Astro 350
Lecture 14
Sept. 26, 2012

Announcements:

- **HW 4** available, due at start of class Friday
- no Discussion this week!

Before exam: nuclear reactions in stars

Q: how do we know the Sun is nuclear powered?

Q: what is the main result of nuclear reactions in the Sun today?

The Stars as Suns

We've proved that Sun is nuclear reactor
but we've seen the Sun is a typical star
  typical mass, typical luminosity
⇒ **all** stars run by thermonuclear fusion

The Night sky, the Universe lit up ultimately by nuclear power

iClicker Poll: Stellar Life Expectancy

Vote your conscience!

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

- A high mass → more fuel → burn longer
- B low mass → low luminosity → burn longer
- C more fuel → more luminosity → same lifespans for all stars

Life Expectancies of Stars

recall “flashlight equation” – energy conservation & star lifetime
(battery) = (wattage) × (lifetime) → $E_{\text{fuel}} = L\tau$
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 $E_{\text{fuel}} \propto M$

⇒ together this means

$$\begin{aligned} \tau &= \frac{E_{\text{fuel}}}{L} \propto M^{-3} \qquad (1) \\ &= \text{10 billion years} \left(\frac{M_\odot}{M}\right)^3 \qquad (2) \end{aligned}$$

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

Star Weight and Fate

the *lifespan* and *fate* of a star
is determined by its **mass** at birth
→ mass sets how much gravity star must fight against

Very Low-Mass Stars: "Immortal"
if $M < 0.8 M_{\odot}$, gravity weak → T low at core
these stars have low L and low temperature
→ nuke burning very slow
→ takes a long time to exhaust H fuel
H burning time (main seq lifetime) $>$ age of Universe
→ none have died yet–"live forever" (well, a very long time...)

Q: low-mass stars are interesting to cosmologists–why?

Brown Dwarfs as Dark Matter Candidates

low-mass stars have low L and low T
- *low luminosity* $L \rightarrow$ not much light produced
- *low temperature* $\rightarrow$ emission mostly in infrared, not visible

recall $L \propto M^4$: lower mass $\rightarrow$ much lower L
- $0.08 M_\odot < M < 0.5 M_\odot$: $L < 0.01\ L_\odot$ "red dwarfs"
- $M < 0.08 M_\odot$: $L < 0.0001\ L_\odot$ "brown dwarfs"

Brown dwarfs:
- have mass
- very low-luminosity = very dim, and only emit in IR
- compact stars don't block light when looking thru halo
- live "forever"

$\Rightarrow$ *brown dwarfs are excellent dark matter candidates!*

Q: how to test for them? ...we will return to this next week

All Good Things Must Come to an End

Recall star life cycle so far:
star life always a struggle against gravity

- stars born from gravitational collapse of cold gas clouds made mostly of hydrogen
- youth/middle age: H → He fusion in core
  energy/heat source keep stars pressurizes and stable
  longest phase in life of all stars

Q: but what happens when H in core is gone?

Helium Burning

Low mass stars burn so slowly, H fuel “never” exhausted
what if mass is higher (e.g., for stars like the Sun?)

Helium Burning–All Stars $> 0.8 M_\odot$
core loses heat → loses pressure → contracts due to gravity
but compression → $T\uparrow$: ignite nuke rxns with helium:

$$^4\text{He} + {}^4\text{He} + {}^4\text{He} \rightarrow \text{carbon} + \text{energy} \tag{3}$$

He ash → fuel to make C: cosmic recycling!

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

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

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

→ star core compresses to a giant, hot, compact solid
outer layers unstable, driven off

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

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

⇒ intermediate mass stars are major source of cosmic carbon
C and He-rich, H-depleted gas → next generation of stars

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

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

high mass → enormous gravity → high T in core

repeated cycles of:

- core nuclear fusion "burning" until fuel exhausted
- contraction, heating
- ash → new fuel

in this way:

helium → carbon → oxygen → magnesium → ... → iron

- energy released, maintains star stability, luminosity
- heavy elements produced up to iron
- burning hotter, faster → 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 → 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
  electrons crushed into protons making neutrons
- burst of neutrinos emitted
- overlying layers fall (at 10%c!) onto core
  then "bounce" back
- launched at 10%$c > v_{\rm esc}$, ejected into space
- explosion seen: supernova!
- 1987: neutrinos seen from nearest SN in 300 years!

`www: supernovae`
`www: SN 1987A`

The Legacy of Supernovae

Supernovae have a major impact on their environment

- gas ejected: contains newly-formed heavy elements
  high-mass stars major source of oxygen up to uranium

- explosion heats, stirs up interstellar gas

- leftover cinder: neutron star or black hole

Origin of the Elements: Nucleosynthesis

Stars are nuclear reactors during their lives
eject reaction products when die
⇒ *stars are element factories*

We will see:
the big bang also produces elements
but only the lightest two: H and He and a tiny amount of lithium
→ all heavier elements made in stars!

intermediate mass stars

- make most carbon, also helium
  the carbon your DNA came from planetary nebulae!

high-mass stars

- make oxygen, iron, & other heavy elements up to uranium
  the iron in your blood comes from supernova explosions!

Cosmologist Carl Sagan

> We are made of star-stuff.

Cosmologist Joni Mitchell

> We are stardust
> We are golden
> We are billion year old carbon

Supernovae[*] and Cosmology

Supernova explosions are excellent cosmological tools for a number of reasons

Q: why? what is advantageous/interesting about observing supernovae all across the universe?

Q: what would be challenging about observing supernovae?

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[*] Cosmo-grammar tip: one supernova, many supernovae (it's Latin, dude!)

Cosmology with Supernovae: Pros

supernovae are powerful, very luminous explosions
marking the deaths of massive stars
→ handy tools for cosmologists

★ supernovae are very luminous
can see from great distances–across the universe!
and since telescopes are time machines...
SN are beacons revealing much of cosmic history

★ supernovae come from massive stars
short-lived → require ongoing star formation
→ SN reveal presence and nature of star formation
at distant places and times

Cosmology with Supernovae: Cons

Supernova events are explosions of massive stars
- don't know ahead of time when a star will blow up
- explosion brightness temporary–dies off after a few months
- $< 1\%$ of stars are massive $\rightarrow$ few die this way
  only few each century in big galaxy like ours
  last observed SN in Milky Way was > 300 yrs ago

Practical challenges:
- ▷ have to monitor many galaxies
  to have good chance of finding a SN
- ▷ want to find peak brightness (flux) F_{peak}
  $\rightarrow$ have to observe each SN more than once
  as it flares up then dims