Astro 350
Lecture 12
Sept. 19, 2011

Announcements:

- Good news: no HW next Friday!
- Bad news: Hour Exam 1 next Friday
  info on course website

Last time: stars
"flashlight equation"

$$\begin{array}{ccccc} \text{fuel supply} & = & \text{wattage} & \times & \text{shine time} \\ E_{\text{fuel}} & = & L & \times & \tau \end{array} \tag{1}$$

for Sun: L and τ huge!
of possible fuels: gravitational, chemical, rotational energy
  all are *way way* too small!
$\rightarrow$ need enormous E_{fuel}

Cosmic Nuclear Reactors

Sun needs huge energy supply–a mystery until 1920's
→ **nuclear energy** discovered, only source that comes close
→ the Sun is a nuclear reactor!
→ all stars are nuclear reactors!

Mechanism: high-energy collisions

$$\text{nucleus}_1 + \text{nucleus}_2 \rightarrow \text{nucleus}_3 + \text{energy} \quad (2)$$

- nuke energy release → stellar power source
- lighter nuclei combine → heavier: fusion
  changes elements → stellar alchemy

To work: need high-energy collisions

- in lab: particle accelerator
- *Q: what about in stars?*

Nuclear Reactions in Stars–and the Universe!

macroscopic temperature $\leftrightarrow$ microscopic atom/particle motion
hotter $\rightarrow$ faster particles, collisions more frequent & energetic

Examples

- cooking food: heat $\rightarrow$ speed up chemical reactions $\rightarrow$ cooks!
- heat gas until particle energy $>$ electron binding to atoms
  e stripped away $\rightarrow$ gas of free e and ionized nuclei
  $\Rightarrow$ "plasma" – occurs for $T \gtrsim 10,000$ K
  $\Rightarrow$ star interiors and eary Universe are plasmas!
- heat a plasma until particle energy $>$ nuclear binding
  i.e., collision energy $>$ energy binding p and n together
  $\Rightarrow$ simulate particle accelerator conditions, get nuke reactions!
  need $T \gtrsim 10^7$ K = 10 million Kelvin

The Lives of Stars

The life of a star is a struggle against its own gravity

Birth

stars formed when cold gas clouds collapse due to gravity
compression $\rightarrow$ heating, until T at center $\rightarrow$ 10^7 K
"birth" when first nuke reactions begin: H $\rightarrow$ He

Midlife (Main Sequence) – All Stars

in core of star, a set of nuke reactions leads to

$$4p + 2e \rightarrow \boxed{{}^{4}\text{He} = 2p2n} + 2\nu_e + \text{energy} \tag{3}$$

- energy release $\rightarrow$ heat $\rightarrow$ maintains outward pressure $\rightarrow$ balances inward gravity $\rightarrow$ stability! ("hydrostatic equilibrium")
- neutrinos ν_e released: we measure them from Sun!
- H "fuel" steadily converted to He "ash"
- process continues until star core only He, no H left
  Q: what happens next?

Very Low-Mass Stars: "Immortal"

if $M < 0.8 M_\odot$, gravity weak $\rightarrow$ T low at core

$\rightarrow$ nuke burning very slow

$\rightarrow$ takes a long time to exhaust H fuel

H burning time (main seq lifetime) ¿ age of Universe

$\rightarrow$ none have died yet–"live forever" (well, a very long time...)

Helium Burning–All Stars $> 0.8 M_\odot$

core loses heat $\rightarrow$ loses pressure $\rightarrow$ contracts due to gravity

but compression $\rightarrow$ $T \uparrow$: ignite nuke rxns with helium:

$$^4\text{He} + {}^4\text{He} + {}^4\text{He} \rightarrow \text{carbon} + \text{energy} \tag{4}$$

He ash $\rightarrow$ fuel to make C: cosmic recycling!

What's next? Depends on star gravity and thus mass M

Death-Throes: Low-Mass Stars $0.8 M_\odot < M < 8 M_\odot$

once He $\rightarrow$ C in core: contract again
but don't heat enough to ignite C

$\rightarrow$ star core compresses to a giant, hot, compact solid
outer layers unstable, driven off

- $\approx$ 50% of star mass ejected, includes newly-made He and C
  observe gasses as "planetary nebula"

- remaining hot solid visible as "white dwarf"
  inert stellar cinder

Q: but what if the star can *ignite carbon?*

High-Mass Stars: $> 8M_\odot$

high mass $\rightarrow$ enormous gravity $\rightarrow$ high T in core

repeated cycles of:

- core nuclear fusion "burning" until fuel exhausted
- contraction, heating
- ash $\rightarrow$ new fuel

in this way:

helium $\rightarrow$ carbon $\rightarrow$ oxygen $\rightarrow$ magnesium $\rightarrow$ ... $\rightarrow$ iron

- energy released, maintains star stability, luminosity
- heavy elements produced up to iron
- burning hotter, faster $\rightarrow$ rapid lifespan
- but when core is iron, game over:
  no energy release in iron fusion
  iron core contracts to ultradense solid
  then becomes unstable to its own gravity $\rightarrow$ collapses

Supernova Explosions: Deaths of Massive Stars

iron core collapses, compressed until
center of star as dense as atomic nucleus

- core becomes hyperdense solid, collapse halts
- overlying layers fall (at 10%c!) onto core then "bounce" back
- launched at 10%$c > v_{\rm esc}$, ejected into space
- explosion seen: supernova!

`www: supernovae`

End results:

- gas ejected: contains newly-formed heavy elements
- explosion heats, stirs up interstellar gas
- leftover cinder: neutron star or black hole

iClicker Poll: Stellar Life Expectancy

Vote your conscience!

What's the connection between low/high mass star lifespans?

A high mass $\rightarrow$ more fuel $\rightarrow$ burn longer

B low mass $\rightarrow$ low luminosity $\rightarrow$ burn longer

C more fuel $\rightarrow$ more luminosity $\rightarrow$ same lifespans for all stars

Life Expectancies of Stars

recall "flashlight equation" – energy conservation & star lifetime
(battery) = (wattage) × (lifetime) $\rightarrow$ $E_{\rm fuel} = L\tau$
for stars:
- more mass → stronger gravity → much hotter burn: $L \propto M^4$

`www: star luminosity data`

so if $M = 2M_\odot$, then $L = 16L_\odot$!
- fuel is mass, so $E_{\rm fuel} \propto M$

$\Rightarrow$ together this means

$$\tau = \frac{E_{\rm fuel}}{L} \propto M^{-3} \quad (5)$$

$$= 10 \text{ billion years } \left(\frac{M_\odot}{M}\right)^3 \quad (6)$$

example: lifespan $\tau(2M_\odot) = \tau_\odot/8 = 1.25$ billion years

so if a bunch of stars are formed with a range of masses
Q: what happens?

trend:

high mass $M \leftrightarrow$ high wattage $L \leftrightarrow$ short lifespan τ

e.g., massive star lifespans = few million years

low $M \leftrightarrow$ low wattage $\leftrightarrow$ long life

e.g., low-mass star lifespans = many billions of years

if many stars born at once–as in a cluster–then
massive stars die first (explode)
then only lower-mass stars left

observed! young cluster have massive stars
old clusters do not