Astro 404

Lecture 29

Nov. 4, 2019

Announcements:

• **Problem Set 9 due Fri Nov 8**

not part of course but of interest:

Astronomy Colloquium Tue Nov 5, 3:45pm

Nan Liu, Washington U. St. Louis

"Laboratory Astronomy Using Microscopes"

stardust in the lab!

Astro Courses for Spring 2019

your ASTR404 superpowers definitely qualify you for

- ASTR 405: Planetary Systems with Prof. Wong
  here especially, 404 knowhow will pay off!
- ASTR 414: Astronomical Techniques with Prof. Shen

and you might consider (talk to instructor)

- ASTR 596 AST: Fundamentals of Data Science
  Astrostatistics from Prof. Narayan
- ASTR 507: Physical Cosmology
  Prof. BDF

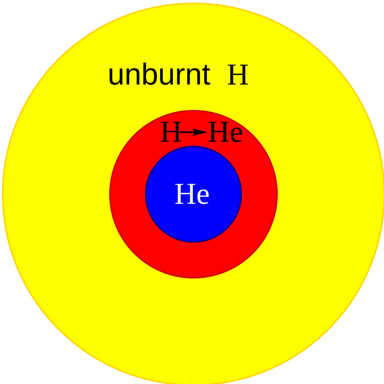
Last time:
lives of stars after the Main Sequence

Part I: low-mass stars, including the Sun

Q: what happens to core when it is entirely helium?

Q: contrast core vs envelope?

Hydrogen Shell Burning



as helium core contracts

- H material overlying core also contracts, heats new fuel, can begin to fuse!
  → **H burning in shell around core**

H shell burning occurs above degenerate core

- high density and temperature: high L
- increases mass of He core, shell thins and propagates out

Q: response of outer layers–envelope?

Red Giant Phase

injection of energy in shell

throws envelope out of equilibrium

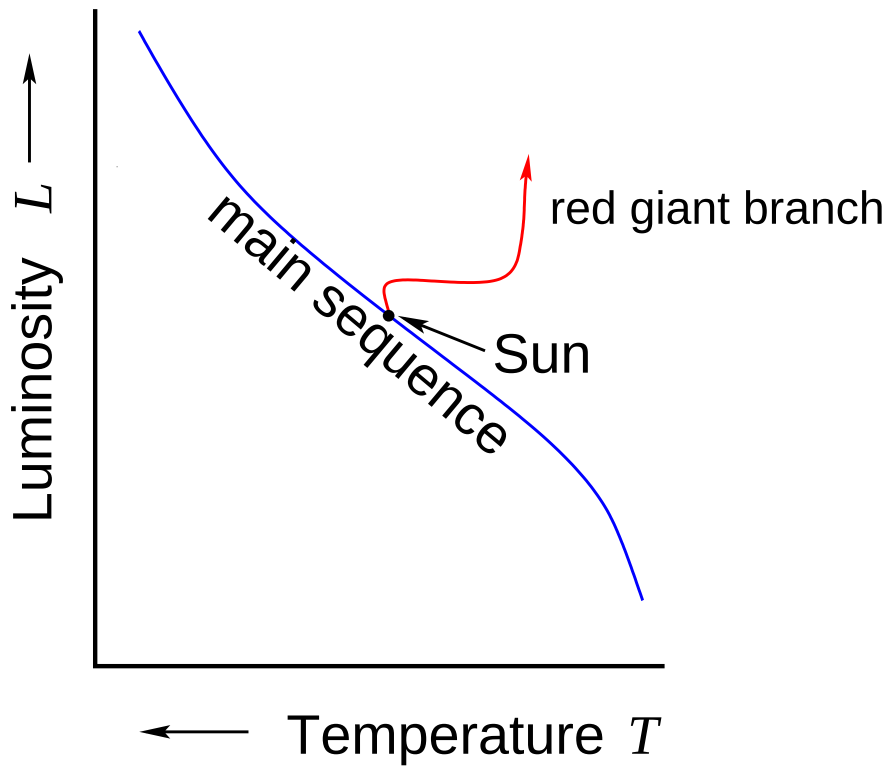
- *star outer layers expand by factor* ~ 100
- so surface $T_{\rm eff} \propto L^{1/4}/R^{1/2}$ drops
- star becomes **red giant**
- for Sun: red giant radius $R_{\rm RG} \simeq 1$ au (PS9)
  Mercury and Venus consumed, unclear if Earth will survive!

"mirror" effect of shell burning:

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

Q: movement of star on HR diagram?

HR Diagram: Red Giant Phase



www: Gaia observed HR diagram for field stars

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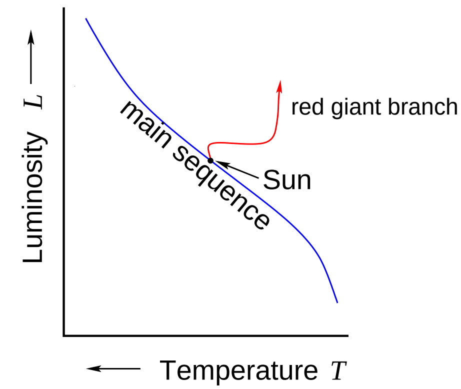
Q: how to test?

Red Giants

shell burning accelerates $\rightarrow L$ increase
envelope temperature levels off
$\rightarrow$ *revisit Hayashi track*
but now with *increasing* luminosity



RG phase takes most of remaining star lifetime
after main sequence: $\tau_{\mathrm{RG},\odot} \sim 2$ Gyr for Sun

degenerate helium core: "baby white dwarf"

- mass M_{He} increases due to shell burning H$\rightarrow$^{4}He
- core radius follows non-relativistic white dwarf scaling $R_{\mathrm{He}} \propto 1/M_{\mathrm{He}}^{1/3}$
- core contracts: density and temperature increase

Q: what happens next?

Core Helium Ignition

core temperature and density increase until ^{4}He can fuse
...but how?

Q: what 2-body reaction(s) possible?

Q: challenges?

Helium Burning: Challenges

2-body reaction $^4\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^8\mathrm{Be} + \gamma$ possible, but...

- this reaction is (just barely) *endothermic*:
  must *supply energy* to go

- nuclear physics: no stable nuclei with mass $A = 5$ and $A = 8$
  so ^{8}Be unstable: radioactive!
  $^8\mathrm{Be} \rightarrow {}^4\mathrm{He} + {}^4\mathrm{He}$ with lifetime $\tau_8 = 8 \times 10^{-16}$ sec

other 2-body reactions even more disfavored

 Q: solutions?

The Triple-Alpha Reaction

in degenerate helium core

- density high
- temperatures high

3-body reactions possible

reaction proceeds in 2 steps

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

net result: $^{4}\mathrm{He} + {}^{4}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{12}\mathrm{C}$

- "triple alpha" with $^{4}\mathrm{He} = \alpha$ shorthand
- net effect *exothermic*
- but less energy release than in H burning

iClicker Poll: Density Scaling of 3α

triple alpha: $3\,{}^4\mathrm{He} \rightarrow {}^{12}\mathrm{C}$

consider energy production rate: luminosity density

What is dependence on density?

A $\mathcal{L} \propto \rho$

B $\mathcal{L} \propto \rho^2$

C $\mathcal{L} \propto \rho^3$

D $\mathcal{L} \propto \rho^4$

Helium Ignition

triple alpha: $3\,{}^4\text{He} \to {}^{12}\text{C}$

stellar recycling: helium ash of hydrogen burning
becomes fuel for helium burning to carbon

helium ignition occurs in degenerate core

- luminosity density

$$\mathcal{L}(3\alpha \to {}^{12}\text{C}) \propto \rho^3\, T^{19}$$

- huge density and temperature sensitivity
- favors first ignition in densest, hottest parts of core

once 3α burning ignited:
Q: effect on T? on P? on ρ?
Q: and so how does burning proceed?

The Helium Flash

triple alpha luminosity density

$$\mathcal{L}(3\alpha \rightarrow {}^{12}\mathrm{C}) \ \propto \ \rho^3 \, T^{19}$$

favors ignition first in densest, hottest parts of core

ignition injects nuclear energy as heat

- raises T
- but degenerate core: P nearly independent of T
  so P and ρ almost unchanged $\rightarrow$ *core does not expand!*
  contrast with stable H burn in Sun: ideal gas
- so nuclear burning $\propto T^{19}$ goes *even faster!*

this is a runaway process!
result is fast and violent: explosion in star core!

Helium Flash

when degenerate core mass reaches $M_{\rm He} = 0.5 M_{\odot}$, helium ignition starts runaway

- innermost He core burned to ^{12}C in *seconds*!
  until core hot enough that degeneracy lifted
  becomes ideal gas and expands, slows burning

- huge energy release: $L \sim 10^{11} L_{\odot}$
  internal explosion: **helium flash**

- but energy absorbed by envelope
  only escapes on diffusion timescale
  explosion not visible externally! aargh!

Tip of the Red Giant Branch

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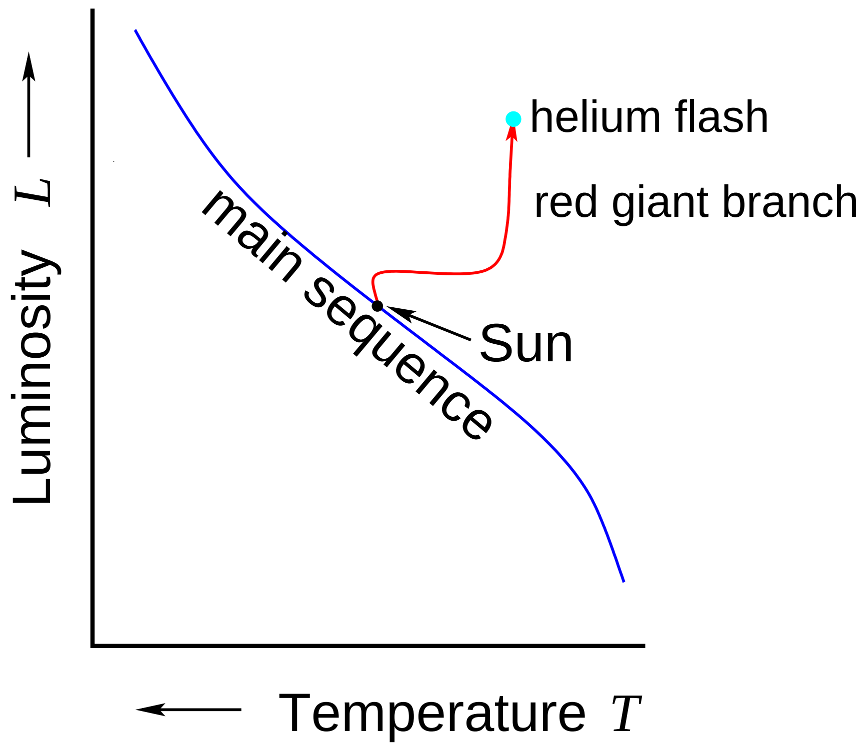
He flash marks maximum rise of luminosity
"tip of the red giant branch"



Core Helium Burning

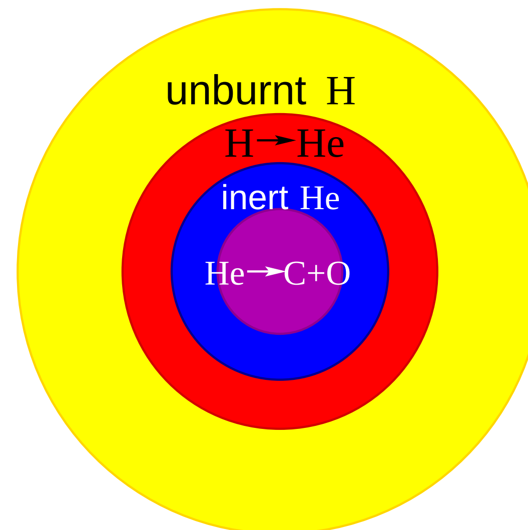
after helium flash, triple alpha continues in core
with stable, non-explosive burning

$$^{4}\mathrm{He} + {}^{4}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{12}\mathrm{C} + \gamma$$

but also: when ^{12}C begins to build up

$$^{4}\mathrm{He} + {}^{12}\mathrm{C} \rightarrow {}^{16}\mathrm{O} + \gamma$$

net result: core converts $^{4}\mathrm{He} \rightarrow {}^{12}\mathrm{C}, {}^{16}\mathrm{O}$
luminosity higher than on main sequence



meanwhile: shell hydrogen burning continues
adding to mass of helium core

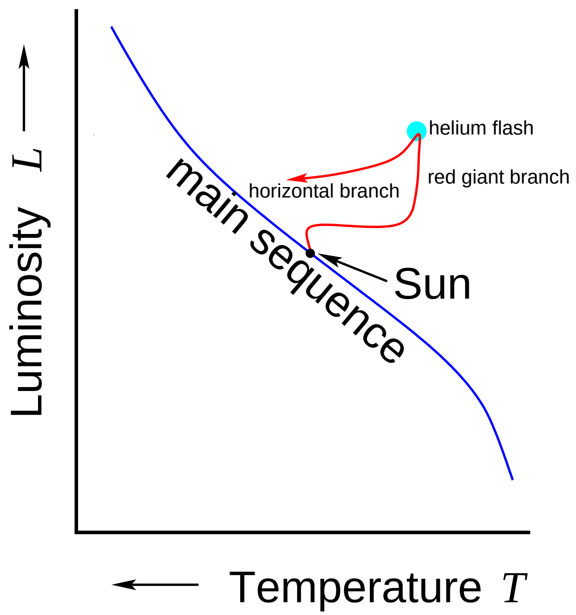
Horizontal Branch

core He burning: long-lived phase
but much shorter than core H burning

- $3\alpha \rightarrow {}^{12}\mathrm{C}$ energy release much lower
- higher luminosity: faster fuel consumption

after core helium burning begins
envelope contracts

on HR diagram: lower L and higher T
horizontal branch



iClicker Poll: Fate of Carbon+Oxygen Core

at the end of core helium burning, star core is carbon+oxygen

Vote your conscience!

What's the fate of the CO core?

A contracts until a new burning phase begins

B contracts until degenerate without further burning

C contracts until catastrophic collapse

Core Helium Exhaustion

fate of the star after core helium exhaustion
CO core contracts, becomes degenerate

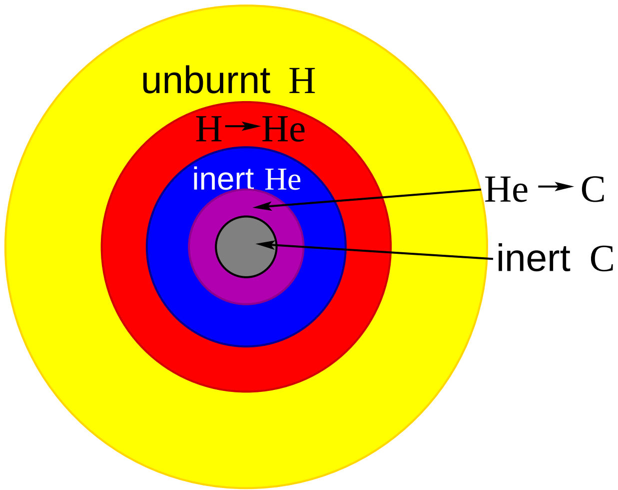
what's next *depends on star mass*

for solar mass stars: degenerate CO supports core
but does not achieve conditions for further burning

we consider this case first, higher masses next

for solar mass stars:
Q: response to CO core contraction?

Burning in Two Shells



for solar mass stars: after CO core forms

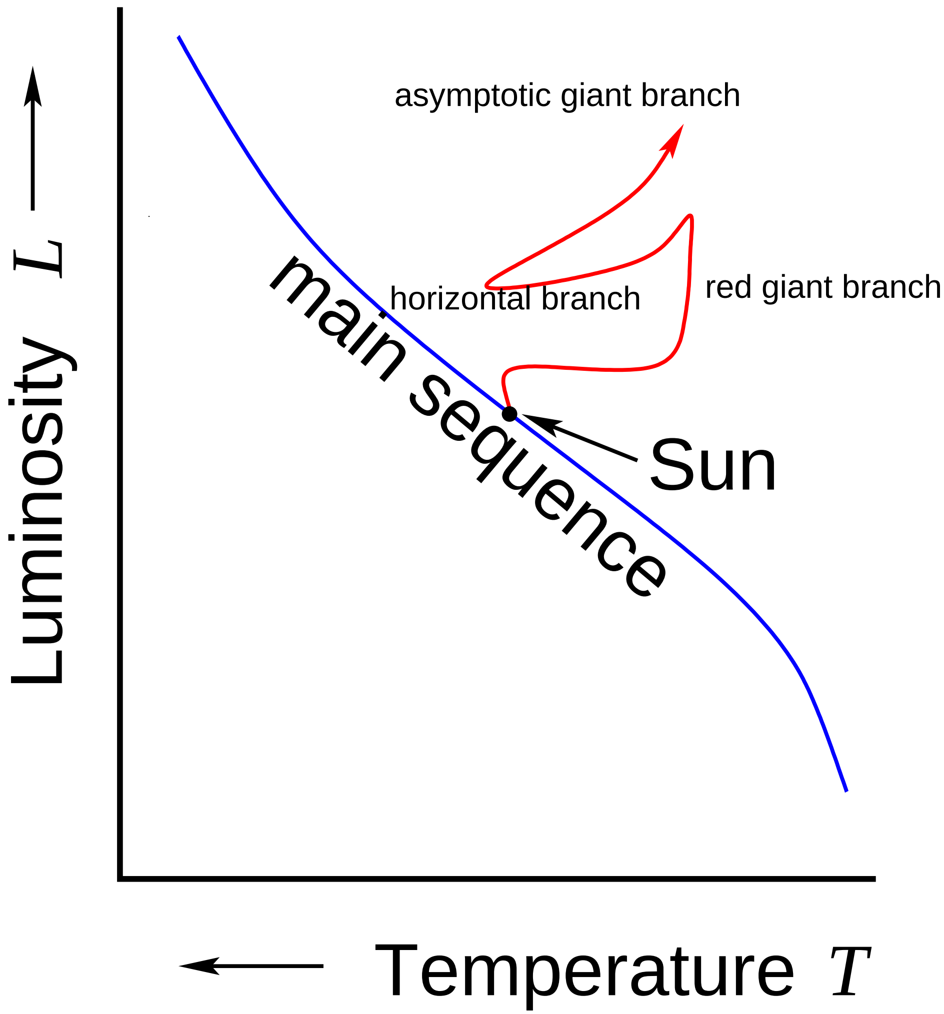
- *helium shell burning begins*
- *hydrogen shell burning continues*

note similarity to end of main sequence

- shell burning raises luminosity dramatically
- shell "mirroring" effect → envelope expands again
- on HR diagram: again approaches giant branch

  asymptotic giant branch star

HR Diagram: Asymptotic Giant Branch



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** wwwMira
much stronger than on Main Sequence
and most intense in AGB phase: **superwind**
$\longrightarrow$ *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 star
often disk geometry – looks like planet
planetary nebula

`www: planetary nebula`

The End: White Dwarf

remaining degenerate core is white dwarf
- supported by degeneracy pressure
- initially hot, cools over time

if no companion: cools indefinitely
eventually will crystalize $\longrightarrow$ phase transition to lattice

if a companion: fate depends on mass transfer