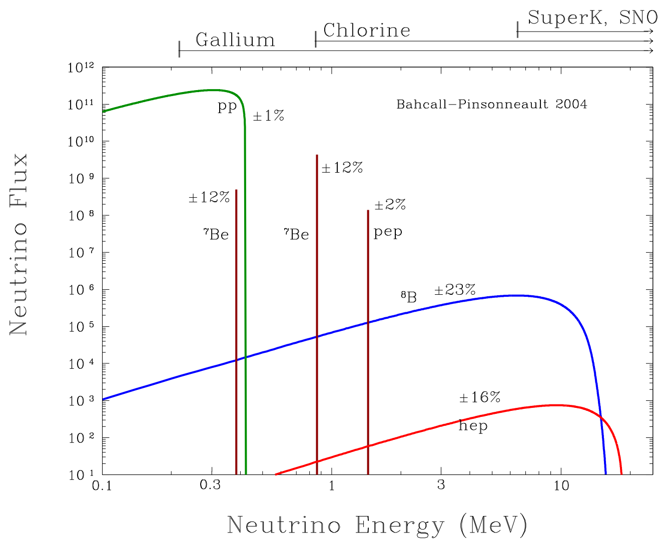
The Sun & Stellar Evolution

Solar Neutrinos



after Bahcall

The solar model predicts a solar neutrino spectrum that can be compared with Earth based measurements. This is the most direct test of theory of stellar structure known.

Problem: Neutrinos are difficult to detect since their interaction cross section is *very small*

$\Longrightarrow$ large detectors are needed.

inelastic neutrino–nucleon cross-section:

$\sigma \approx 10^{-43}\,\mathrm{cm}^2\,(E/\mathrm{MeV})^2$

The first neutrino experiment in the Homestake mine (J. Davis et al., 1968ff.).

Based on reaction

$$\nu_e + {}^{37}\mathrm{Cl} \longrightarrow {}^{37}\mathrm{Ar} + e^-$$

Use Chlorine in large tetrachloroethylene tank (615 T), detect Ar with radiochemical methods.

Sensitive for electron neutrinos at energies above ~0.8 MeV, which are rare.

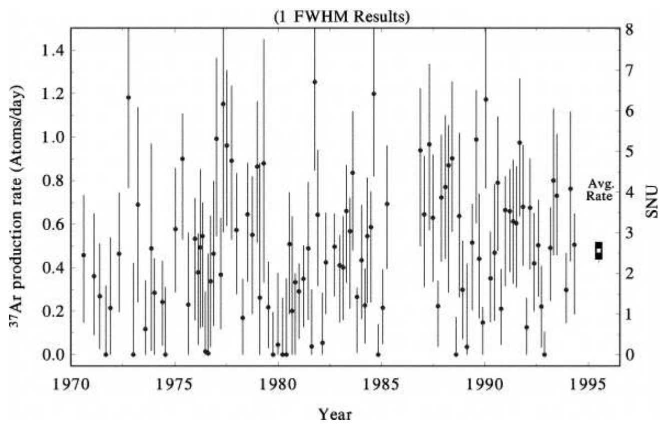
Expected rate: 8.5 ± 1.9 SNU

Detected rate: 2.6 ± 0.2 SNU

1 SNU: 10^{-37} captures target atom^{-1} s^{-1}.

Brookhaven National Laboratory

Solar Neutrinos



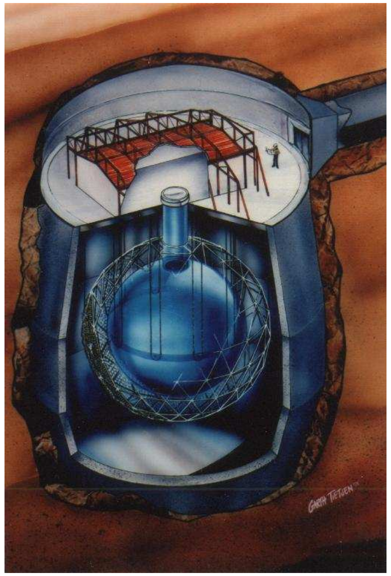
Cleveland et al. (1998, ApJ 596, 505; a total of 875 ^{37}Ar atoms were detected in the experiment, 766 of which were solar)

Low flux from early Homestake runs was confirmed in the early 1990s by Kamiokande.

Solar Neutrino Problem: Solar neutrino flux is ~ 1/3 of predicted neutrino flux.

Most particle physicists believed that reason for the solar neutrino problem is that the standard solar model is wrong. They were wrong.

Solar Neutrinos



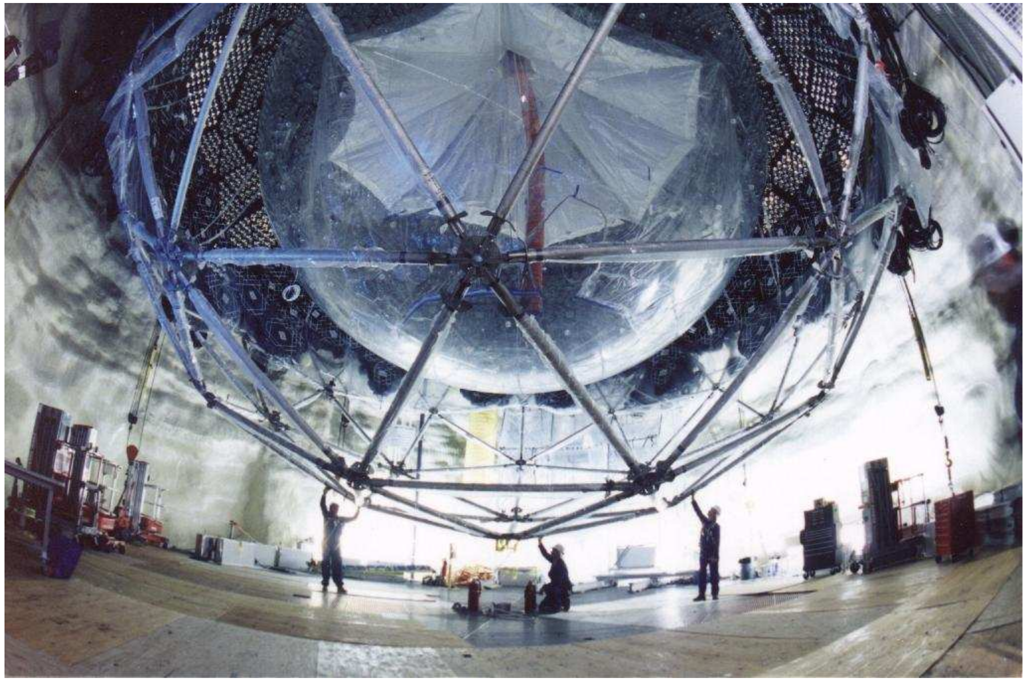
Sudbury Neutrino Observatory: uses 1000 T of heavy water, i.e., D_2O, 2000 m below ground.
Possible neutrino reactions:

$$\text{charged current:} \quad \nu_e + D \to p + p + e^- - 1.442\,\text{MeV}$$
$$\text{neutral current:} \quad \nu + D \to p + n + \nu - 2.224\,\text{MeV}$$
$$\text{elastic scattering:} \quad \nu + e^- \to \nu + e^- - 2.224\,\text{MeV}$$

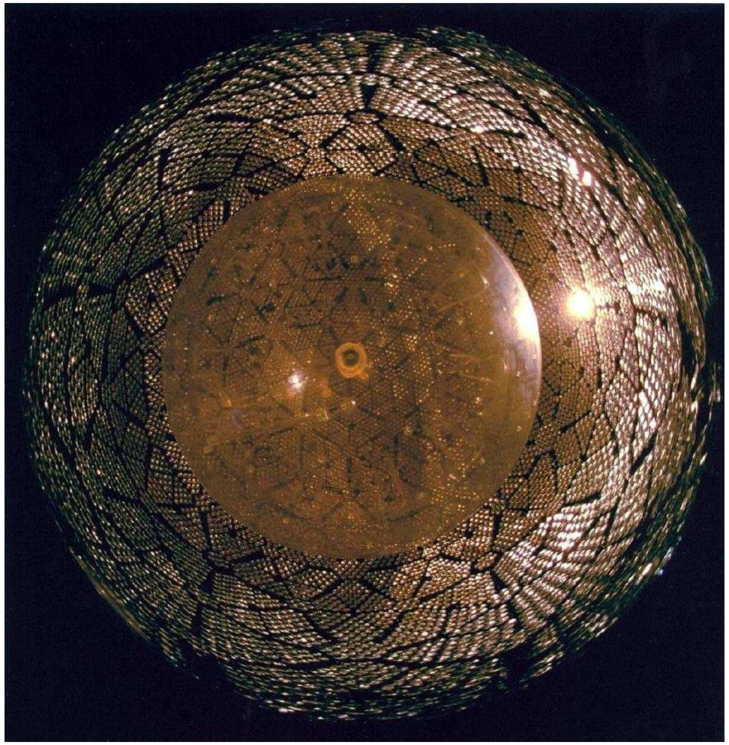
The neutral current reaction is sensitive to *any* flavor of neutrino.

SNO detects ∼5000 neutrino events per year.

courtesy SNO



courtesy SNO



Acrylic vessel surrounded by photomultiplier tubes.

View through fisheye lens.

courtesy SNO

VOLUME 87, NUMBER 7 PHYSICAL REVIEW LETTERS 13 AUGUST 2001

Measurement of the Rate of $\nu_e + d \to p + p + e^-$ Interactions Produced by ^{8}B Solar Neutrinos at the Sudbury Neutrino Observatory

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(Received 18 June 2001; published 25 July 2001)

Solar neutrinos from ^{8}B decay have been detected at the Sudbury Neutrino Observatory via the charged current (CC) reaction on deuterium and the elastic scattering (ES) of electrons. The flux of ν_e's is measured by the CC reaction rate to be $\phi^{CC}(\nu_e) = 1.75 \pm 0.07(\text{stat})^{+0.12}_{-0.11}(\text{syst}) \pm 0.05(\text{theor}) \times 10^6\ \text{cm}^{-2}\,\text{s}^{-1}$. Comparison of $\phi^{CC}(\nu_e)$ to the Super-Kamiokande Collaboration's precision value of the flux inferred from the ES reaction yields a 3.3σ difference, assuming the systematic uncertainties are normally distributed, providing evidence of an active non-ν_e component in the solar flux. The total flux of active ^{8}B neutrinos is determined to be $5.44 \pm 0.99 \times 10^6\ \text{cm}^{-2}\,\text{s}^{-1}$.

DOI: 10.1103/PhysRevLett.87.071301 PACS numbers: 26.65.+t, 14.60.Pq, 95.85.Ry

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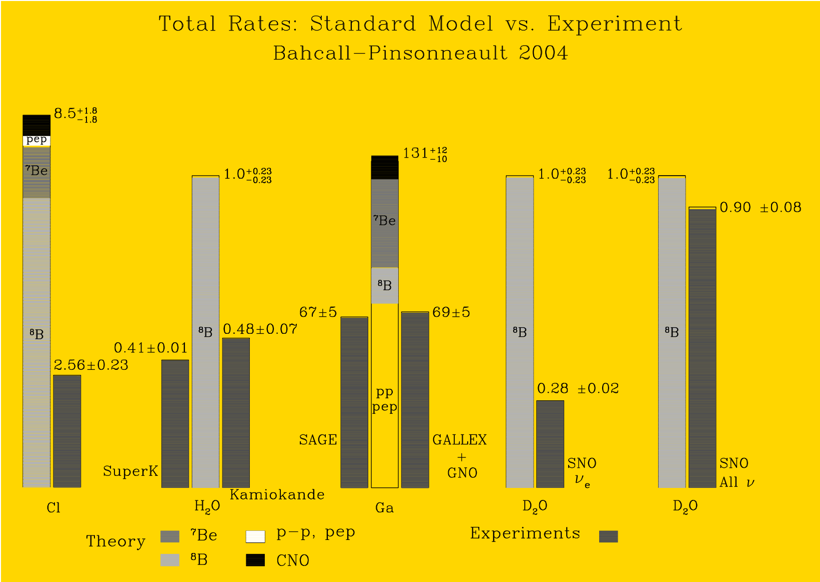
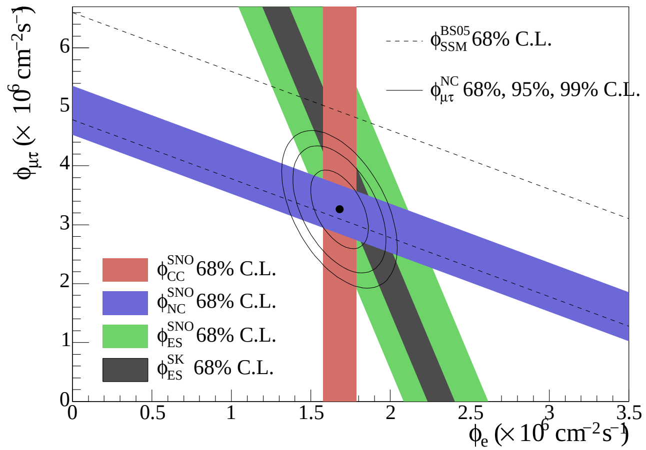


Bahcall

SNO (2001): When taking *all* neutrino flavors into account, the measured and predicted neutrino fluxes agree $\Longrightarrow$ Neutrinos change their flavor.

Solar Neutrinos



Aharmin et al., 2005 (dashed line: prediction of standard solar model)

SNO (2001): 2/3 of all ν_e produced in Sun change into ν_τ or ν_μ on their way from Sun to Earth: neutrino oscillations $\Longrightarrow$ physics beyond the standard model of particle physics!

Stellar Evolution

Principle:

1. Construct stellar model by solving equations of stellar structure for given radial abundances.
2. Evaluate change in elemental abundances as a function of radius based on the local fusion processes.
3. Change abundances appropriately for a time step Δt.
4. goto step 1

We start with looking at models of the Sun in detail and then take a look at typical stellar evolution paths.

Characteristic Timescales

Main sequence: Hydrogen burning at the center.

Evolution timescale dominated by the nuclear timescale = timescale needed to use the fuel in the center of the star.

According to simulations, this is ∼10% of the available Hydrogen.

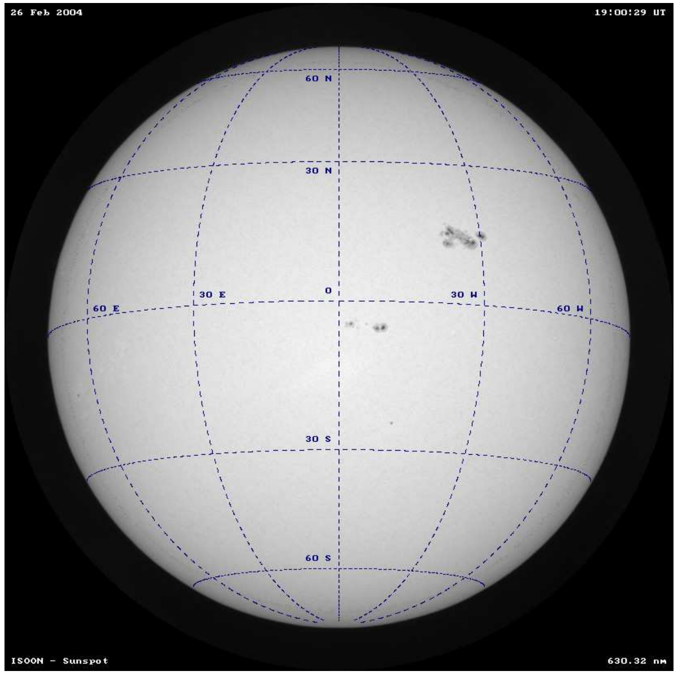
Since 0.7% of $M_{\text{core}}c^2$ converted into He, the nuclear timescale is

$$t_{\text{n}} = \frac{0.007 \cdot 0.1 Mc^2}{L} = \frac{M/M_\odot}{L/L_\odot} \cdot 10^{10}\,\text{years} \qquad (10.1)$$

A second important timescale is the timescale the star would need to radiate its stored thermal energy: thermal timescale.

Roughly given as

$$t_{\text{t}} = \frac{0.5GM^2/R}{L} = \frac{(M/M_\odot)^2}{(R/R_\odot)(L/L_\odot)} \cdot 2\times 10^7\,\text{years} \qquad (10.2)$$



The Sun

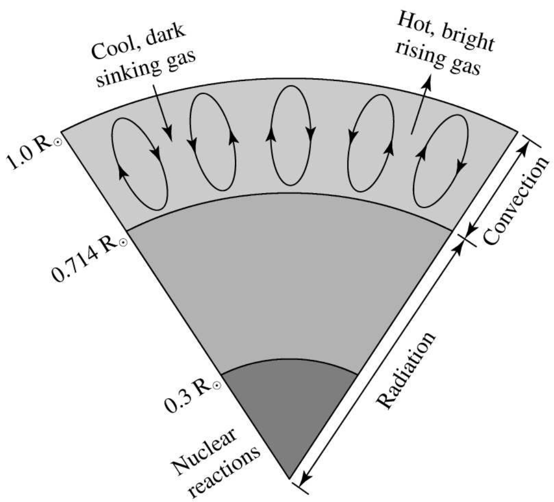
Solar Structure

Based on observations of

- Solar Mass: $1\,M_\odot = 1.997 \times 10^{30}\,\mathrm{kg} = 1.997 \times 10^{33}\,\mathrm{g}$
- Solar Luminosity: $1\,L_\odot = 3.846 \times 10^{26}\,\mathrm{W} = 3.846 \times 10^{33}\,\mathrm{erg\,s^{-1}}$
- age: $t = 4.5 \times 10^9$ yrs
- Solar chemical composition (=elemental abundances) at the surface: 73.81% H, 24.85% He, 1.34% metals (by mass)

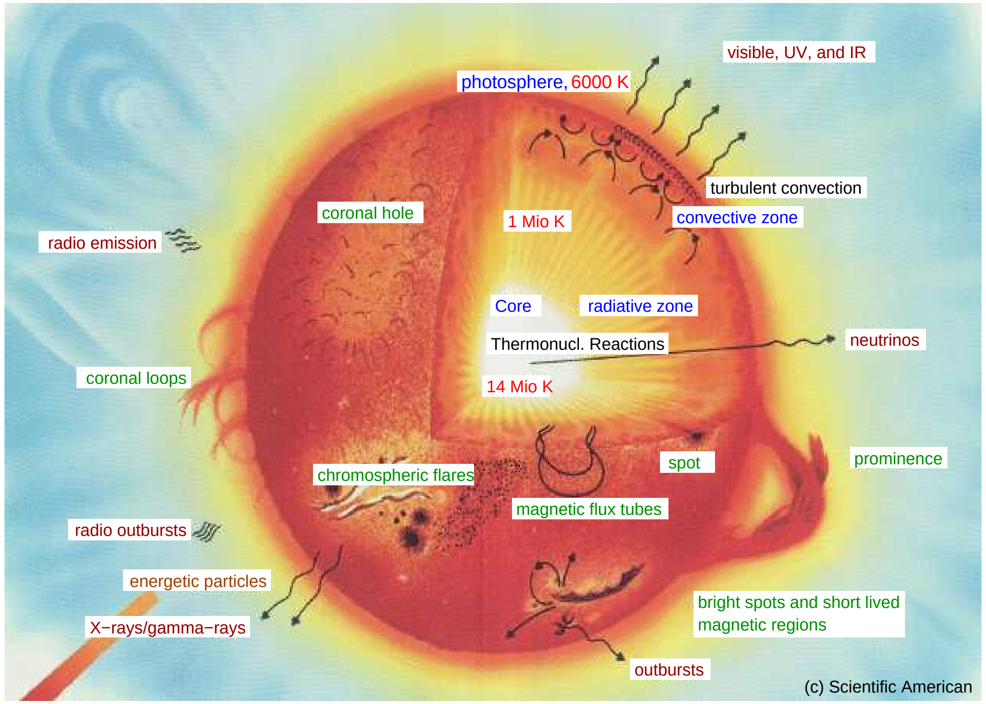
it is possible to use the equations of stellar structure to determine a model for the structure of the Sun, i.e., M_r, L_r, $\rho(r)$, $T(r)$, abundances(r) starting with a homogenous model and allow for 4.5 Gyrs of evolution.

Solar Structure

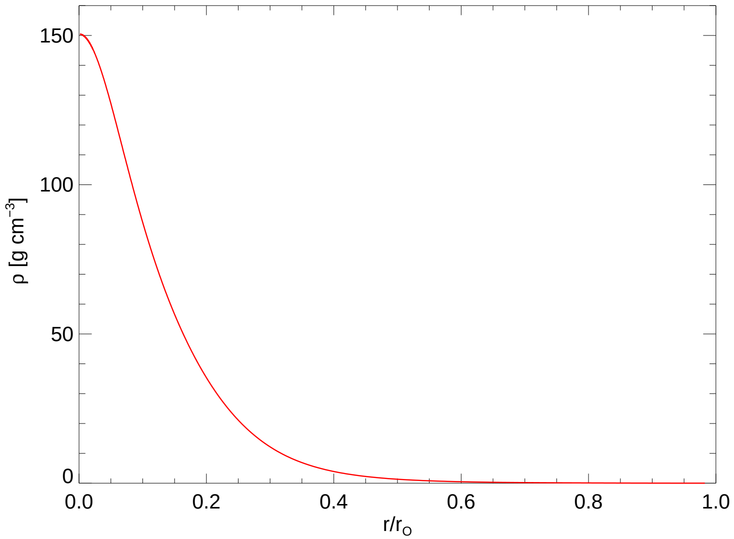


central conditions in the Sun:

- $T_\mathrm{c} = 1.57 \times 10^7\,\mathrm{K}$
- $P_\mathrm{c} = 2.34 \times 10^{16}\,\mathrm{N\,m^{-2}}$
- $\rho_\mathrm{c} = 1.53 \times 10^5\,\mathrm{kg\,m^{-3}}$
- Hydrogen fraction:
  $X = 0.34$ (by mass)
- Helium fraction:
  $Y = 0.64$ (by mass)

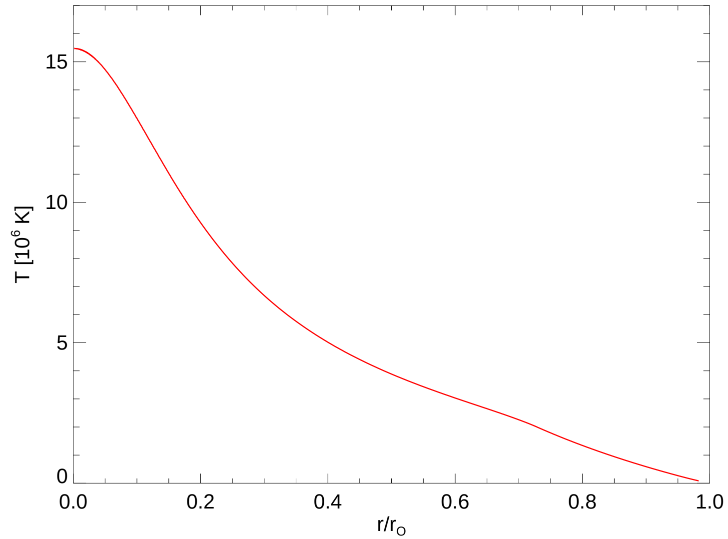


Standard Solar Model



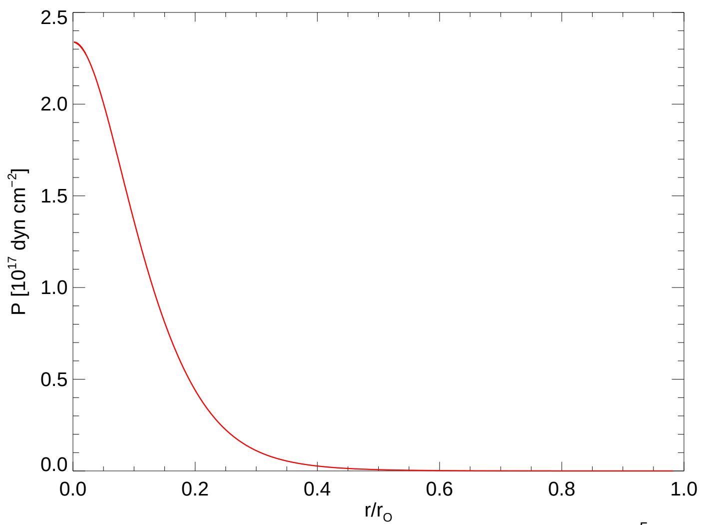
Standard solar model of Bahcall & Serenelli (2005, ApJ 626, 530)

Standard Solar Model



Standard solar model of Bahcall & Serenelli (2005, ApJ 626, 530)

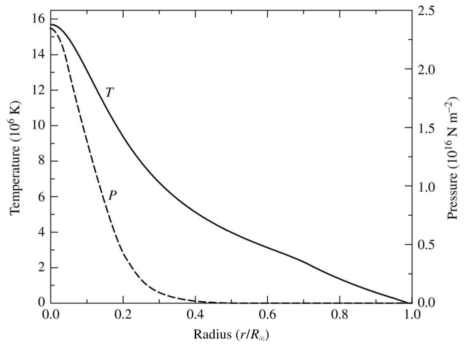
Standard Solar Model



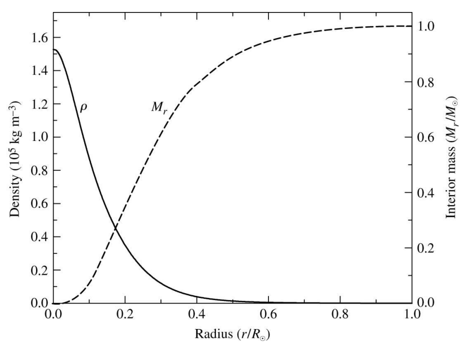
Standard solar model of Bahcall & Serenelli (2005, ApJ 626, 530; 1 dyn $=10^{-5}$ N, 1 dyn cm^{-2} $=$ 0.1 Pa)

Standard Solar Model

Standard solar model:



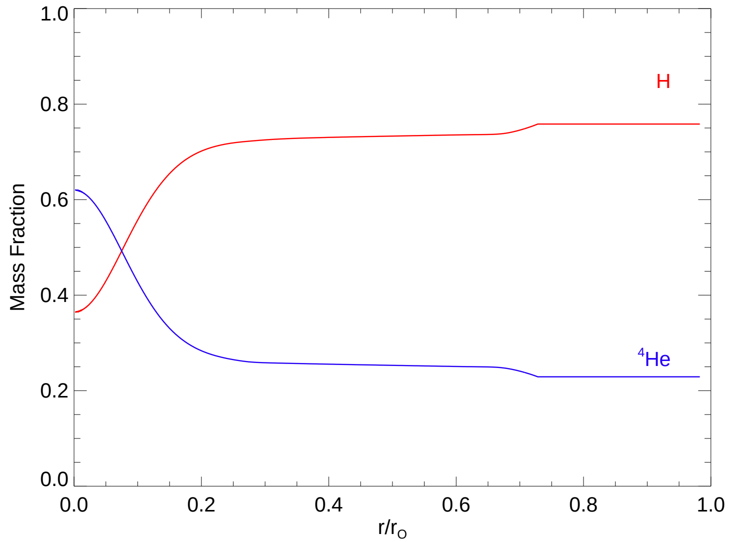
Temperature & pressure profile



Density & interior mass profile

(Carroll & Ostlie)

Standard Solar Model



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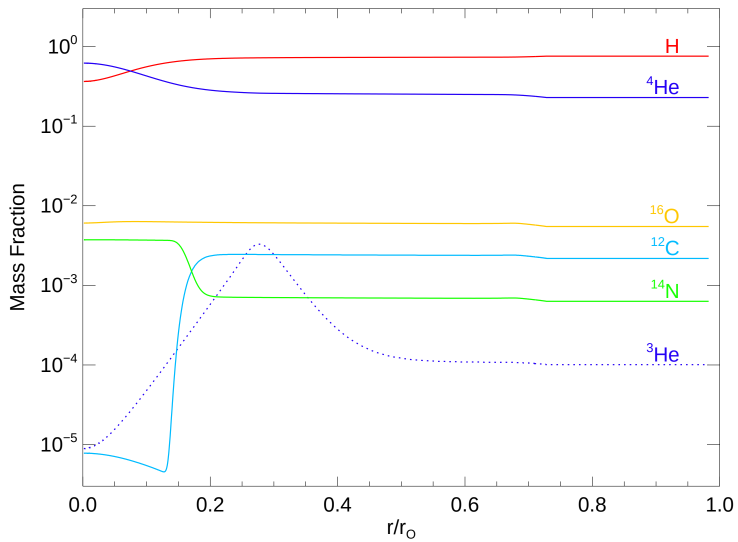
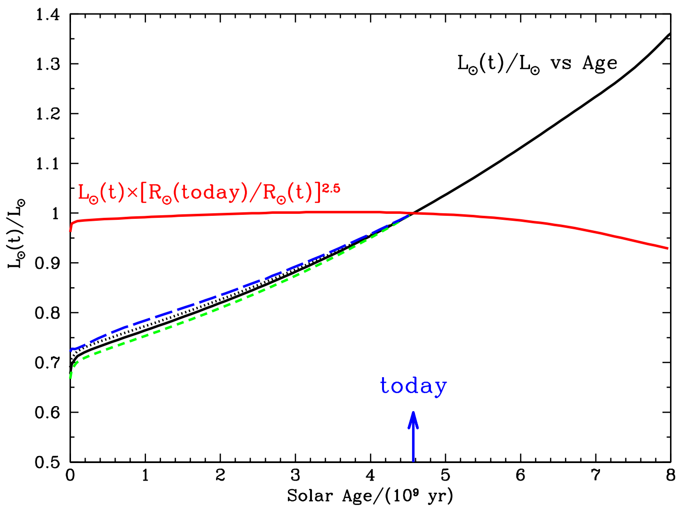
Standard Solar Model



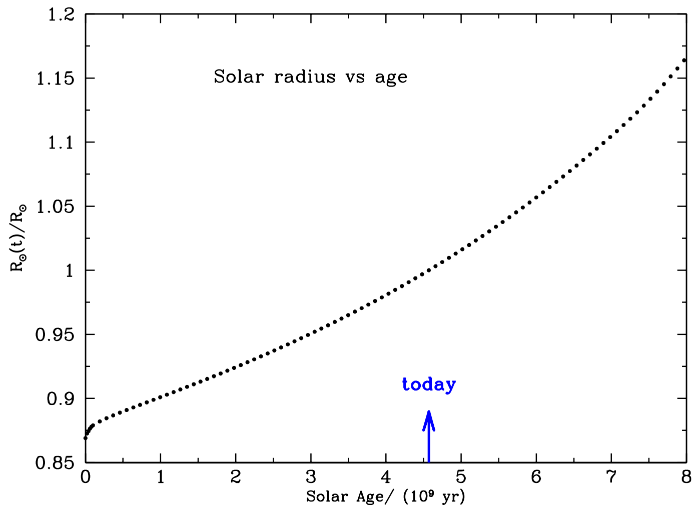
Standard solar model of Bahcall & Serenelli (2005, ApJ 626, 530)

Solar Evolution: Luminosity



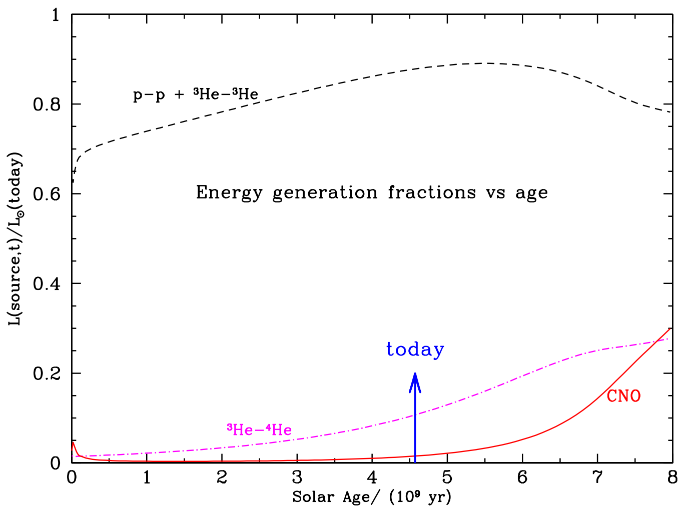
Bahcall, Pinsonneault & Basu (2001, ApJ 555, 990)

Solar Evolution: Radius



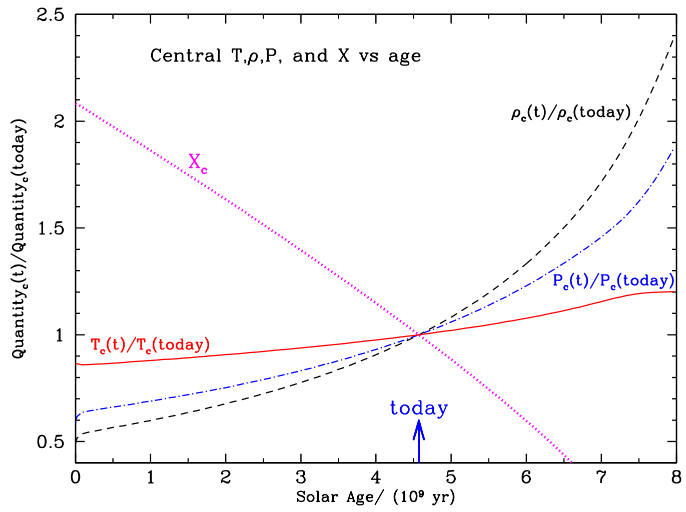
Bahcall, Pinsonneault & Basu (2001, ApJ 555, 990)

Solar Evolution: Energy Generation



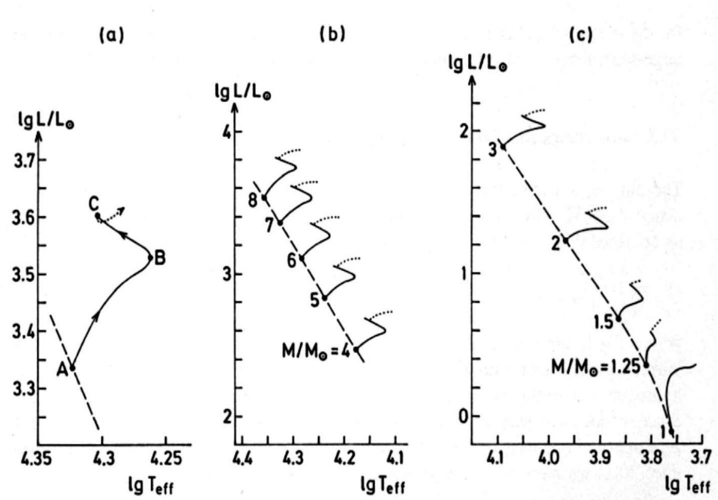
Bahcall, Pinsonneault & Basu (2001, ApJ 555, 990)

Solar Evolution: Center



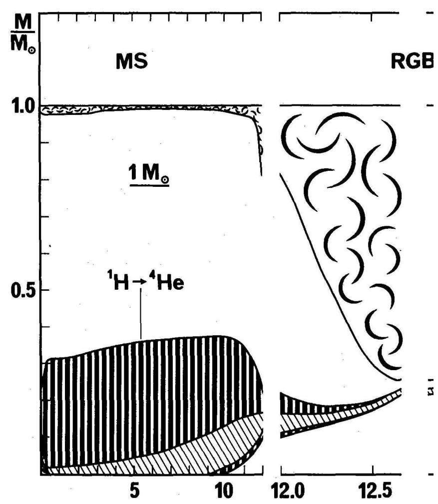
Bahcall, Pinsonneault & Basu (2001, ApJ 555, 990; X_c is the central H fraction)

Main Sequence Evolution



main sequence evolution from zero age to helium exhaustion

Post Main Sequence

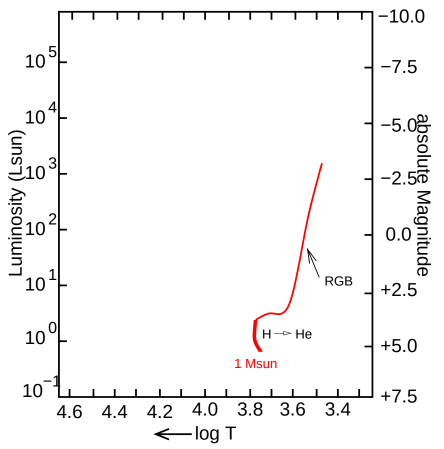


(Maeder & Meynet, 1989)

Once H is exhausted in center: H continues to burn in a shell around the He core ("shell burning").

For stars with $M \lesssim 1\,M_\odot$: Star reacts by expanding convective envelope until it is almost fully convective.

Post Main Sequence



(after Iben, 1991)

Once H is exhausted in center: H continues to burn in a shell around the He core ("shell burning").

For stars with $M \lesssim 1\,M_\odot$: Star reacts by expanding convective envelope until it is almost fully convective.

$\Longrightarrow$ luminosity increases, temperature decreases

$\Longrightarrow$ motion in HRD horizontally towards the right, then upwards to higher L: red giant stage.

Post Main Sequence

Reminder: stars are in hydrostatic equilibrium: inwards gravitational pressure balanced by outwards gas pressure

Since the gas pressure is $P = nkT$: energy source needed to heat gas (=fusion).

This is a problem for the core during the red giant stage, as virtually no fusion ongoing

$\Longrightarrow$ Core gets compressed

$\Longrightarrow$ ρ and T increase

BUT:

collapse cannot continue indefinitely!

$\Longrightarrow$ once ρ has increased appreciably, there must be a point where quantum mechanical effects become important.

QM interlude

Quantum mechanics: The Pauli exclusion principle:

For particles such as electrons ("Fermions"), at least one of their quantum numbers must be different.

Quantum numbers are, e.g.,

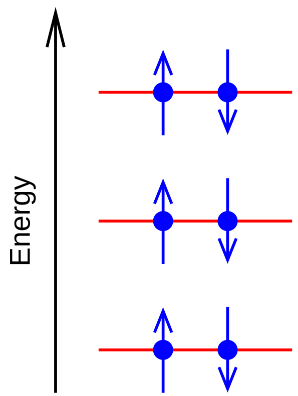
- position (x, y, z),
- momentum p ($p_x = mv_x$, $p_y = mv_y$, $p_z = mv_z$),
- angular momentum,
- spin (s)

All of these numbers are quantized, i.e., can only have discrete values (e.g., spin: $+1/2, -1/2$).

Heisenberg's principle: (6-d) phase space is quantized: $\Delta p \times \Delta V \approx h^3$
Each cell in phase space can host two electrons of different spin

In a typical gas, this is not a problem ("phase space is (almost) empty")
once it becomes dense $\Longrightarrow$ exclusion principle kicks in.

QM interlude



Energy of electrons at the same position in space

Effect of high density on electron energy:

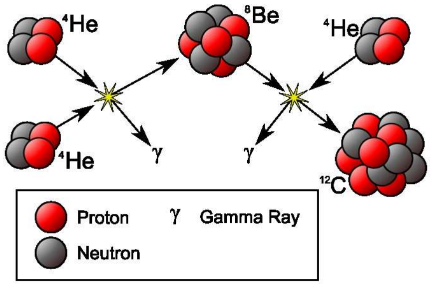
In degenerate electron gases, electrons have much higher energies than in thermal gas.

Interaction of electrons results in degeneracy pressure:

$$P = \frac{\hbar^2}{m_\mathrm{e}} n_\mathrm{e}^{5/3} \propto \rho^{5/3}$$

Note: The degeneracy pressure is independent of the temperature!

Post Main Sequence



In the degenerate core, once $T_{\text{core}} \sim 100 \times 10^6$ K: Triple alpha process starts:

$$^4\text{He} + {}^4\text{He} \leftrightarrow {}^8\text{Be}$$
$$^8\text{Be} + {}^4\text{He} \rightarrow {}^{12}\text{C}$$

Since ^{8}Be has a half life of only 2.6×10^{-16} s: this can only work effectively if 3 α-particles collide.

But core is degenerate:

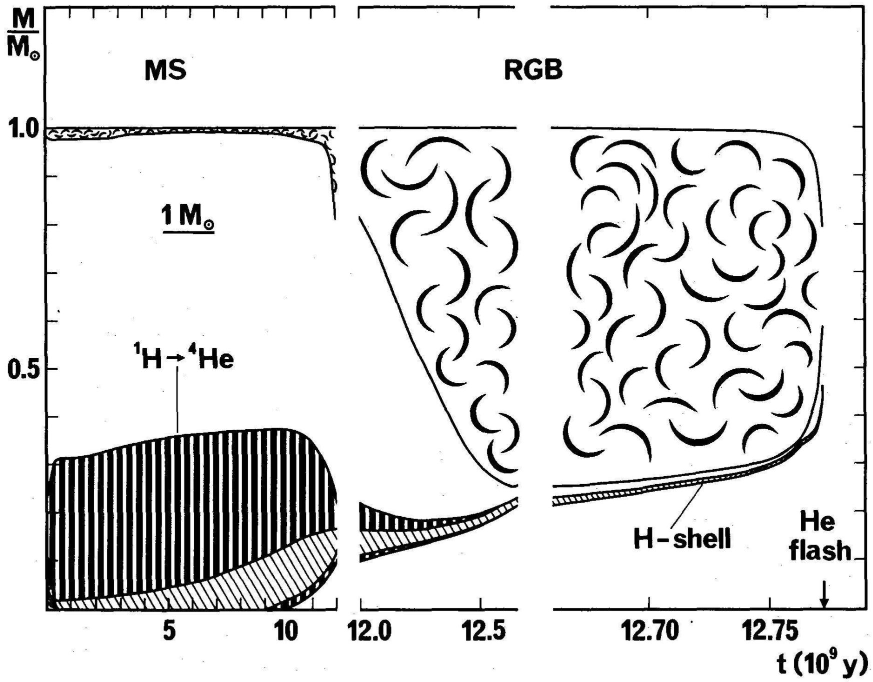
$\Longrightarrow$ High thermal conductivity of electrons

$\Longrightarrow$ core has uniform temperature

$\Longrightarrow$ 3α onset is rapid

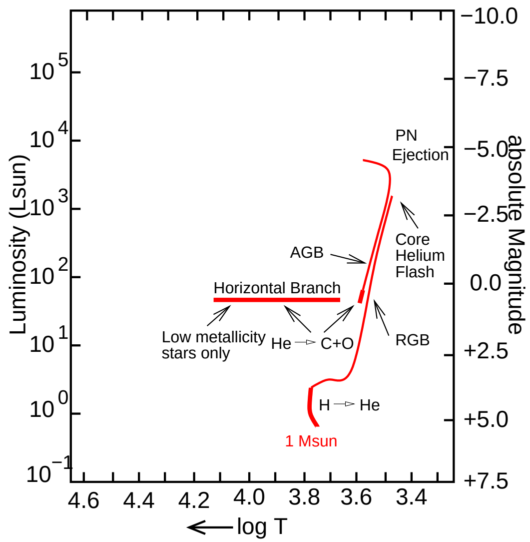
$\Longrightarrow$ He flash

Not seen on surface ("buffered" by convective envelope).



Evolution of the structure of a 1 $M_\odot$ star to the Helium flash (Maeder & Meynet, 1989).

Post Main Sequence



After the He flash star has He burning in core and H shell burning

$\Longrightarrow$ starts to expand again

$\Longrightarrow$ "asymptotic giant branch"

Instable He fusion processes ("thermal pulses") lead to ejection of outer layers ($\sim$50% of total mass!)

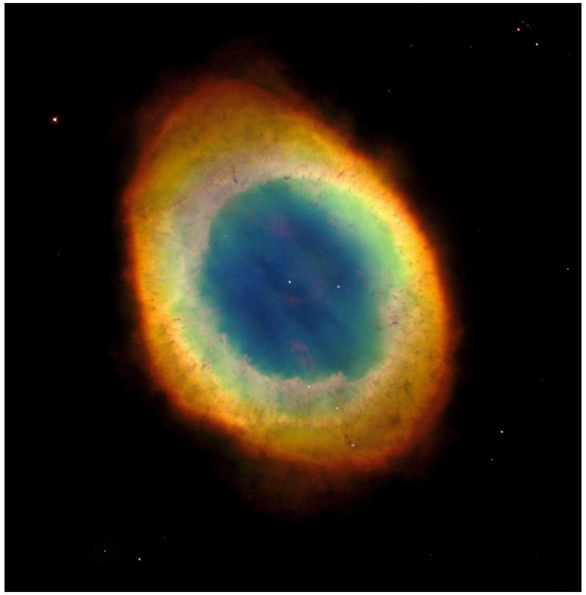
Effect of He core being unable to transport energy away quickly enough.

$\Longrightarrow$ inner (hotter) parts of star become visible.

after Iben, 1991

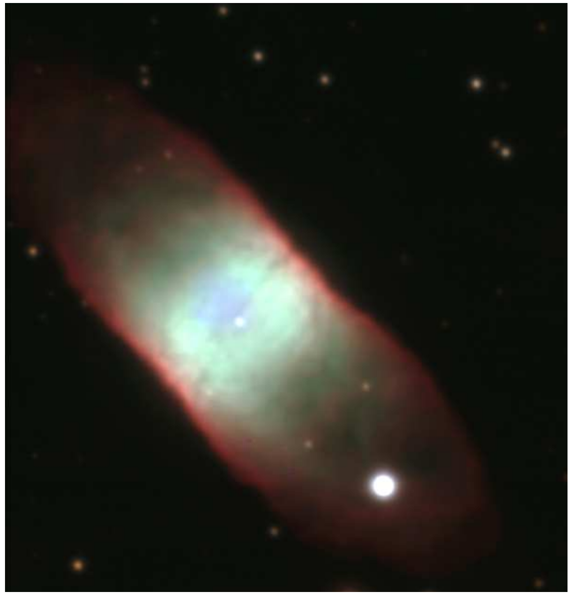
Abell 39 (WIYN, AURA, NOAO, NSF)

planetary nebulae: material ejected during AGB phase, photoionized once remaining core of former star has shed enough mass to emit UV photons.



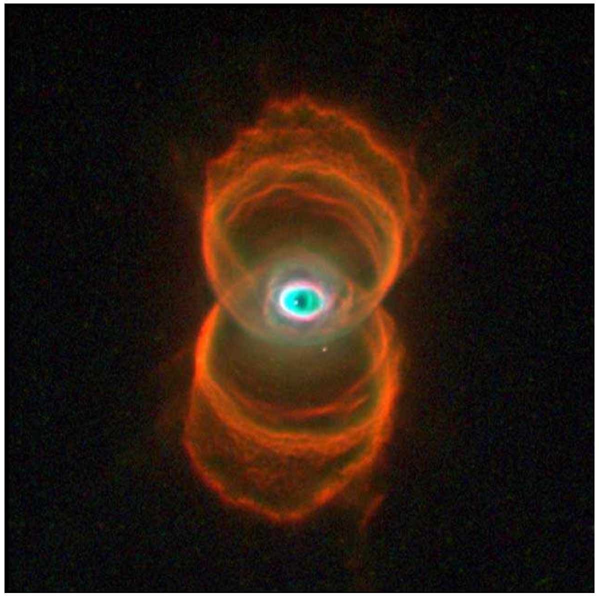
Ring Nebula (HST/STScI/NASA)

planetary nebulae: material ejected during AGB phase, photoionized once remaining core of former star has shed enough mass to emit UV photons.



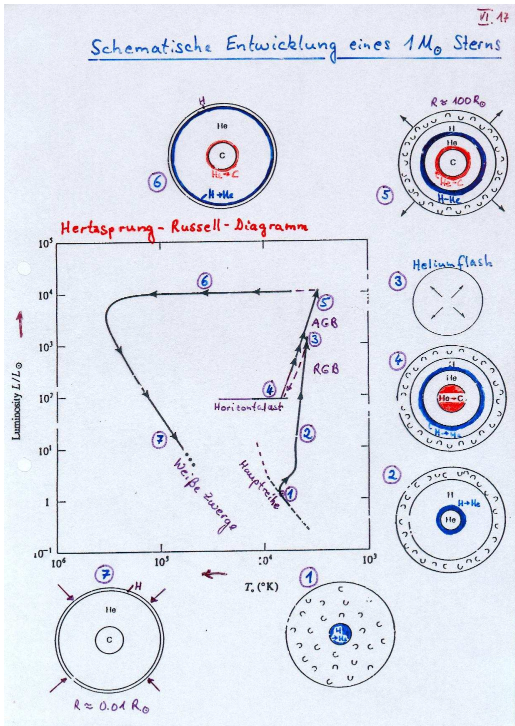
IC4406 (ESO VLT)

planetary nebulae: material ejected during AGB phase, photoionized once remaining core of former star has shed enough mass to emit UV photons.



Hourglass Nebula (HST/Sahai/Trauger)

planetary nebulae: material ejected during AGB phase, photoionized once remaining core of former star has shed enough mass to emit UV photons.



Summary: Evolution of Low Mass Stars:

1. Main sequence (MS) = core H burning
2. Red giant branch (RGB) = H shell burning
3. Tip of RGB: core helium flash = helium ignition in degenerate electron gas
4. Horizontal branch (HB) = core He burning
5. Asymptotic giant branch (AGB) = 2 shell burning (H + He) Tip of AGB: envelope ejection through dust formation & pulsations
6. Planetary nebula (PN): hot star excites the ejected envelope to shine
7. white dwarf = degenerate C/O remnant

Reminder: Main Sequence

Structure on the Main Sequence: Simulations show existence of two regimes:

lower main sequence : stars have structure similar to Sun:

- energy generation: pp-chain ($\epsilon \propto T^5$)
- inner radiative core
- convective envelope

upper main sequence : for central temperatures of 18 $\times$ 10^6 K (1.5 $M_\odot$ stars): pp-chain and CNO-cycle produce equal amounts of energy. Above that: CNO dominates.

- energy generation: CNO-cycle ($\epsilon \propto T^{17}$)
- inner convective core since energy generation from CNO cycle strongly peaked towards center.
- outer radiative envelope

Stars born with masses $> 8\,M_\odot$

Evolution on MS similar, however, faster than for low mass stars.

More massive stars reach threshold temperature for 3α and subsequent nuclear burning before reaching degeneracy

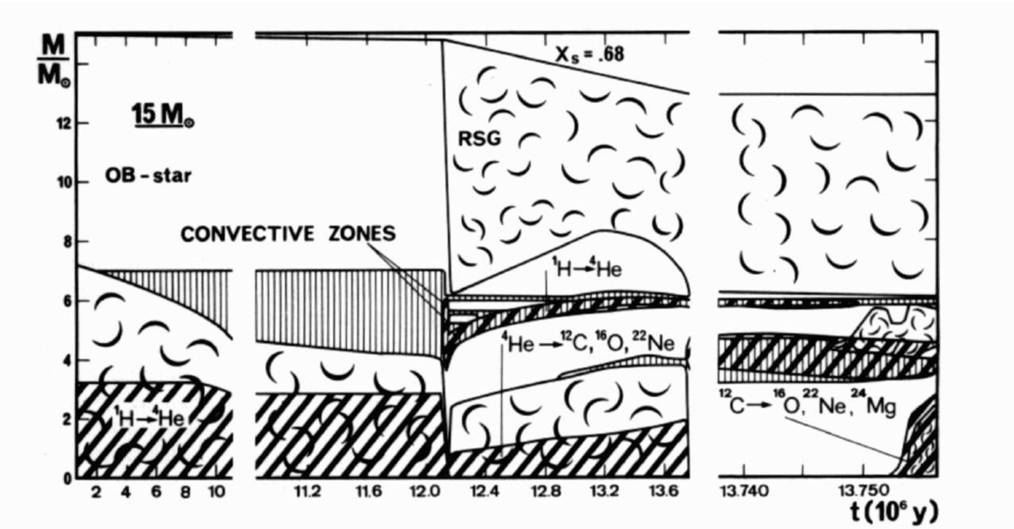
$\Longrightarrow$ He just starts to burn.

In these objects, higher order fusion processes can kick in (but are energetically unimportant): alpha reactions

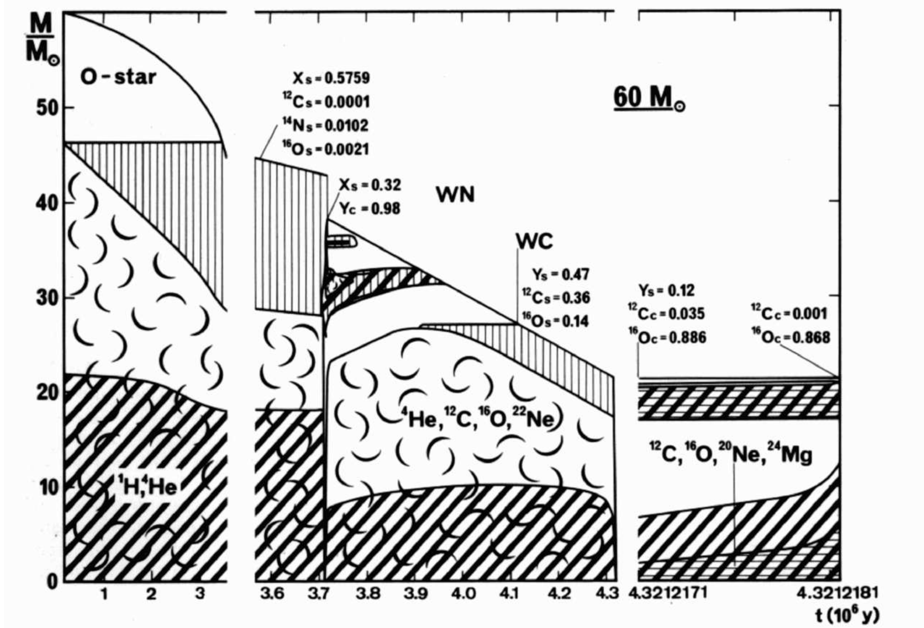
$$^{12}\text{C} + {}^{4}\text{He} \rightarrow {}^{16}\text{O} + \gamma$$
$$^{16}\text{O} + {}^{4}\text{He} \rightarrow {}^{20}\text{Ne} + \gamma$$
$$^{20}\text{Ne} + {}^{4}\text{He} \rightarrow {}^{24}\text{Mg} + \gamma$$

Outer layers continue H shell burning.

During evolution of star on red giant branch: convective envelope moves deeper into core, can mix fusion products into outer layers.

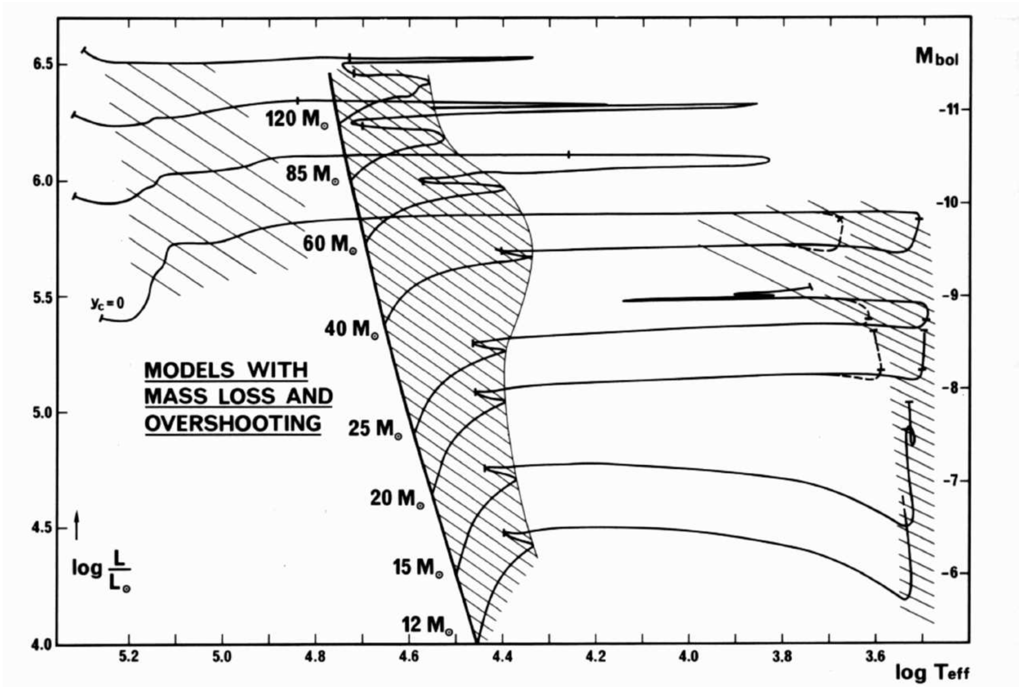


Evolution of the internal structure of a 15 $M_\odot$ star.



Evolution of the internal structure of a 60 $M_\odot$ star.

Note the very strong mass loss!



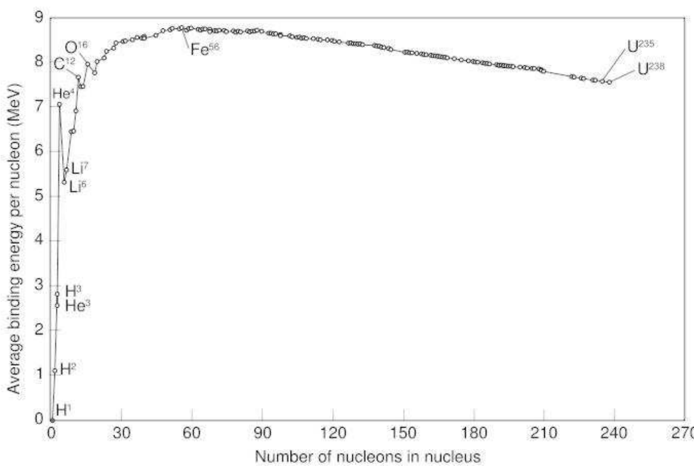
Summary: Evolution of massive stars in the HRD.

Stars born with masses $> 8\,M_\odot$

Nuclear reactions in massive ($> 8\,M_\odot$) stars:

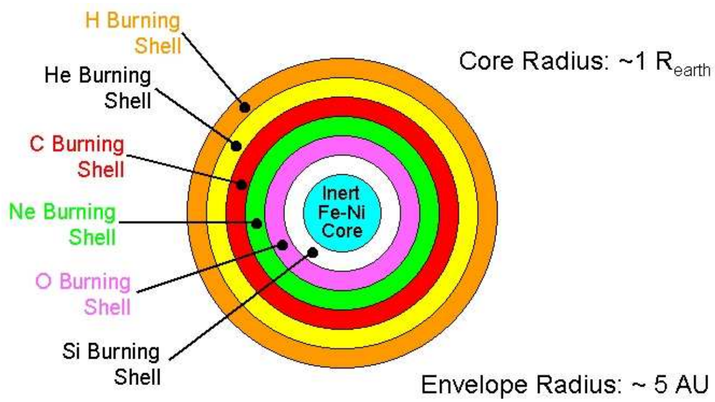
Reaction	above T $[10^6$ K$]$	Energy gain [MeV]
Hydrogen burning		
$4\,^1$H $\longrightarrow$ ^{4}He	4	6.55
Helium burning		
$3\,^4$He $\longrightarrow$ ^{8}Be $+$ ^{4}He $\longrightarrow$ ^{12}C	100	<0.61
Carbon burning		
^{12}C $+$ ^{4}He $\longrightarrow$ ^{16}O	600	<0.54
$2\,^{12}$C $\longrightarrow$ ^{4}He $+$ ^{20}Ne		
^{20}Ne $+^4$ He $\longrightarrow$ n $+$ ^{23}Mg		
Oxygen burning		
$2\,^{16}$O $\longrightarrow$ ^{4}He $+$ ^{28}Si	1000	<0.3
$2\,^{16}$O $\longrightarrow$ $2\,^4$He $+$ ^{24}Mg		
Silicon burning		
$2\,^{28}$Si $\longrightarrow$ ^{56}Fe	3000	< 0.18

Stars born with masses $> 8\,M_\odot$



^{56}Fe is one of the most tightly bound nucleons $\Longrightarrow$ Star has a problem once ^{56}Fe reached: fusion processed become endotherm

Stars born with masses $> 8\,M_\odot$



successive stages of nuclear burning: final state: onion-shell model

1. H burning, ash: He
2. He burning, ashes: C, O, Ne, Mg
3. C burning, ashes: Ne, Na, Mg
4. Ne burning, ashes: O, Mg . . .
5. O burning, ashes: Si, P, S, . . .
6. Si burning, ashes: Fe, Ni