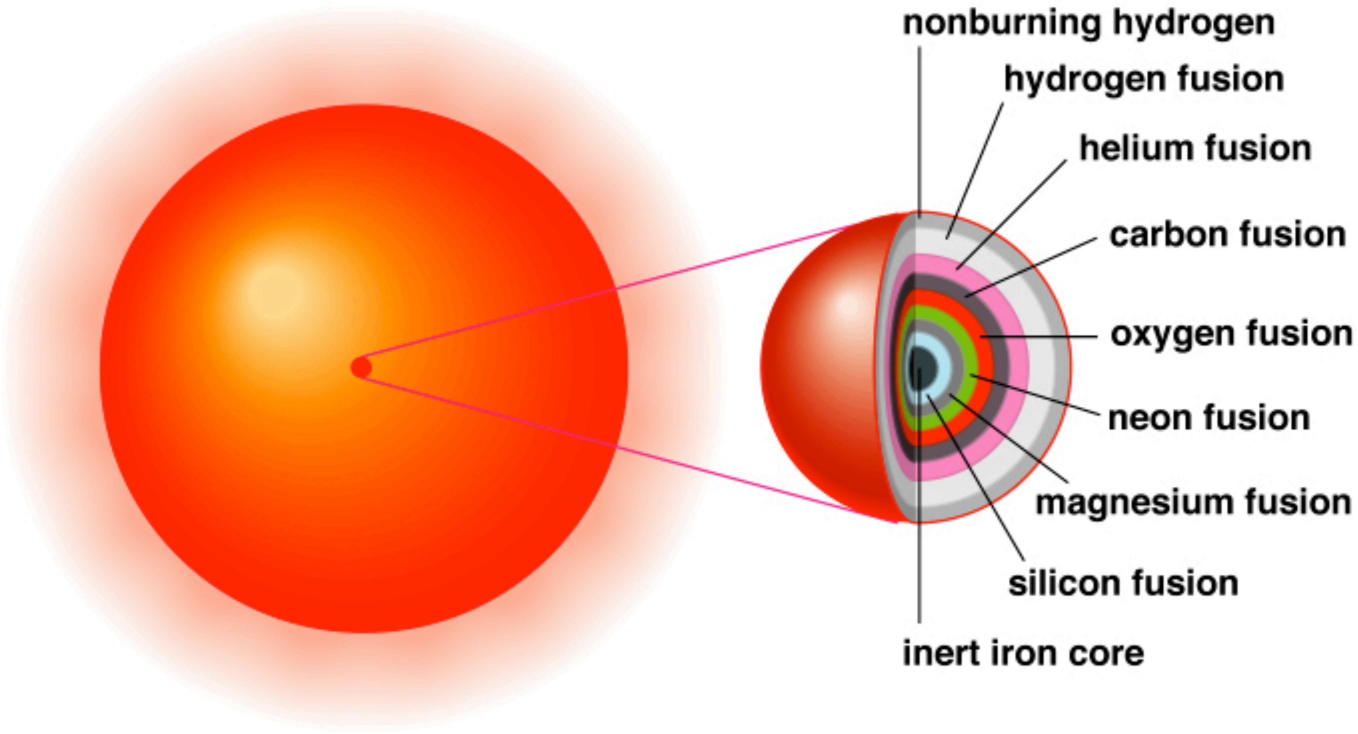
Evolution of High Mass Stars

- Stars more massive than $9M_\odot$ on the main-sequence differ in evolution from low- and intermediate mass stars in that they ultimately produce white dwarf cores that, even with mass loss, try to exceed the Chandrasekhar limit $M_{\mathrm{Ch}} = 1.4\ M_\odot$.
- The consequence is that one round of nuclear fusion turns into another: H into He, He into C and O, C and O into Mg and S, etc.
- Each new exhaustion of a core source, followed by core contraction and ignition of a new shell, tends to send the star to the right in the H-R diagram (increasing radii and decreasing effective temperature, almost at constant luminosity, because high-mass stars have a large capacity to diffuse radiation at a constant rate).
- Each ignition of a new core source (of what was previously ash) followed by core expansion and shell source weakening, sends the star to the left (decreasing radii and increasing effective temperature).
- This pattern continues until nuclear burning has created iron-group elements in the core.



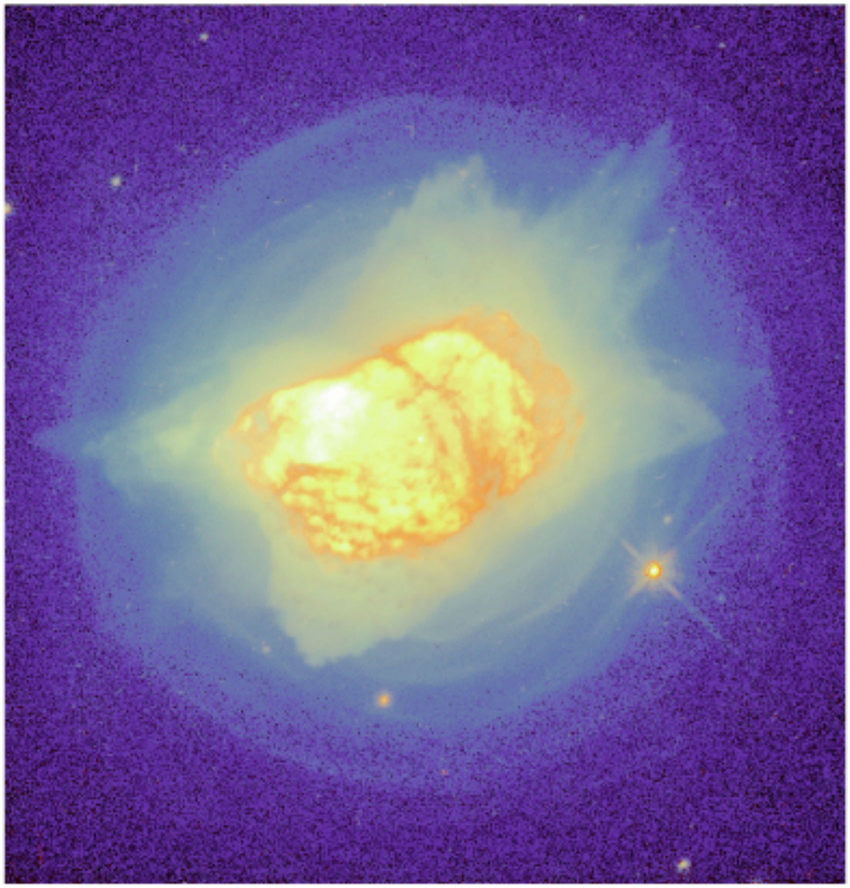
Addison-Wesley

Pre-supernova Star



A star in the pre-supernova state has an onion-shell structure. At the center of the onion is an inert iron core that approaches the Chandrasekhar limit as nuclear ash continues to drop in from the burning layers above. Since iron cannot yield energy by either fusion or fission, it is unable to stop the inexorable contraction of the superhot electron-degenerate core to ever smaller radii.

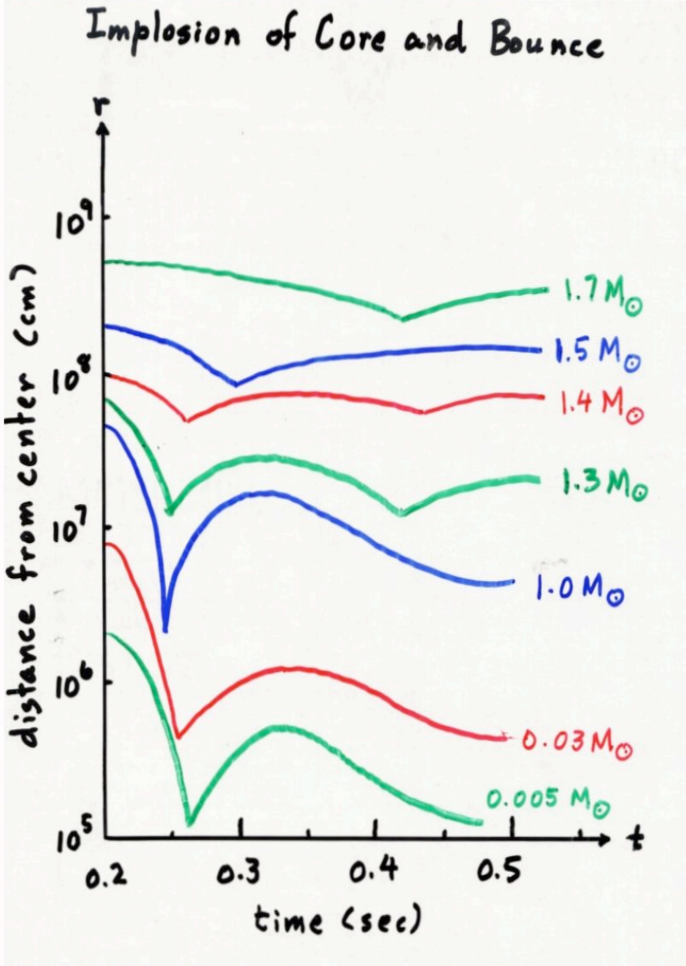
Eta Carina – A Pre-Supernova



The furious burning of many shell sources above the inert but contracting iron core causes the outer layers of a pre-supernova star to expand to a grotesque size and shape.

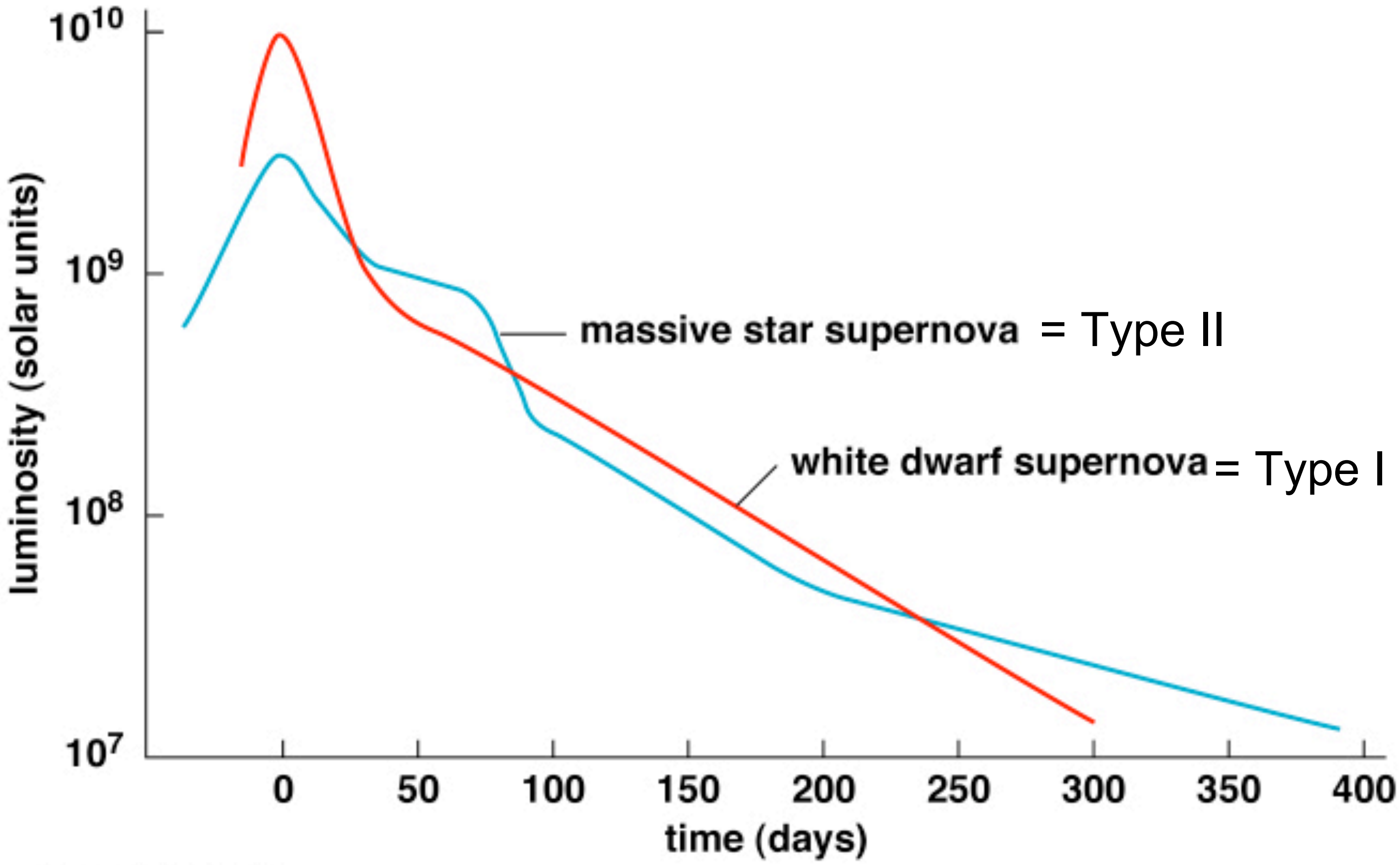
Implosion of Core and Bounce

- As the inert iron core (layers with enclosed masses below $1.4\,M_\odot$) contracts and heats; eventually temperature reaches several billion K, a value where matter prefers more particles rather than larger binding energy.
- Nuclei of iron-group elements begin to photo-dissociate into numerous smaller nuclei (primarily alpha particles), robbing the core of heat.
- Core goes into collapse, accelerating breakup of atomic nuclei into constituent protons and neutrons, robbing the core of even more heat.
- Density becomes high enough to force electrons to combine with protons into neutrons, a conversion that releases copious numbers of neutrinos in the process, adding to those created thermally.
- When the mass of neutrons reach nuclear densities, it attempts a dynamical "bounce," which detailed numerical simulations show is unable to effect a prompt explosion.
- Instead, a delayed explosion (taking a few sec) may occur from the outwardly streaming neutrinos transferring a small amount (0.1%) of their energy release (the binding energy of a neutron star ~ 10^{47} joule) to reverse the infall of the envelope.
- Creation of elements heavier than Fe in neutron-rich expelled material by rapid neutron capture followed by radioactive decay.



Analogy of dropped soccer ball atop of which rests a tennis ball.

Light Curves for Type I and Type II Supernova



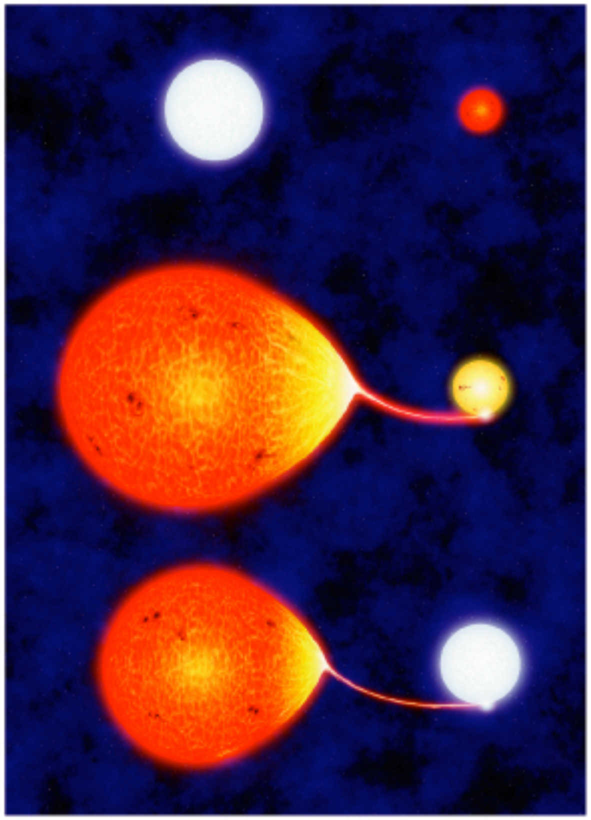
= Type II

= Type I (no H lines)

Because SN at their peak of all types are so bright, they can be used as calibrators of distance to great distances if all SN of a given type look more-or-less the same. The latter holds better for SN Ia (WD SN) than any other types .

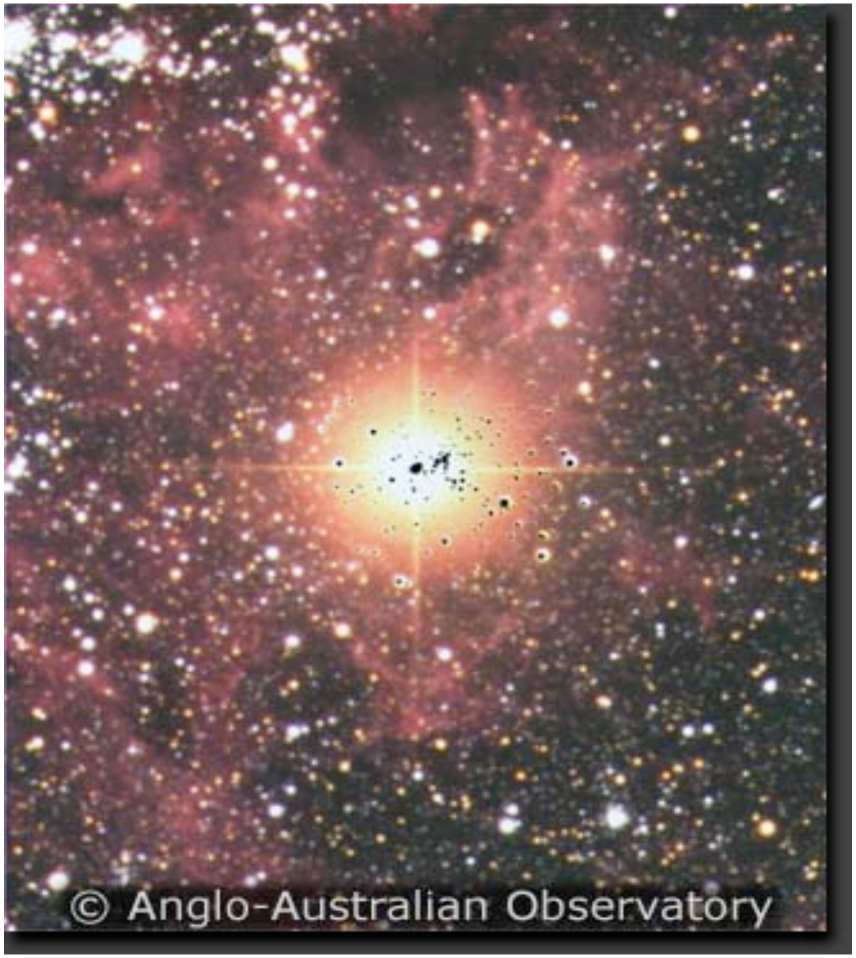
A WD in a Mass Transfer Binary Can Acquire Mass, Exceed the Chandrasekhar Limit, and Supernova

When a WD at exactly Chandrasekhar's limit explodes, it should behave as a "standard candle." This is useful for calibrating distances in cosmology. A difference may come from the rotational modification of Chandrasekhar's criterion. Fortunately, empirical corrections can be made assuming that supernovae with the same light-curve shape have the same luminosity.



Supernova 1987A and its Precursor Star in the LMC (extra material)

- Large and Small Magellanic Clouds (LMC & SMC) are nearby satellite galaxies of our own Galaxy, the Milky Way System (Lecture 18).
- Named after Magellan who saw them during his round-the-world voyage that took him to the Southern Hemisphere.
- First recorded observations in tenth century by Al Sufi, although LMC and SMC must have been known to the Mayans & Aztecs.
- A SN of type II exploded in 1987 in the LMC.
- It was shown later that the timing of the light outburst was simultaneous with a burst of excess neutrinos recorded by the Super-Kamiokande and other solar neutrino experiments.
- Number of neutrinos that arrived within a few seconds is consistent with SN predictions.
- At peak neutrino output, SN 1987A released as much energy per second (in neutrinos, not light) as the rest of the observable universe combined!



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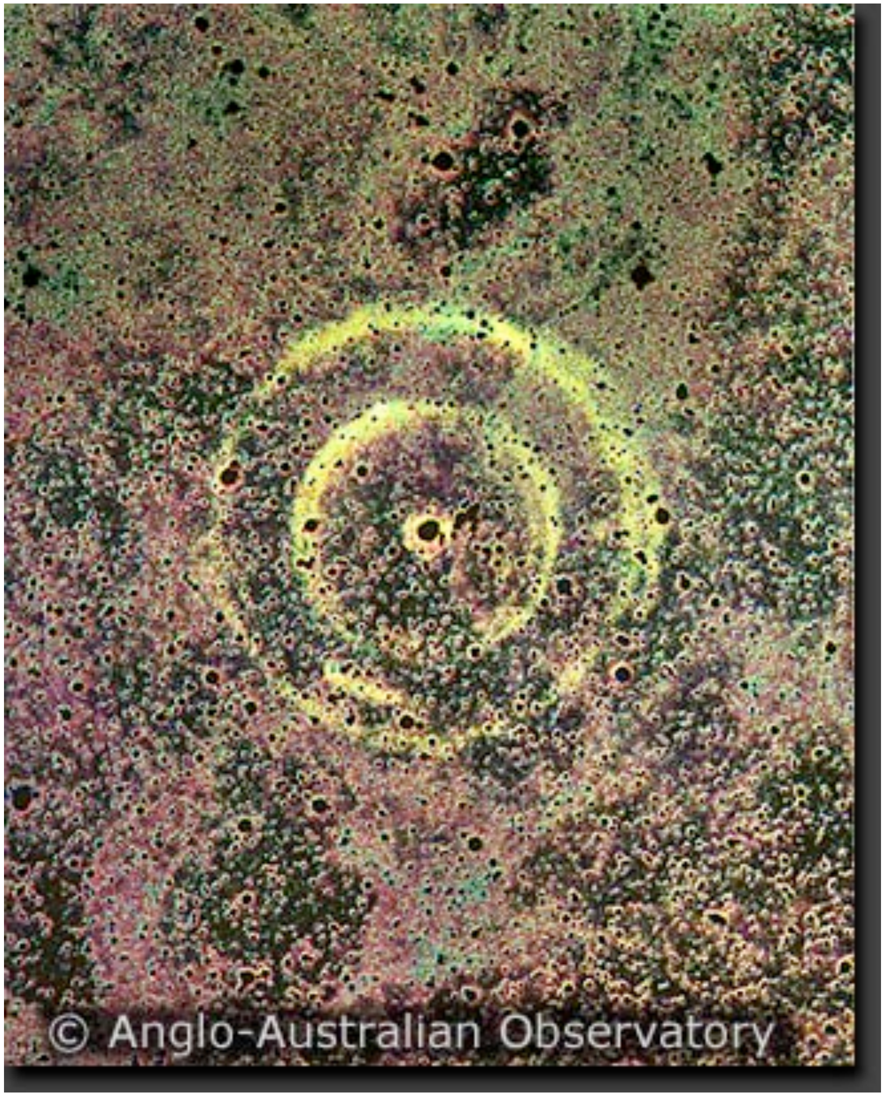
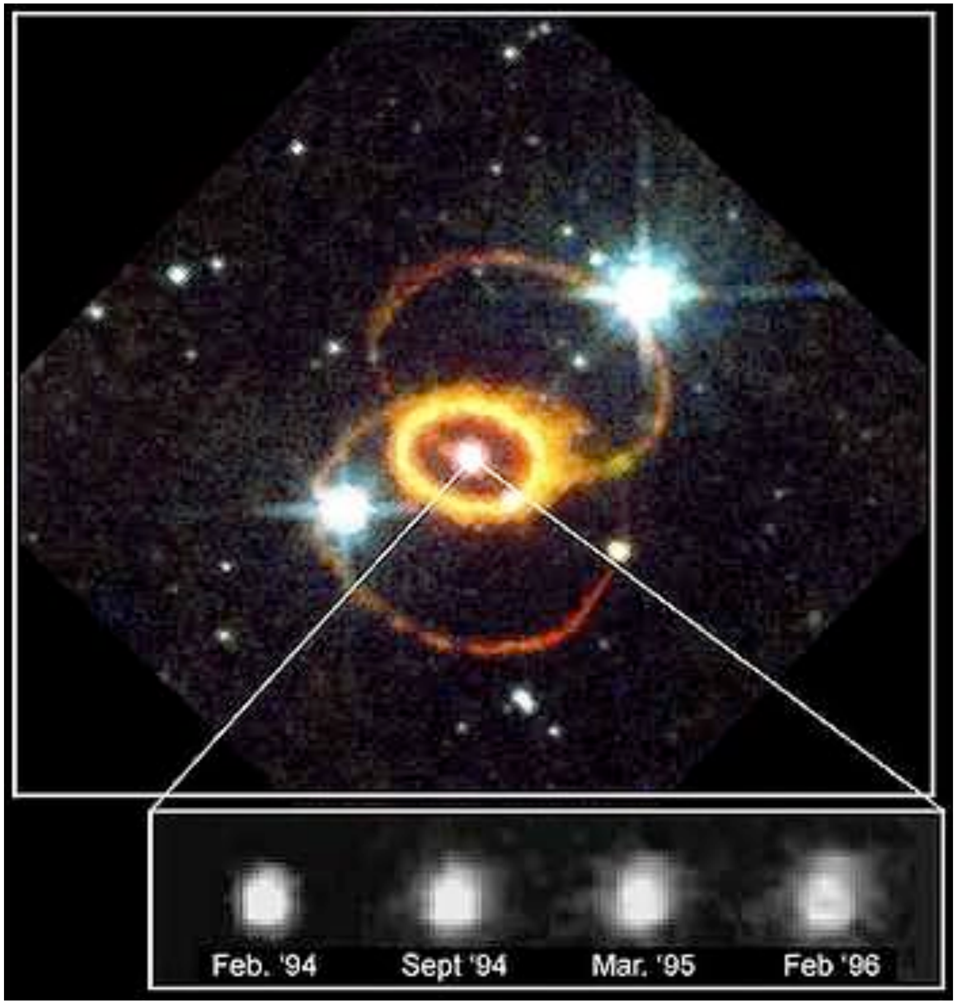
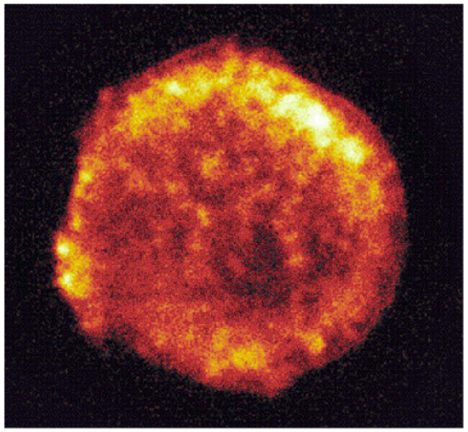
Light Echoes from SN 1987A Allow Accurate Measurement of Distance to LMC (extra material)

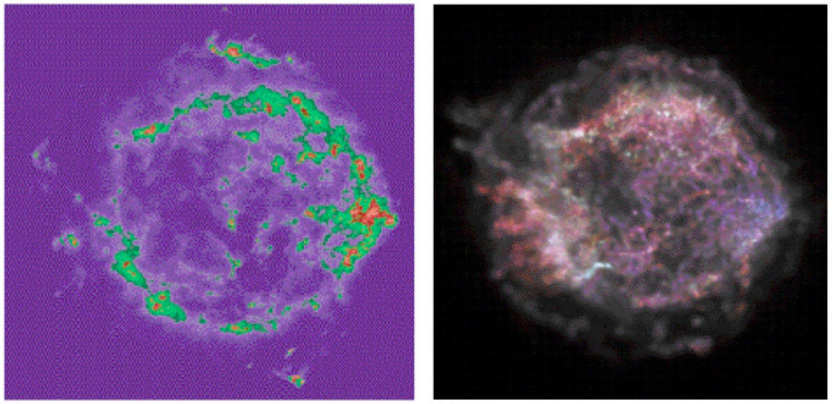


SN 1987A Left Behind a Fascinating Remnant (extra material)

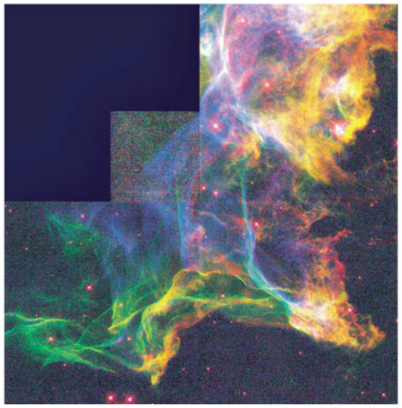


Older Supernova Remnants in Our Own Galaxy (extra material)



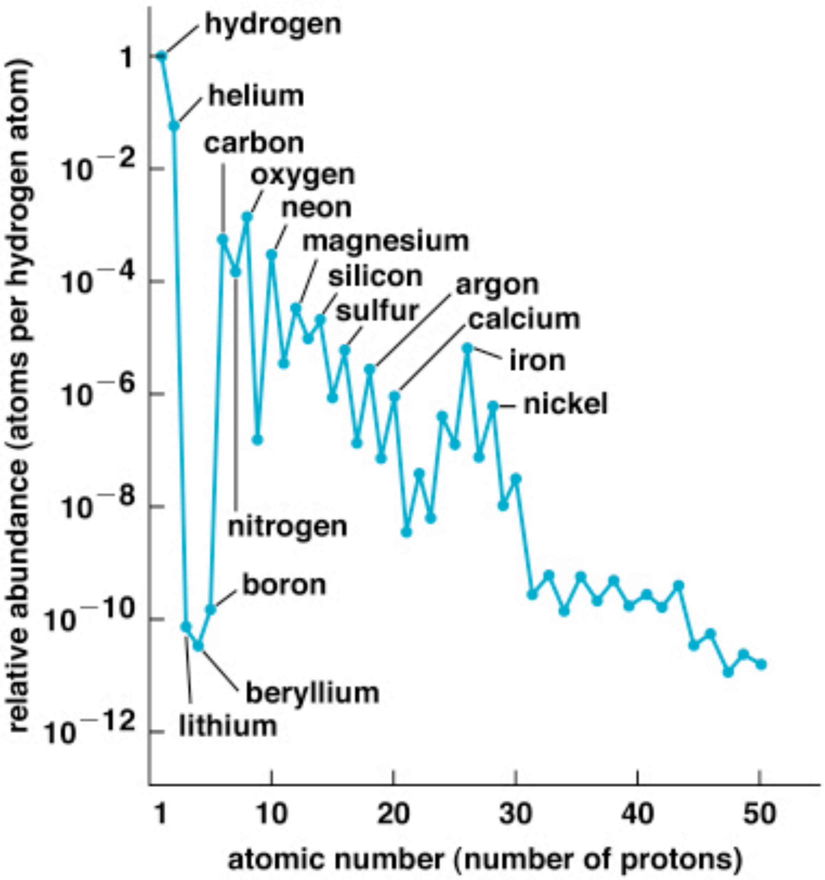


(a) (b)



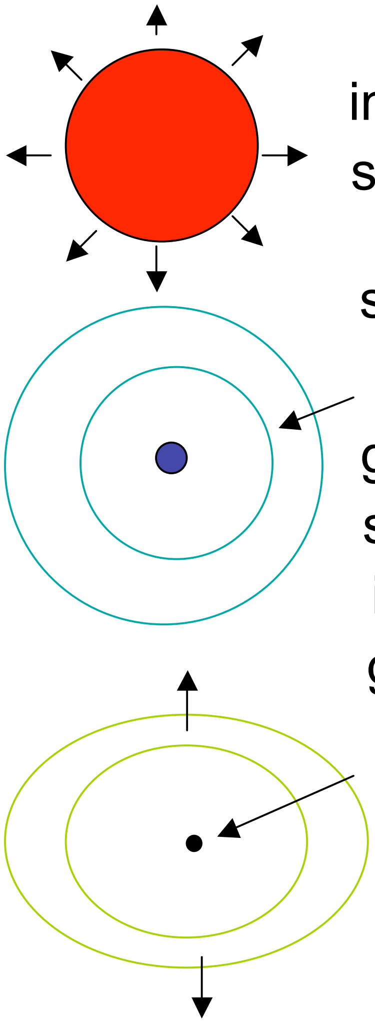
(b)

Stellar Processing Determines Relative Abundances of the Elements Heavier than H and He



Summary of Dying Stars

- Red Supergiant:
  - Dust grains form in cool outer atmosphere and expelled by
    ISM
    radiation pressure.
- Planetary Nebula:
  - Shell of gas and dust illuminated and excited by hot central star, which is exposed core of red supergiant destined to become WD.
- Supernova Remnant:
  - Ejecta of processed matter from high-mass star which impacts with ISM and forms supernova remnant that is a source of cosmic rays.



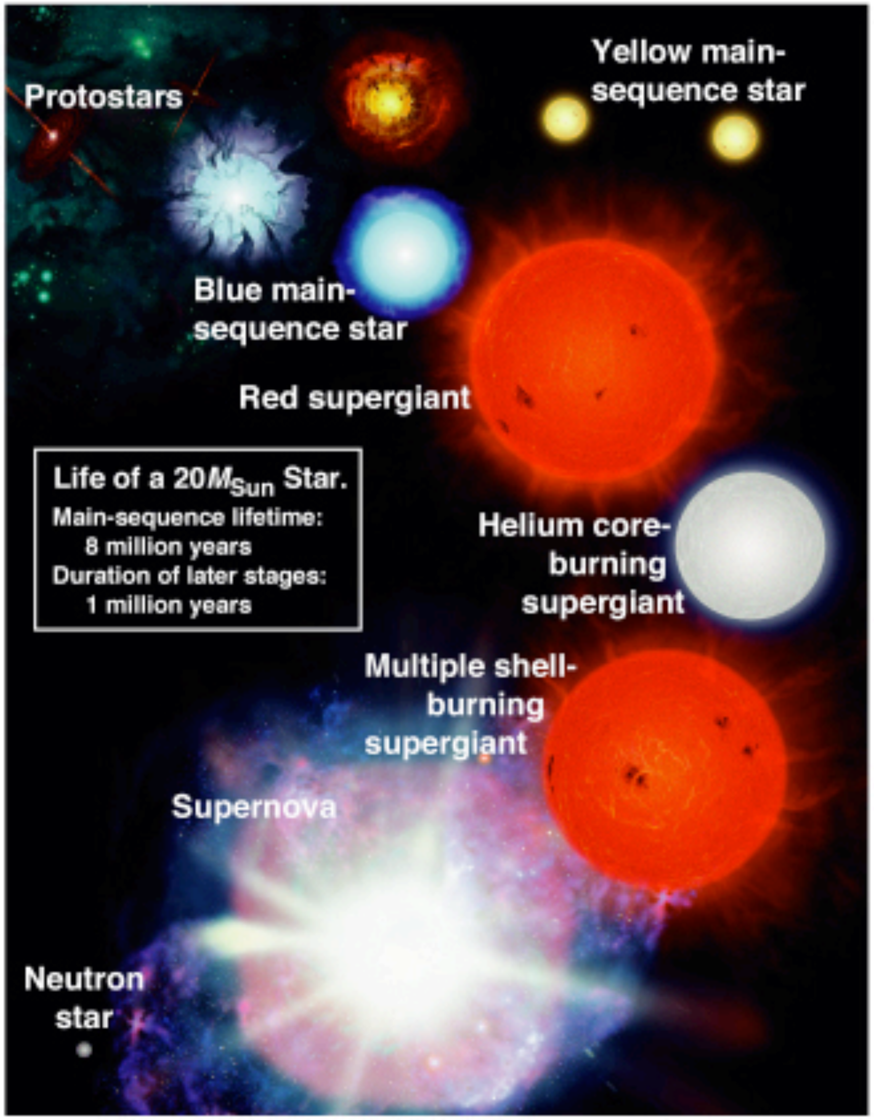
input of small solids

glowing shell of ionized gas

neutron star or black hole

Life Cycle of Stars (extra material)

- Stars begin their lives primarily as self-gravitating balls of H and He.
- Nuclear fusion reactions inside stars gradually transform initial supply of H and He into progressively heavier elements.
- In low-mass stars (which become WDs with $M < M_{Ch}$), the fusion process stops at the formation of C and O, or earlier.
- In high-mass stars (which become NSs or BHs), the fusion process proceeds to the iron peak (in nuclear binding energy). In the subsequent implosion and explosion, elements beyond the iron peak can form by neutron capture reactions.
- The expulsion of processed material into the ISM by dying stars provide matter (gas and dust) enriched in elements heavier than H and He that gets incorporated into the bodies of new generations of stars and planets.
- Without stars, i.e., with only H and He, the universe would have the capability to form essentially only one important molecule H_2, and chemistry and biochemistry would be virtually nonexistent.



Miscellaneous Comments (extra material)

- A high-mass star begins its (main-sequence) life as a ball of protons and electrons (mostly), and it ends its life as a ball of neutrons (if it becomes a NS).
  - But neutrons have more mass-energy than separated protons and electrons. Thus, nuclear transformation is ultimately, a *sink*, and not a source of energy for such stars!
  - From where then did the energy come for the luminous power of the normal star and the sound and the fury of the supernova explosion?
  - Answer: *gravity power* – the gravitational potential energy of a NS is much more negative than the gravitational potential energy of a main-sequence star.
  - Alternatively, we may say that the mass of the NS is about 10% smaller than the Chandrasekhar-mass WD progenitor that made it.
  - From the last point of view, nuclear transformation has turned many atomic nuclei into one super-massive atomic nucleus (the neutron star).
- If stars are continuously transforming H (and He) into heavier elements, why do we have any H (and He) left in the universe?
  - Either H must be continuously manufactured to make up for the gradual and steady transformation, or
  - The Universe must not be infinitely old, i.e., the Universe must have experienced a *creation event* (“big bang”) from which emerged matter mostly in the form of H and He, the two simplest elements in the periodic table.