Astro 210

Lecture 33

April 13, 2018

Announcements:

- **HW9 due online in PDF, Today 5:00 pm**
- HW10 posted, due next Friday
- **Solar Observing - Last Chance** first clear day next week
  11:15 am to 2:45 pm   Campus Observatory
  allow 20-30 min. bring **worksheet**. take **selfie**
- Hour Exam 2 grades up by Sunday

The Life and Death of the Sun: Recap

A star's life is a struggle against its own gravity

Q: how do main sequence stars fight gravity?

Q: what will happen when all H fuel burned to He in Sun?

Q: how will the Sun die? what remains are left?

Q: evidence on HR diagram?

$1M_\odot$ Star: The End

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

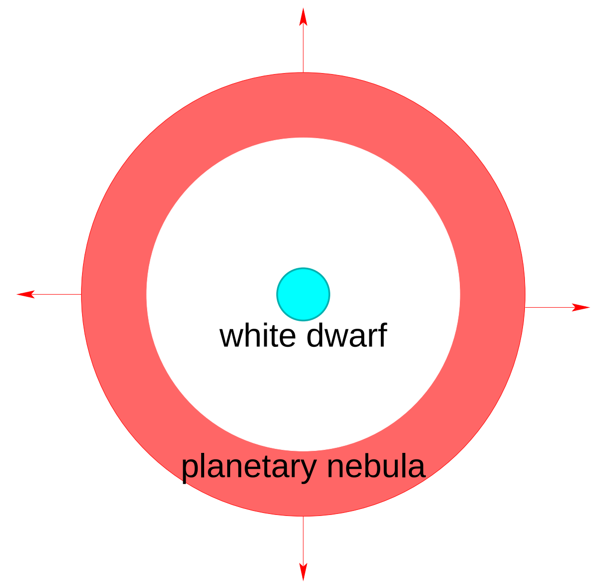
wind $\longrightarrow$ hot ejected gas
$\longrightarrow$ **planetary nebula**

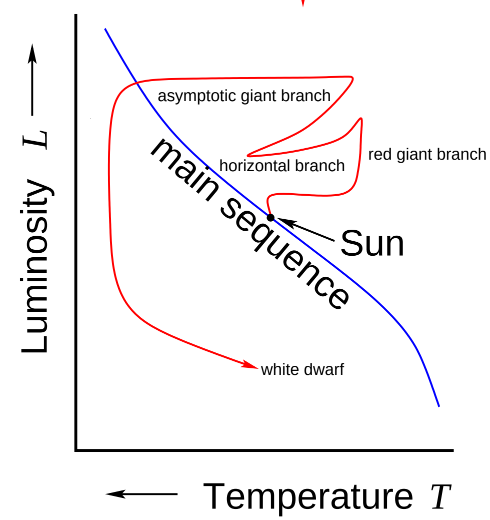
`www: HST planetary nebulae`

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

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

$\Rightarrow$ becomes **white dwarf**





White Dwarfs

"stellar corpse" – leftover after $1M_\odot$ star death

and for other low-mass stars too; see below

nearby example: Sirius B

`www: X-ray image`

- $M = 0.96 M_\odot$
- $R = 0.0084 R_\odot = 0.8 R_{\rm Earth}$!
- $\rho = (M/R^3)\rho_\odot \approx 2 \times 10^6 \rho_\odot = 2 \times 10^9\ \mathrm{kg/m^3}$!

  $\Rightarrow$ 1 cm^3 contains 2 tons!

  compact! ultradense!

to followup from last time *Q: what if you throw H onto a WD?*

White Dwarf Structure

white dwarf *not* an ideal gas
supported by degenerate electrons $\rightarrow$ ultradense solid
equation of state:

$$P = K\rho^{\gamma} \begin{cases} \gamma = 5/3 & \text{“low” density} \\ \gamma = 4/3 & \text{“high” density} \rho \gg 10^9 \text{ kg/m}^3 \end{cases} \tag{1}$$

hydrostatic equilib gives $R^2 P \sim GM^2/R^2$
$\Rightarrow$ use this to eliminate P, relate M and R

Lower density white dwarfs: $\gamma = 5/3$
$GM^2/R^4 \sim KM^{5/3}/R^5$
$\Rightarrow R \propto M^{-1/3}$
Mass increases $\rightarrow$ radius *decreases!*

High density white dwarfs: $\gamma = 4/3$

for pressure to balance gravity: $GM^2/R^4 \sim KM^{4/3}/R^4$

$\Rightarrow M \sim (K/G)^{3/2}$!

mass is indep of R, ρ! numerically:

$$\boxed{M = M_{\text{Chandra}} = 1.4 M_\odot}$$

Chandrasekhar limit! S. Chandrasekhar 1931(!!)

Q: what if white dwarf has $M < M_{\text{Chandra}}$?

Q: what if white dwarf has $M > M_{\text{Chandra}}$?

if high-density WD has $M < M_{\text{Chandra}}$
then pressure (more than) enough to balance gravity
$\rightarrow$ *WD is stable against collapse*

but: *if high-density WD has $M > M_{\text{Chandra}}$*
then pressure *not enough* to balance gravity
$\rightarrow$ gravity force not balanced
$\rightarrow$ *star unstable $\rightarrow$ collapses under its own weight!—*
$\rightarrow$ catastrophe!

conclusion: *Chandrasekhar mass is*
maximum *mass of white dwarfs!*
i.e., most massive possible "ordinary solid" = supported by e degeneracy

Confirmed! All observed white dwarfs have $M < M_{\text{Chandra}}$

Testing Stellar Evolution

recall: stellar evolution depends on mass

thus far: looked in detail at $1 M_{\odot}$ evolution
now need to know: how do other stars evolve?

Q: what about very low mass stars?

Beyond $1 M_\odot$: Low-Mass Stars

since $\tau = 10^{10}$ yr$/m^3$
long lifetime if $m < 1 M_\odot$
$\tau = 14$ Gyr $=$ age of universe for $m \sim 0.9 M_\odot$
$\rightarrow$ if m lower, "live forever"

for $m \lesssim 0.08 M_\odot$, core too cool to burn H
"brown dwarfs"
Q: what (if any) is heat source? how does star evolve?

Bottom line:
not much going on with low-mass stars
but (by number) most stars are low-mass
high-mass stars are rare...but spectacular...

Lives and Deaths of Stars

a star's life history, death controlled by it **mass**

$M < 0.9 M_\odot$

history like that of the Sun to date

burn H $\rightarrow$ He

lifetime $>$ age of universe: live "forever"

i.e., none have yet died

$0.9 M_\odot < M < 8 M_\odot$

history like that of the Sun

life: burn H $\rightarrow$ He ("main sequence" phase)

then giant/HB/AGB phases, burns He $\rightarrow$ C

death: eject $>$ 50% of mass as enriched gas–"planetary nebula"

leave behind compact object: white dwarf

$M > 8 M_\odot$

history begins like Sun, but then very different...

Evolution of High Mass Stars

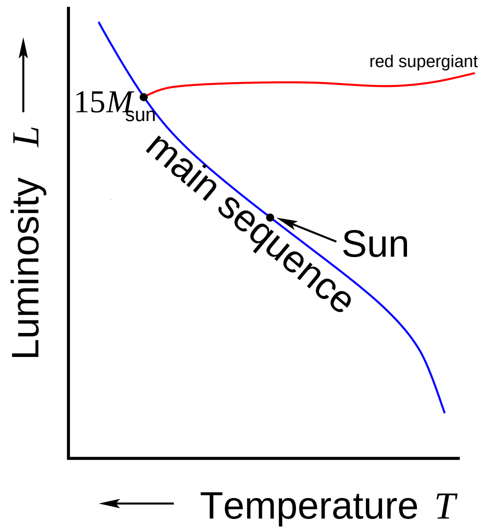
high mass: $M > 8M_\odot$ (approximate–low mass limit not precisely known)
initially: burn H $\rightarrow$ He in main sequence phase

after core H gone:

- contract, ignite core He $\rightarrow$ C burning
- shell H burning: outer layers expand to **supergiant**

`www: HST Betelguese`

`www: HR diagram`



Mass large $\rightarrow$ gravity strong $\rightarrow$ core T large
can and do burn carbon, heavier elements

High Mass Star: Burning Phases

recall: nuclear fusion releases energy
because *lighter nuclei are less tightly bound*
= less binding energy
than heavier nuclei
so: *fusion of* lighter $\rightarrow$ heavier nuclei *releases energy*

this powers (and stablizes) massive stars

massive stars undergo ever more rapid cycles:
core contraction $\rightarrow$ heating $\rightarrow$ ignition $\rightarrow$ burning
C+He $\rightarrow$ O
O+He $\rightarrow$ neon
... up to iron
ash $\rightarrow$ fuel: cosmic recycling!

iClicker Poll: Burning Times in Massive Stars

massive star cores burn progressively heavier elements
H $\rightarrow$ He, He $\rightarrow$ C, ..., Si $\rightarrow$ Fe

How to the temperatures and burning times compare?

A each later phase has *higher* T and takes *more time*

B each later phase has *higher* T and takes *less time*

C each later phase has *lower* T and takes *more time*

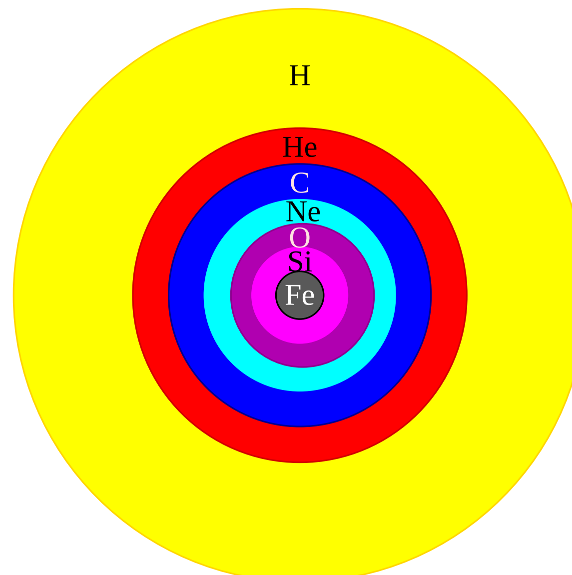
D each later phase has *lower* T and takes *less time*

Massive Stars: The End Approaches

outside core:

- onion-skin structure develops
- previous phases “remembered” in shell burning
- the star’s structure recapitulates “summarizes” its history!

`www: pre-SN structure`



core fusion: makes ever heavier elements

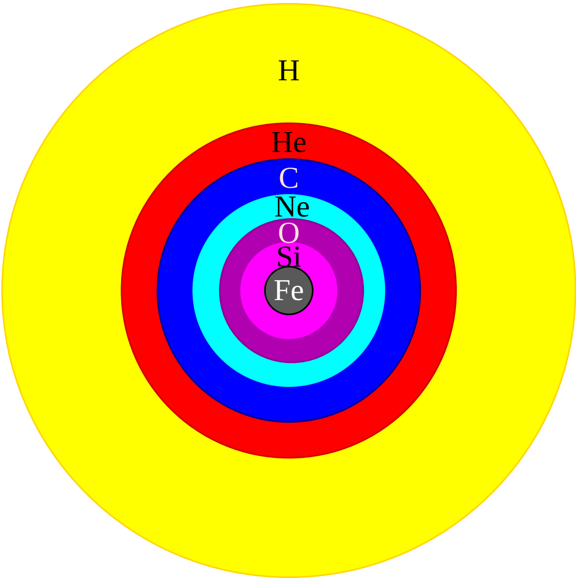
burning phases ever hotter, faster

from H burning: $5 - 10$ Myr

down to *Si burning: 1 day!!*

cycles of contraction and ash → fuel
and fusion release of nuclear energy
cannot continue forever

stops when core is iron (Fe)



nuclear physics: *iron is most stable nucleus*
that is, *the most tightly bound*
→ fusion with iron endothermic and not exothermic
Q: what does this mean?

Fe fusion endothermic:
$\longrightarrow$ Fe can't be fuel! inert!

in *iron core:*

- *fusion stops*
- *core solidifies: iron white dwarf forms!*

but immediately outside of iron core
shell burning of silicon $\longrightarrow$ iron
$\longrightarrow$ iron core mass increases
$\longrightarrow$ this is a losing game!
Q: why? what happens?

The End: Core Collapse

Star structure:
- inert (non-burning) iron core
- supported against gravity by quantum motion of degenerate electrons: **core is an iron white dwarf**
- but shell burning keeps increasing core mass

but recall: *white dwarfs have maximum mass!*
eventually Si →Fe shell burning: $M_{\text{core}} > M_{\text{Chandra}}$:
gravity overwhelms degeneracy pressure
star finally loses lifelong struggle against gravity!

Catastrophic results:
→ **core collapses!** → infall speeds $\sim 10\% c$!
→ overlying layers lose support, collapse too: **implosion!**
Q: what next?

Massive Star Death: Supernova Explosions

Gravitational Collapse

core compression to tiny volume!
→ nuclei "touch": nuclear density
very hard to compress more!
core → giant atomic nucleus, supported by nuclear force

infalling envelope "bounces" off stiff core
ejected at high speed (up to 10% c)
→ supernova explosion
Demo: AstroBlaster

one supernova briefly as luminous as a Galaxy of stars
`www: SN 1994D`

Q: what's left after explosion? what are the leftovers like?