Astro 210

Lecture 34

November 15, 2010

Announcements

- this week's homework computer-based
  pick one of two:
  for the theory-inclined: simulate a star
  for the observation-inclined: cosmology data analysis

Last time: life and death of a $1 M_\odot$ star

Q: what are the two longest phases in a $1 M_\odot$ star's life?

Q: what causes the final end?

Q: what are the end products? what happens to them afterwards?

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`

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

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

  compact! ultradense!

White Dwarf Structure

white dwarf *not* an ideal gas

supported by degenerate electrons $\rightarrow$ ultradense solid

equation of state:

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

HW: you showed hydrostatic equilib gives $P \sim GM^2/R^4$

$\Rightarrow$ use this to eliminate P, relate M and R

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!*

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!"

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 $M < M_{\rm Chandra}$
then pressure (more than) enough to balance gravity
$\rightarrow$ WD is stable against collapse

but: if high-density WD has $M > M_{\rm Chandra}$

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!

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

Testing Stellar Evolution

recall: evolution depends on mass

thus far: looked in detail at $1M_{\odot}$ evolution

now need to know: how do other stars evolve?

iClicker Poll: Lifestyles of the Stars

Consider two stars, with masses M_{lo} and M_{hi}
such that $M_{\text{lo}} < M_{\text{hi}}$

How do their lifestyles (luminosity L, lifespan τ) compare?

A M_{hi} is **less** luminous, and has a **sorter** lifespan

B M_{hi} is **less** luminous, and has a **longer** lifespan

C M_{hi} is **more** luminous, and has a **sorter** lifespan

D M_{hi} is **more** luminous, and has a **longer** lifespan

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" phase burning 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: "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`

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

increasing 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!

outside core:

- onion-skin structure develops
- previous phases "remembered" in shell burning
- the star's structure recapitulates its history!

`www: pre-SN structure`

core burning (fusion): makes ever heavier elements
phases ever hotter, faster
but this can't go on forever

when core is iron (Fe)
nuclear physics: iron is most stable nucleus
$\rightarrow$ fusion with iron endothermic and not exothermic
Q: what does this mean?

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

when core is Fe:
- fusion stops
- core solidifies: iron white dwarf forms!

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

Massive Stars: The End

Star structure:

- inert (non-burning) iron core
- supported against gravity by quantum motion of degenerate electrons (i.e., a white dwarf = solid)
- but shell burning keeps increasing core mass

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

Catastrophic results:
$\rightarrow$ core collapses!
$\rightarrow$ speeds $\sim 10\% c$!
$\rightarrow$ overlying layers lose support, collapse too

Supernova Explosions (Type II)

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?

Supernova Debris

supernova ejects $> 90\%$ of star's initial mass

Ejecta are:

1. hot
2. fast–up to $10\% c$
3. enriched with products of nuclear burning
   heavy elements (e.g., O, iron)

`www: Cas A Chandra image`