Astro 404
Lecture 29
Nov. 1, 2021

Announcements:

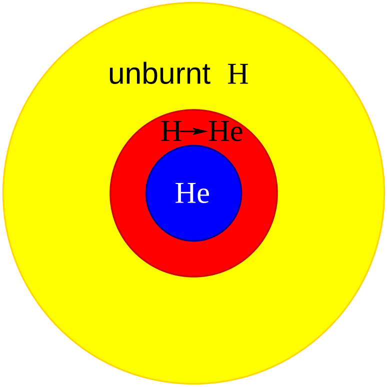
- **PS9 due next Friday**
- **no class meeting this Wednesday Nov 3!**
  BDF conflict: giving research seminar
- Office hours: BDF Wed 11:00-ish via usual class Zoom
  TA: 2:30–3:30 pm

Last time: low-mass stars after main sequence

Q: burning phases?

Q: shell burning "mirror" principle?

Low-Mass Stars After Main Sequence



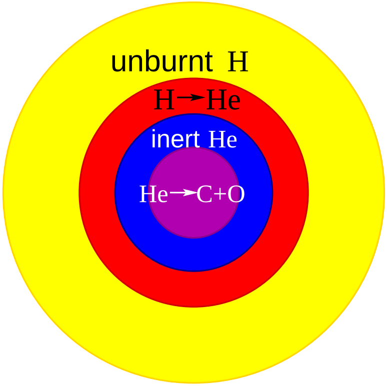
⋆ helium core contracts

H burning in shell around core

outer layers expand → $\boxed{\textbf{red giant}}$

"mirror" effect of shell burning:

- core contraction, envelope expansion
- total gravitational potential energy Ω roughly conserved
  core becomes more tightly bound, *envelope less bound*



⋆ **helium ignition degenerate core**

runaway burning: *helium flash*

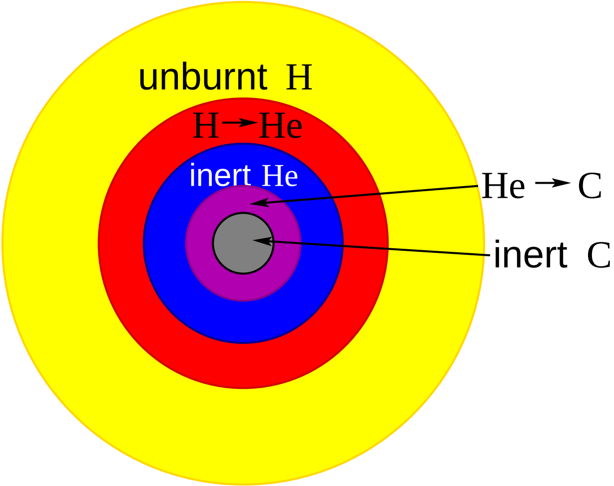
then core helium burning $3\alpha \rightarrow {}^{12}\mathrm{C}$

and shell H burning

"horizontal branch" star

★ for solar mass stars: after CO core forms

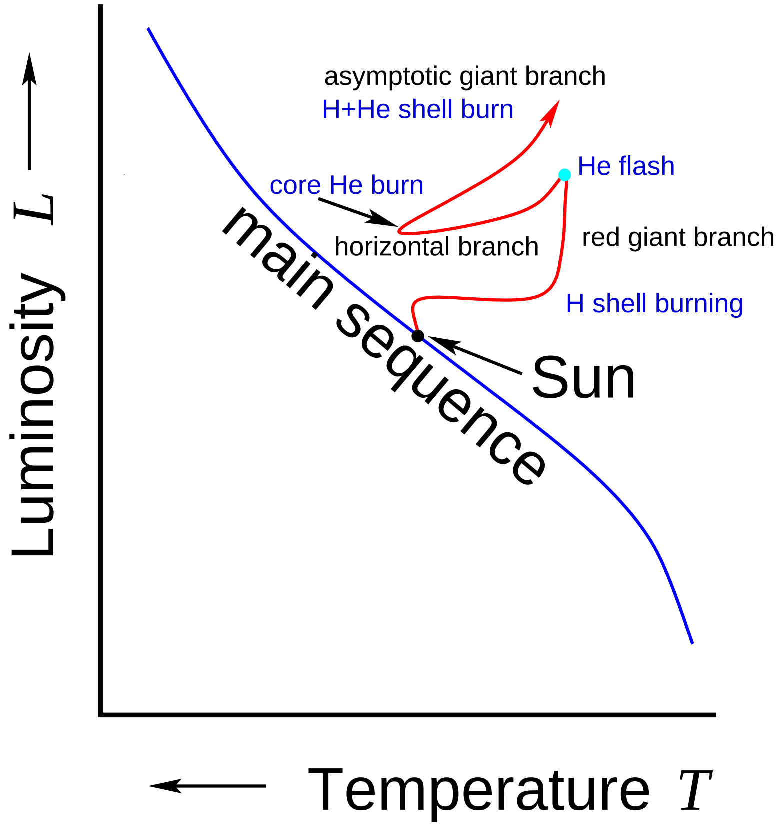
- *helium shell burning begins*
- *hydrogen shell burning continues*



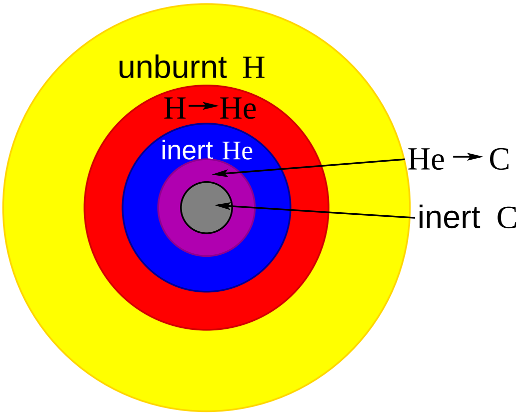
Q: star path on HR diagram during these phases?

Low-Mass Post-Main-Sequence: HR Diagram

- ⋆ H shell burning ↔ red giant
- ⋆ He flash marks “tip of the red giant branch”
- ⋆ core He fusion ↔ horizontal branch
- ⋆ He + H shell burning ↔ asymptotic giant branch



Two-Shell Instability



try to apply "mirror principle" to
He layer between H and He burning shells

- beneath H burning shell → expect *contraction*
- above He burning shell → expect *expansion*

contradiction hints at result of detailed models:
intershell He layer is *unstable!*

He burning extremely sensitive to density and temperature:
energy generation $\mathcal{L}(3\alpha \rightarrow {}^{12}\mathrm{C}) \propto \rho^3 T^{19}$
starts in degenerate conditions: mini helium flash!

Q: and then?

Thermal Pulses in AGB Stars

He shell burning runaway injects huge energy

- He and H layers expand
- burning shut down in both layers
- then cooling layers contract
- H shell burn requires less extreme conditions, ignites first
- adds to mass of He layer until He "shell flash" erupts again

lather, rinse, repeat!

net result: **star undergoes cyclic pulsations**
triggered by short periods of He shell burning
followed by long periods of H shell burning

Mass Loss

in Red Giant and AGB phases
- high luminosity
- large envelope with low density and temperature

envelope cool enough to form *atoms*
then forms *molecules*
then forms microscopic solids: *dust*

these absorb the light: driven by *radiation pressure*
star develops **wind** `www: Mira`
much stronger than on Main Sequence
and most intense in pulsing AGB phase: **superwind**
→ *drives off* $\sim$ 50% *of star's mass*

Q: how can we tell?

Planetary Nebula

effects of red giant wind and AGB superwind

- *mass loss exposes stellar core!*
- *outer layers unbound*, driven away
  escape to interstellar space
- *gas nearest star illuminated by hot core*
  UV radiation excites atoms: re-emit lines
  as in neon lamp

observationally: extended emission around hot star
if spherical, shell is disk on sky – looks like planet
observe as **planetary nebula**
Q: what if binary companion? signatures of pulses?
`www: examples of planetary nebulae`

The End: White Dwarf

remaining *degenerate core* is white dwarf

- supported by degeneracy pressure
- stable if mass $M_{\mathrm{wd}} < M_{\mathrm{Chandra}} = 1.4 M_{\odot}$
- initially hot, cools over time

if no binary companion

- white dwarf remains stable: *white dwarfs are forever!*
- final compact remains of the star: **the end!**
- cools indefinitely
- eventually will crystallize → phase transition to lattice

if a companion: fate depends on mass transfer
we will return to this later

Convection and Mixing in Low-Mass Stars

convection plays important role in post-main-sequence
recall: high T gradient drives convection

during main sequence: low-mass stars have

- radiative core: energy transport by photon diffusion
  stable against convection → *new He not transported out*
- convective envelope: seen in Solar granulation

during main sequence:
He burn sensitive to local conditions $\mathcal{L}(3\alpha \rightarrow {}^{12}\mathrm{C}) \propto \rho^3 T^{19}$

- *drives convection* at helium flash, and during AGB phase
- *circulates burning products to star surface* → visible!
- new elements ejected in winds, seen in planetary nebulae

Q: which elements ejected? Consequence?

Stellar Nucleosynthesis: Low-Mass Stars

stars are element factories
cosmic sites of alchemy: new nuclei produced!
element production: *stellar nucleosynthesis*
Nobel Prize 1983: Willy Fowler

low-mass stars:

- **helium** produced during core and shell H burning
- **carbon** and **oxygen** made during core and shell He burn
- later we will see: shell burning makes
  trace but important amounts of much heavier elements

AGB stars are dominant source of carbon in the Universe!
the carbon in your DNA came from
helium burning in stars that died before Sun born
and whose remains were mixed into the solar nebula
`www: the circle, the circle of life`

“We are made of star-stuff”
– Astrophysicist Carl Sagan

We are stardust
Billion year old carbon
We are golden
Caught in the devil’s bargain
And we’ve got to get ourselves
Back to the garden
Astrophysicist J. Mitchell, “Woodstock” (1970)

Stellar Evolution Across Masses: Central Conditions

PS9: for a star of mass M in hydrostatic equilibrum
and with *core in ideal gas regime*:
central density ρ_c and temperature T_c approximately obey

$$\rho_c \propto \frac{T_c^3}{M^2} \tag{1}$$

$\boxed{\text{at fixed } M}$ central density and temperature related by $\rho_c \propto T_c^3$
denser → much hotter

$\boxed{\text{at fixed } T_c}$ $\rho_c \propto 1/M^2$

- *lower density for higher mass*
  and radiation pressure more important at high masses
  $\beta_c = (P_{\rm rad}/P_{\rm ideal})_c \propto T_c^3/\rho_c \propto M^2$
- lower mass → denser → closer to degeneracy
  high mass far from degeneracy.

Post-Main Sequence: Lowest-Mass Stars

We have focused on solar-mass and solar-ish mass stars
what about other masses?

Lowest Masses: $M \lesssim 0.8 M_\odot$
main sequence luminosity $L(M) \approx (M/M_\odot)^{3.5}\ L_\odot$ very low
lifetime $\tau_{\rm ms}(M) > 13.6$ Gyr: longer than age of Universe!
$\Rightarrow$ *none of these stars have died yet!*

live "forever," do not contribute to element nucleosynthesis

also note: as mass decreases, outer convection zone deeper
at $M \lesssim 0.3 M_\odot$: star is fully convective!
all of star H available as fuel
further extends already-long stellar lifetime

Poll: Very Low Mass Stars

Consider very low mass stars: $M < 0.08 M_\odot$

Compared to main sequence stars of other masses, these stars have

A higher central density

B lower central density

C the same central density

Q: ans so?

Brown Dwarfs

stars with very low masses $M \lesssim 0.08 M_\odot$
controlled by trend in ideal gas regime $\rho_c \propto 1/M^2$
low mass → denser → closer to degeneracy

pre-Main Sequence: `www: MESA pre-MS results`
contraction increases density until core is degenerate
degenerate core contracts until in hydrostatic equilibrium

hydrogen burning never occurs!

- no internal energy source (similar to Jupiter, but higher mass)
- the stars radiate away the heat from their formation and cool as a result: temperatures are low
- the stars are degenerate → high density → small radius low luminosity

low luminosity and low temperature: brown dwarf
like white dwarfs, live forever, constantly cooling

Post-Main Sequence: Intermediate Mass Stars

intermediate-mass stars: $2M_\odot \lesssim M \lesssim 8M_\odot$

on main sequence:
- envelope radiative except for very thin atmosphere
- H burning by CNO cycle: $\mathcal{L}_{\rm CNO} \propto \rho^2 T^{16}$
- core convective, mass of convective zone grows with M mixes new hydrogen fuel until He core is convective region

as H exhausted: *core non-degenerate*—still ideal gas
when $M_{\rm core} \sim 0.1M$, core unstable: can't support itself
rapidly collapses → H shell burning starts → *red giant*

He core remains non-degenerate → no helium flash!
instead: helium burning stars slowly, then L increases
- also core He burning + H shell burning phase
- followed by 2-shell AGB phase
- final products: white dwarf + planetary nebula

High-Mass Stars

High-Mass Stars: Main Sequence

high-mass stars: $M \gtrsim 8 M_\odot$

main sequence structure: radiative envelope, convective core •
high central density and temperature $\rho_\mathrm{c}, T_\mathrm{c}$
• H burning from CNO: $\mathcal{L}_\mathrm{CNO} \propto \rho^2 T^{16}$

net result: huge luminosity

Q: consequences of high L, and high surface T_eff?

Massive Stars: Main Sequence Implications

hot photosphere: $T_{\rm eff} \sim 10^4 - 10^5$ K

- OB main sequence stars are blue/UV
- important sources of high-energy photons
  with $E_\gamma > E_{\rm bind,H} = 13.6$ eV: rips apart hydrogen
  surrounding hydrogen is ionized (H ii regions)

huge luminosity $L \sim (10^3 - 10^5) L_\odot$

- overrepresented in observed (flux-limited) star counts
- huge nuclear burning rates...
- ...and so *short main sequence lifetime* ($\lesssim$ 30 Myr)
- short life: don't travel far from birth sites
  massive stars trace ongoing star formation

Q: recall effect of huge L on outer layers of star?