

Astro 210
Lecture 32
November 10, 2010

Announcements

- HW 9 due
- Solar Observing due
- next week's homework computer-based
pick one of two:
for the theory-inclined: simulate a star
for the observation-inclined: cosmology data analysis
- Hour Exam 2: not forgotten!
Grader (=yours truly) is slow, apologizes.

Last time: stellar mass

┌

- related to luminosity: $L \propto M^4$
- lifespan vs mass: $\tau \propto M^{-3}$

Stellar Lifetimes: Implications

Some Facts:

- stellar (“main sequence”) mass-lifetime relation:

$$\tau = 10 \text{ billion yr} \left(\frac{1M_{\odot}}{M} \right)^3 \quad (1)$$

- age of Sun and solar system: $t_{SS} = 4.5$ billion yr
- age of the Universe (we'll find): $t_0 = 13.7$ billion yr

Implications:

- $\tau(0.5M_{\odot}) = 80$ billion years $\gg$ age of Universe!
→ all such stars ever born remain alive today!
- $\tau(10M_{\odot}) = 10$ million years $\ll$ age of U., SS
→ most such stars have come and gone!
→ any massive stars seen today were recently born

So as our Galaxy makes stars

- low-mass stars live “forever” (but are dim)
- high-mass stars die quickly

→ expect mostly low masses (in a fair sample)

but beware bias – rare, luminous stars easier to see
example of “selection effect”

Theory Building: Stellar Life Cycles

Q: what is involved in making a model of a star's life?

for example, consider a model of the Sun's life

Q: what physics goes in?

Q: what data needed as inputs and/or checks on model outputs?

Q: what kind of predictions can such a solar model make?

The Life and Death of a $1M_{\odot}$ Star

Evolution of a $1M_{\odot}$ Star: Birth

protostar

raw material: H, He, dust (heavy elements)
in cold molecular cloud

www: Eagle Nebula

‘free fall’ collapse

most material $\rightarrow$ protostar

nonzero angular momentum $\rightarrow$ protoplanetary disk

(see solar system origin notes)

protostar contracts $\rightarrow$ heats

- core $T \uparrow$ until hot enough for
nuclear reactions to turn on, then

- H burning starts: heat supply

- gas pressure maintained

- hydrostatic equilibrium achieved $\rightarrow$ star stabilized

$1M_{\odot}$ Star Mid-Life: “Main Sequence”

“main sequence” = burn $H \rightarrow He$ in core

most of a star’s lifespan spent in this phase

Q: how does star core change in composition during this time?

Q: how will the Sun respond to this change?

Evolution of the Sun's Luminosity

in star core: $\text{H} \rightarrow \text{He}$ “burning”

→ over time: H “fuel” → He “ash”

→ fuel supply goes down

e.g., today, Sun's core $< 50\%$ H !

how does core respond to H depletion?

- still need to generate nuclear energy
- but with less fuel, have to burn hotter

→ core T goes up

→ star responds by *increasing* L !

∞ 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: Old Age

after core H exhausted

- core cools $\rightarrow$ loses pressure support
core can't maintain hydrostatic equilibrium
- core contracts!
- H material overlying core also contracts, heats new fuel, can begin to burn!
 $\rightarrow$ H burning in “shell” around core
 $\rightarrow L \uparrow$
- outer layers (“envelope”) of star expands
 $\rightarrow$ cools: $T \downarrow$

red giant

The Dense Core

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

pressure $P_{\text{degen}} = K\rho^{5/3}$

depends only on ρ , not T ($\neq$ ideal gas!)

structure: degenerate core, H-burning shell, envelope

core heats $\rightarrow$ He fusion ignites

normal gas: $T \uparrow, P \uparrow \rightarrow$ expand $\rightarrow$ cool

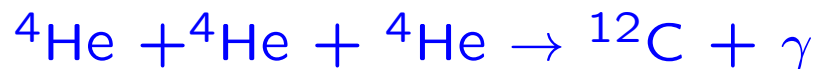
degen. gas: $T \uparrow, P$ const: no exp, cool:

$\rightarrow$ reaction speedup $\rightarrow$ explosion!

helium flash (few min)

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

after flash: core He burning



ash $\rightarrow$ fuel!

similar to H-burning (main seq) but hotter, faster burn

most red giants in this phase

Q: what happens when core He exhausted?

$1M_{\odot}$ Star: Death Throes

ultimately, core runs out of ${}^4\text{He}$
now 2 shells: H- and He- burning
unstable! $\rightarrow$ thermal pulses
(every 10^3 yrs, for a few yrs)
expel mass in “superwind”
hot ejected gas $\rightarrow$ “planetary nebula”

www: HST planetary nebulae

hot core exposed! $\rightarrow$ cools rapidly
star core is exposed as bare “cinder”
supported by degeneracy pressure (electrons)

- very hot, but
 - very compact $\rightarrow$ small
- $\Rightarrow$ becomes white dwarf

White Dwarfs

“stellar corpse”

supported by degenerate electrons

eq. of state:

$$P = K\rho^\gamma \begin{cases} \gamma = 5/3 & \text{“low density”} \\ \gamma = 4/3 & \text{high density } \rho \gg 10^9 \text{ kg/m}^3 \end{cases} \quad (2)$$

HW: $P \sim GM^2/R^4$

combine with $P = K\rho^\gamma \sim K(M/R^3)^\gamma$:

for pressure to balance gravity:

$$\frac{GM^2}{R^4} \sim \frac{KM^\gamma}{R^{3\gamma}} \quad (3)$$

Low 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!**