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:

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

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

Implications:

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

$\rightarrow$ 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 maintanted
- 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: 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?
• still need to generate nuclear energy
• but with less fuel, have to burn hotter
$\rightarrow$ core T goes up
$\rightarrow$ 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 aslo 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: $T \downarrow$

$\boxed{\text{red giant}}$

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

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

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?

$1 M_\odot$ Star: Death Throes

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

`www: HST planetary nebulae`

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

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

$\Rightarrow$ becomes white dwarf

White Dwarfs

"stellar corpse"
supported by degenerate electrons
eq. of state:

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

HW: $P \sim GM^2/R^4$
combine with $P = K\rho^{\gamma} \sim K(M/R^3)^{\gamma}$:
for pressure to balance gravity:

$$\frac{GM^2}{R^4} \sim \frac{KM^{\gamma}}{R^{3\gamma}} \tag{3}$$

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 decreses!