Astro 210
Lecture 32
April 11, 2018

Announcements:

- **HW9 due online in PDF, Friday 5:00 pm**

- Office hours: instructor 2:00–3:00 pm today
  TA 3:30–4:30 tomorrow

- **Solar Observing continues today and tomorrow**
  11:15 am to 2:45 pm Campus Observatory
  allow 20-30 min. bring **worksheet**. take **selfie**

probably one final date next week (first clear)

but go now if you possibly can

Stellar Evolution: the Story thus Far

Last time we saw:

the Sun is a Main Sequence star

Q: what does this mean observationally?

Q: what does this tell about the HR diagram Main Sequence?

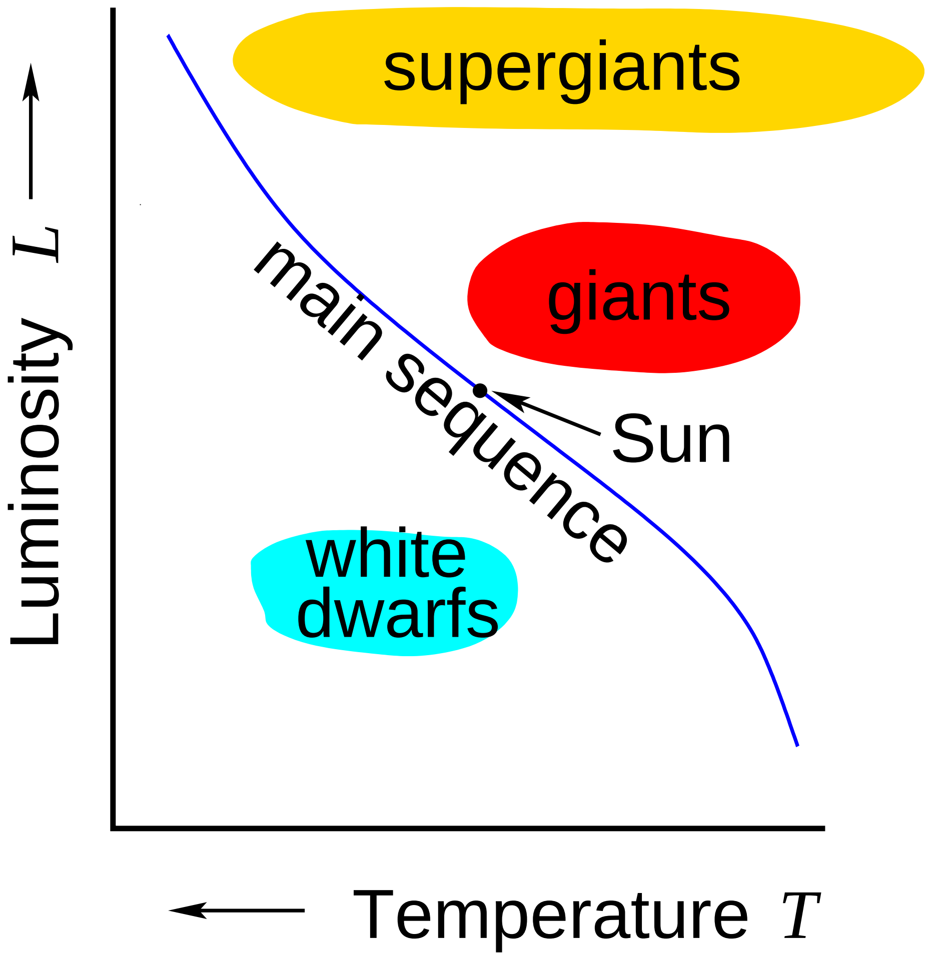
Q: what's the (main) difference between stars at different points along the Main Sequence?

Q: what are the other main features of the H-R diagram?

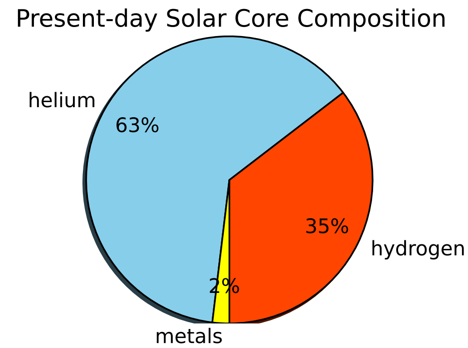
Q: what do you expect is their origin?

Q: what is the effect of nuclear reactions on the Sun's core?

HR Diagram: All Stars



The Sun: Main Sequence Evolution



on MS: in solar core: H $\rightarrow$ He "burning"
$\rightarrow$ over time: H "fuel" $\rightarrow$ He "ash"
$\rightarrow$ fuel supply goes down
e.g., today, Sun's core $<$ 50% H!

how does core respond to H depletion?
$4p + 2e \rightarrow {}^{4}\text{He}$ means *fewer but heavier particles*

consequences:

- pressure $P = nkT = \frac{\rho}{\mu} kT$:
  larger avg particle mass μ $\rightarrow$ pressure drop
- but Sun interior must still support Sun's weight
  $\Rightarrow$ pressure must stay *same*

Q: how would Sun respond?
Q: consequences for photon mean free path, escape?

main sequence $4p + 2e \rightarrow {}^4\mathrm{He}$ means

fewer but heavier particles

so average particle mass μ *increases*

but must maintain pressure support against gravity

• $P = \frac{\rho}{\mu} T$: with higher μ

compensate with *higher core T*

alsp: fewer particles $\rightarrow$ fewer scatterers

photons have longer mean free path

$\rightarrow$ light can escape more easily, faster

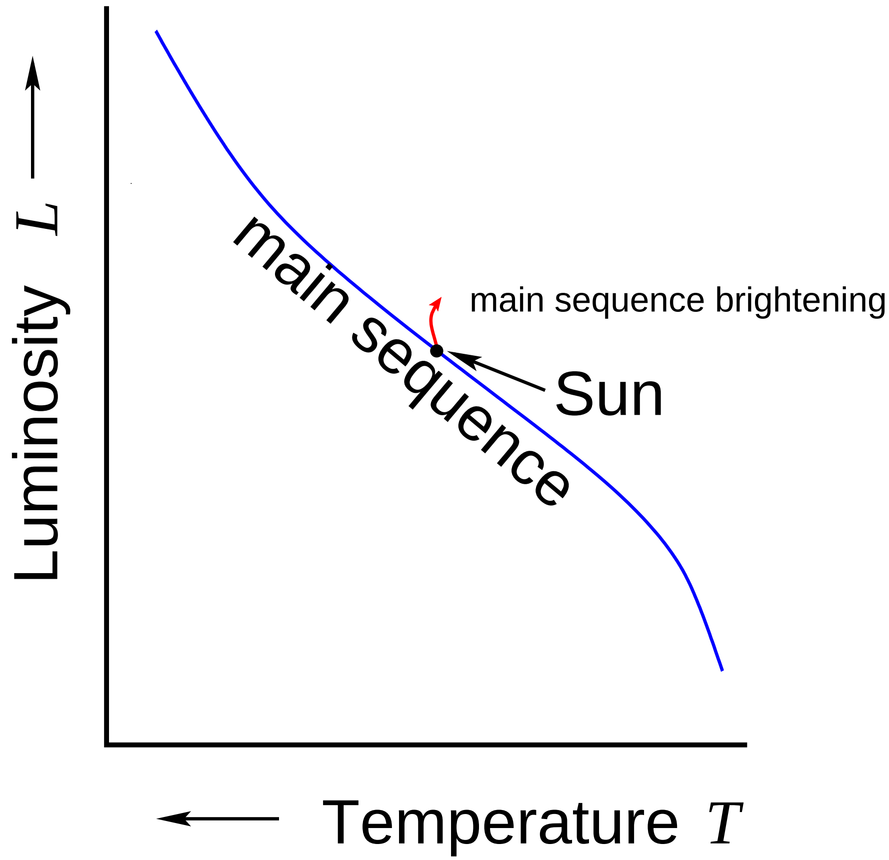
$\rightarrow$ luminosity goes *up*!

main sequence brightening

Q: affect on HR diagram?

Main Sequence Brightening on HR Diagram

Today: sun $\sim 50\%$ brighter than at birth!



iClicker Poll: A Helium-Core Sun

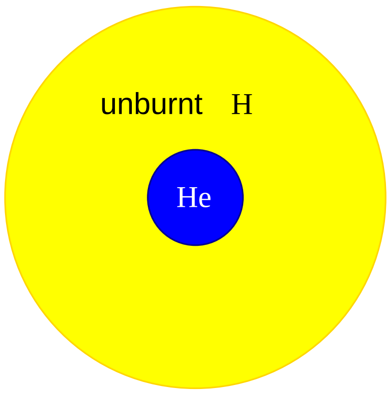
What happens when *all* core H converted to He?

A the Sun's core expands

B the Sun's core contracts

C the Sun begins to burn helium

D the Sun ignites unburnt hydrogen outside core



$1M_\odot$ Star: Leaving Main Sequence

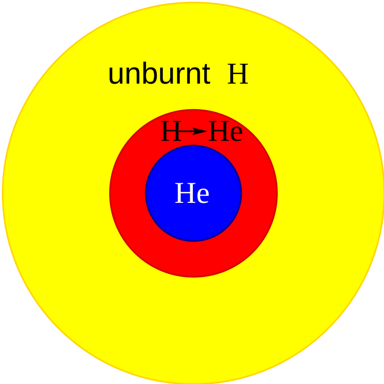
after core H exhausted

- core cools $\longrightarrow$ loses pressure support
  core can't maintain hydrostatic equilibrium
- core contracts!
- H material overlying core also contracts, heats
  new fuel, can begin to burn!
  $\longrightarrow$ H burning in "shell" around core

$\longrightarrow$ L increase!

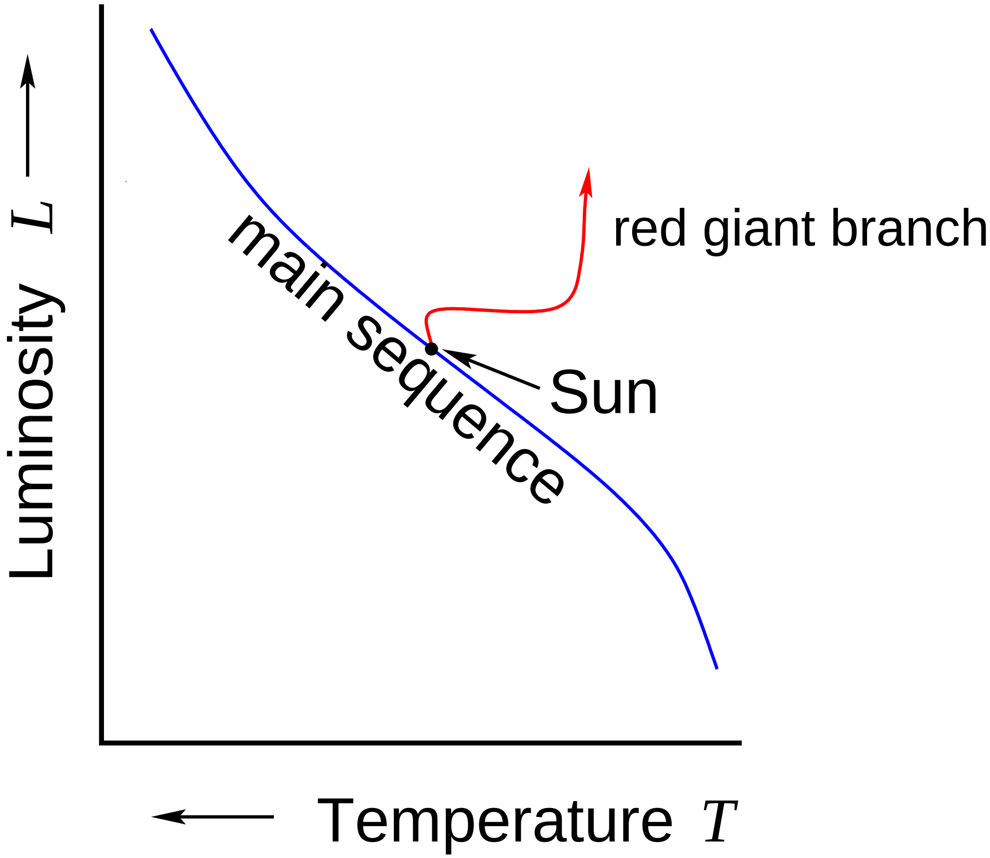
- outer layers ("envelope") of star expands
  $\longrightarrow$ cools: $T \downarrow$

red giant



∞ *Q: HR diagram appearance?*

HR Diagram: Red Giant Phase



Q: how to test?

Late Stellar Evolution: Globular Clusters

⋆ some star clusters *are* gravitationally bound
over long timescales stellar orbits come to equilibrium
in cluster gravitational field → spherical ball of stars
observe as **globular cluster** `www: examples`

long times required to achieve equilibrium
globular clusters are *old stars*

Q: globular cluster HR diagram prediction?

`www: HR diagram`

HR Diagram: Comparing Burning Phases

Note: *in fair sample of stars:*
main sequence makes up about 90% of the population
red giants make up most of the remaining 10%

`www: HR diagram`

Q: what does this tell us?
hint–imagine snapshot of fair sample of people
for example, attendance at White Sox/Cubs

HR Diagram and Stellar Life Stages

Main Sequence

- $\approx 90\%$ of stars
- hydrogen burning: $4p \rightarrow {}^4\text{He}$

Red Giants

- $\approx 10\%$ of stars
- helium burning: $3\,{}^4\text{He} \rightarrow {}^{12}\text{C}$

if stars born at roughly constant rate

most stars will be seen in longest life phase

$\Rightarrow$ *main sequence phase longest, most of star life*

red giant phase $\approx 1/10$ *as long*

Q: what happens to inert He core?

The Dense Core

inert He core: no heat source, so *cools*
gravity force unbalanced $\rightarrow$ *contracts*

core $\rightarrow$ *high density* ρ
contraction slowed by Pauli exclusion principle
$\rightarrow$ quantum law: can't put $2e$'s in same state

at high densities:
quantum "degeneracy" pressure resists compression
like in ordinary solids, but more extreme

in high-density gas/solid:
pressure $P_{\text{degen}} = K\rho^{5/3}$
depends only on ρ, not T ($\neq$ ideal gas!)

Core Burning Reloaded: Helium Flash

red giant structure: degenerate core, H-burning shell, envelope

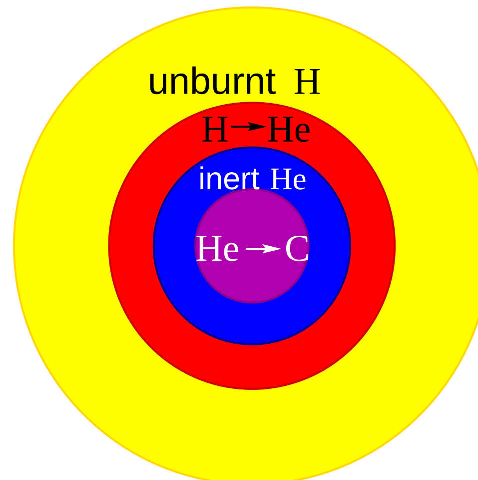
core heats $\longrightarrow$ He fusion ignites

normal gas: $T\uparrow$, $P\uparrow$ $\longrightarrow$ expand $\longrightarrow$ cool
degenerate gas: $T\uparrow$, P const: no exp, cool!
$\longrightarrow$ reaction speedup $\longrightarrow$ explosion!
helium flash (few min)

but note: flash occurs deep in star
$\longrightarrow$ hidden by envelope!

Q: and then?

Cosmic Recycling: Core Helium Burning



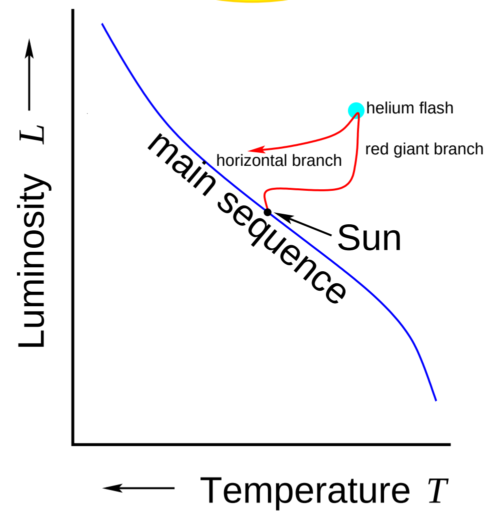
after flash: core He burning

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

ash → *fuel!*

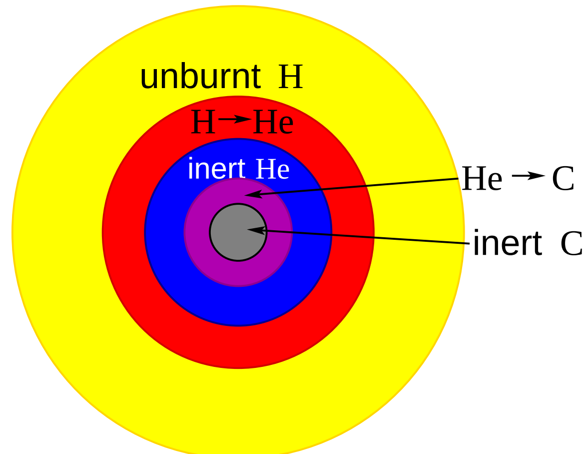
cosmic recycling!

phase similar to H-burning (main seq)
but hotter, faster burn
"horizontal branch" on HR diagram

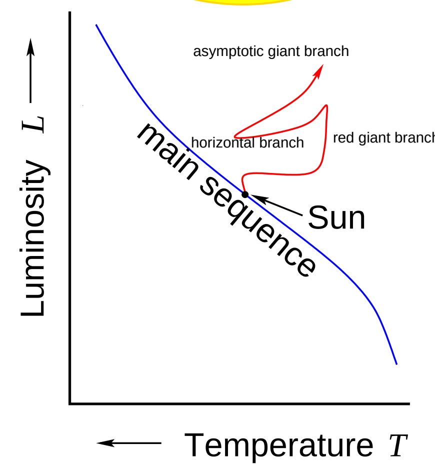


Q: what happens when core He exhausted?

$1M_\odot$ Star: Death Throes



ultimately, core runs out of ^{4}He
now 2 shells: H-burning and He- burning
similar situation to red giant phase
star again expands toward RG region of HR
asymptotic giant branch



2-shell burning unstable! $\longrightarrow$ thermal pulses
(every 10^3 yrs, for a few yrs)
expel mass in "superwind"

Q: what should this lead to?
Q: what would it look like?

$1M_\odot$ Star: The End

AGB phase: dense, inert C+O core
surrounded by unstable shell burning

wind $\rightarrow$ hot ejected gas
$\rightarrow$ **planetary nebula**

`www: HST planetary nebulae`

star coreexposed! $\rightarrow$ cools rapidly
a bare "cinder," supported by
degeneracy pressure (electrons)

- very hot, but
- very compact $\rightarrow$ small

$\Rightarrow$ becomes **white dwarf**