Astro 404

Lecture 27

Oct. 27, 2021

Announcements:

- **PS8 due Friday**
- Office Hours:
  Instructor–Wed after class, or by appointment
  TA: Thur 2:30–3:30

Last time: **convection**

*Q: what is it? everyday examples?*

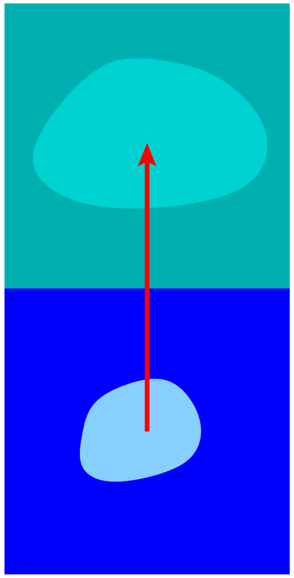
## Convection

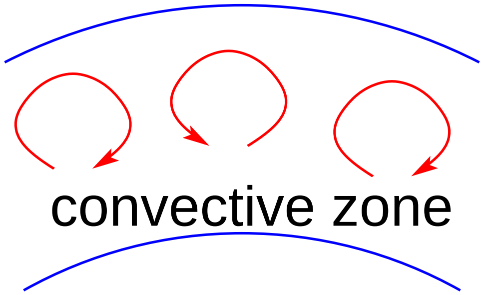
instability in unevenly heated fluids
when supported by gravity

heated fluid rises, cooler fluid falls
"boiling" motion develops
as in water/soup on stove
`www: stellar examples`

effects of convection

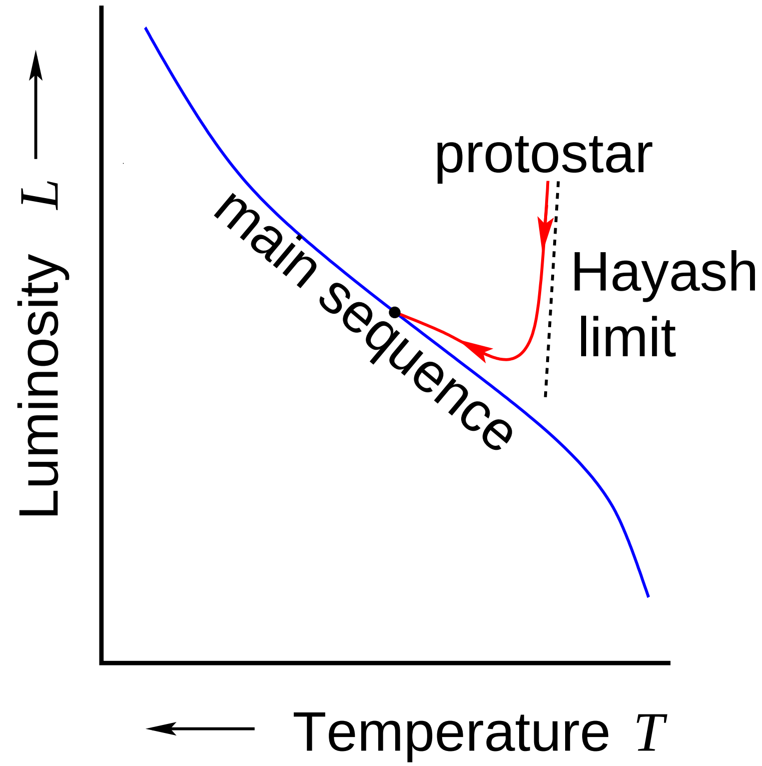
- transports heat outwards
- smooths temperature gradients
- mixes material in convective zone





# Proto-Stars: Pre-Main Sequence

- Initial contraction: nearly freefall
- density increases, becomes opaque
  compressional heating trapped
  becomes fully convective
  on HR: near steep Hyashi limit
- heat destroys molecules, ionizes atoms
  on HR: minimum $L$
- fully ionized star contracts and heats
  on HR: $L$ increases
- hydrogen burning stabilizes star
  on HR: zero age main sequence



## Poll: Guess the Convection

Which main sequence stars have convective cores?

*Hint:* convection driven when temperature gradient $|dT/dr|$ steep
in which stars is H burning heating most uneven?

A high-mass main sequence stars

B low-mass main sequence stars

# Convection on the Main Sequence

*convection driven by strong temperature gradients*
think soup on a stove!

high-mass stars:
• have high $\langle kT \rangle \sim GMm_{\rm g}/R$
• burn H in CNO cycle: energy generation $q_{\rm CNO} \propto T^{16}$!
severe $T$ dependence drives $T$ gradient and thus convection

so high-mass main sequence stars have convective cores
• burn fuel more efficiently, extends still-short lifetime
• at end of main sequence, convection sets
mass and size of helium core

but *core of low-mass stars (including Sun) not convective*
• energy transport is radiative diffusion
• helium core size set by region of helium production

# Beyond the Main Sequence

# Post-Main Sequence Stellar Evolution

recall: energy conservation teaches: *all stars must die!*

*how a star dies is controlled primarily by its* **mass**
though binarity, rotation, composition also important

at end of main sequence: *helium core is about 10% of star mass*

we first consider effects for low-mass stars
$M \lesssim 2M_\odot$ – this includes the Sun

# Poll: A Helium-Core Sun

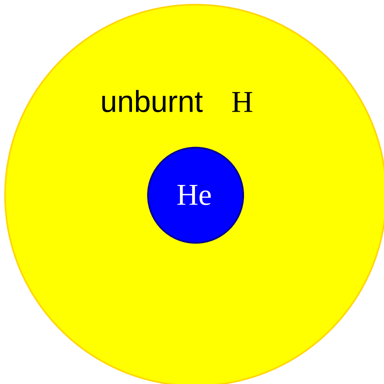
What happens *first* when *all* core H converted to He?

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



# Low Mass Stars: Core Hydrogen Exhaustion

as core hydrogen exhausted, core fusion ends
heat loss $\rightarrow$ lower temperature $\rightarrow$ lower pressure

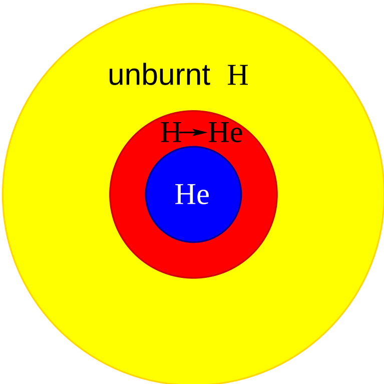
hydrostatic equilibrium lost: *core contracts*

- core density rises until degeneracy sets in

- contraction halts when degeneracy pressure supports core

*Q: effect on region surrounding helium core?*

# Hydrogen Shell Burning




as helium core contracts

- H material overlying core also contracts, heats new fuel, can begin to fuse!
- **H burning ignites 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* $\sim 100$
- so surface $T_{\text{eff}} \propto L^{1/4}/R^{1/2}$ drops
- star becomes **red giant**
- for Sun: red giant radius $R_{\text{RG}} \simeq 1$ au (PS9)
  Mercury and Venus consumed, unclear if Earth will survive!

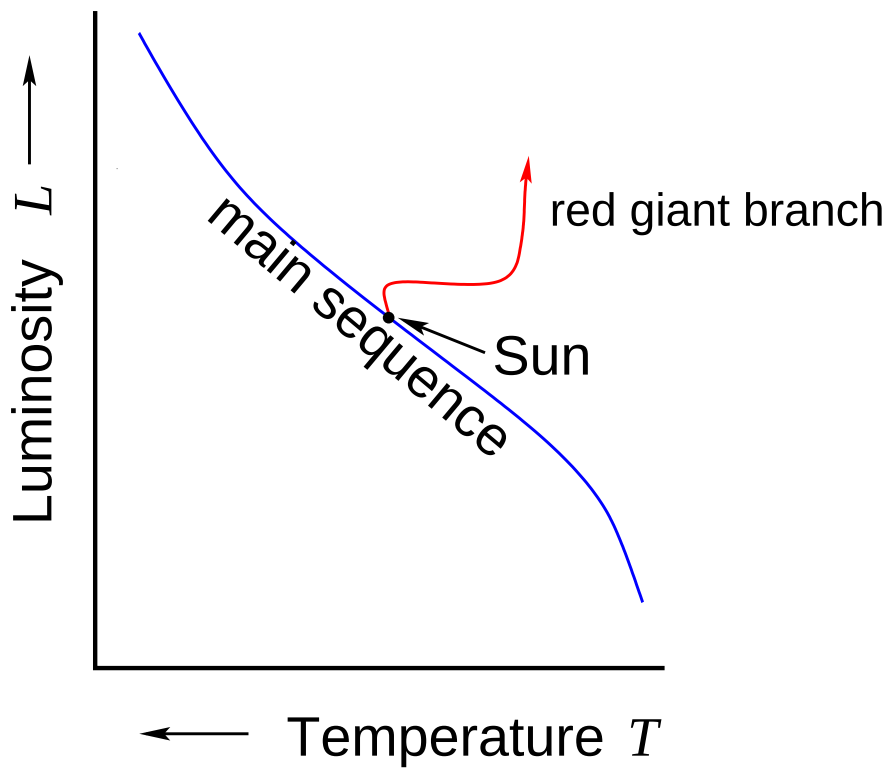
**"mirror" effect of shell burning:**

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



*Q: movement of star on HR diagram?*

# HR Diagram: Red Giant Phase



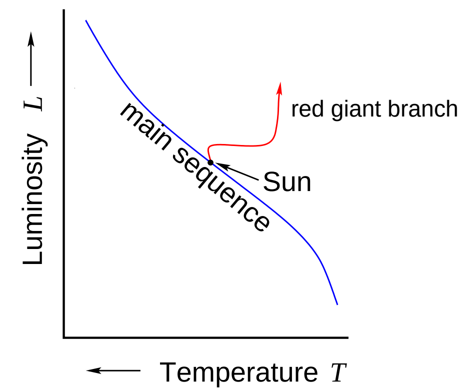

`www: Gaia observed HR diagram for field stars`



*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 $M_{\mathrm{He}}$ 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

# Poll: Density Scaling of $3\alpha$

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: $3\,{}^4\mathrm{He} \to {}^{12}\mathrm{C}$

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

**helium ignition occurs in degenerate core**

- luminosity density

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

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

once $3\alpha$ burning ignited:

*Q: effect on $T$? on $P$? on $\rho$?*

*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 $\rho$ 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 $M_{\mathrm{He}} = 0.5 M_{\odot}$,
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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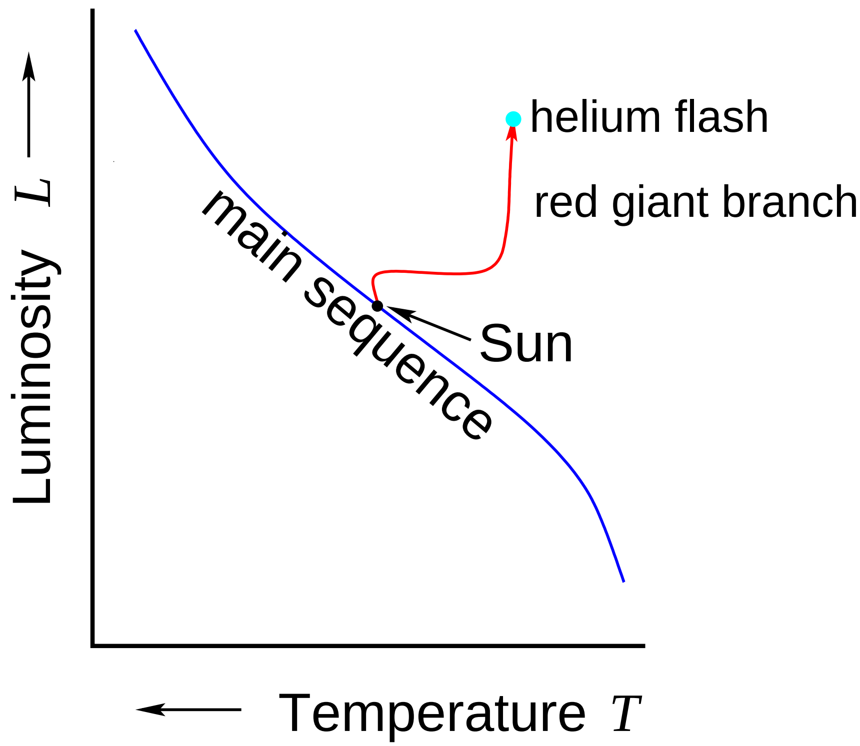
He flash marks maximum rise of luminosity
"tip of the red giant branch"



# Core Helium Burning

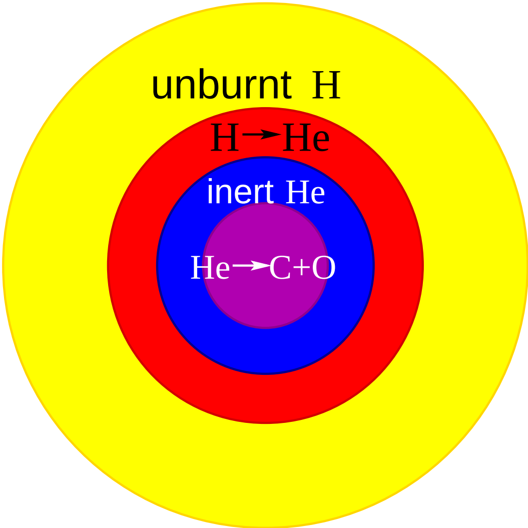
after helium flash, triple alpha continues in core
with stable, non-explosive burning

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

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

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

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




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

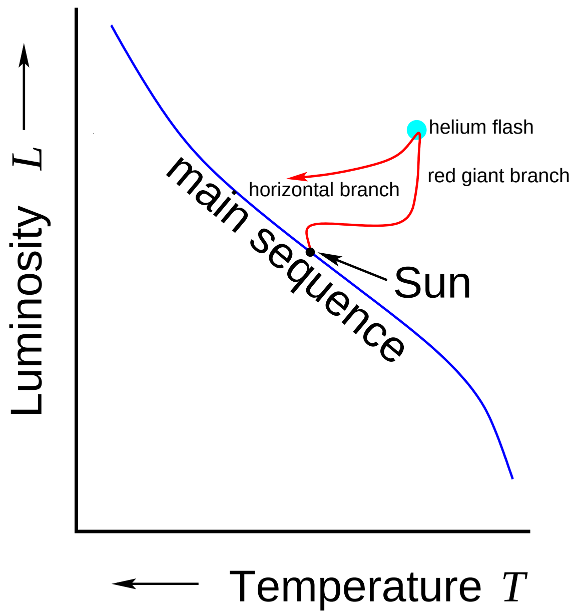
# Horizontal Branch

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

- $3\alpha \rightarrow {}^{12}\text{C}$ 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*

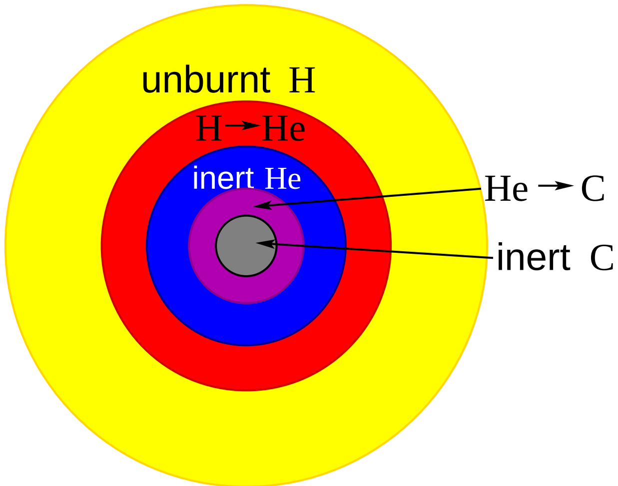
what's next *depends on star mass*

*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

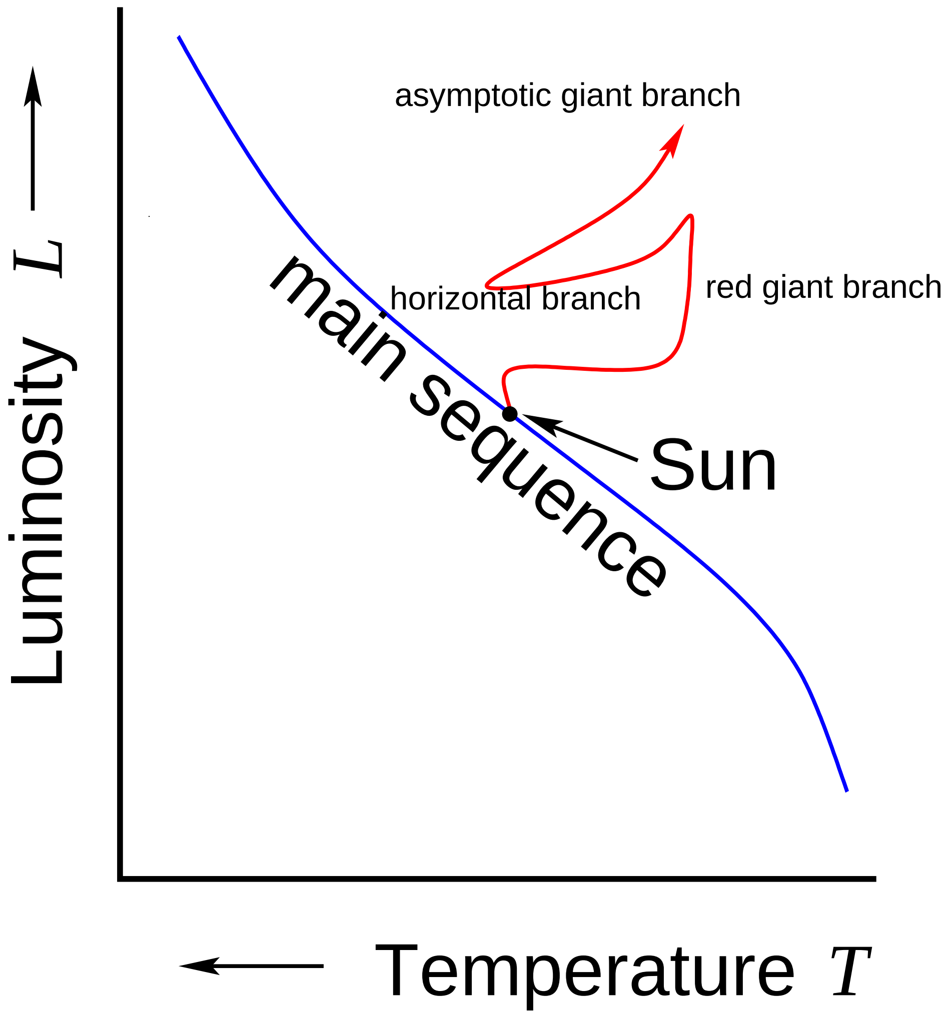
- *helium shell burning begins*
- *hydrogen shell burning continues*

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**
$\rightarrow$ *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 $\rightarrow$ phase transition to lattice

if a companion: fate depends on mass transfer