Astro 350
Lecture 17
February 28, 2022

Announcements:

- **Discussion 4 due Wednesday**
- **Homework 5 due Friday**
- Exam (and HW): grading elves at work

Before exam: stars and cosmology
having understood how the Sun shines
today we witness the life cycles of stars

Star Diversity and Mass

The main factor controlling a stars life is its **mass**

- determines size, temperature, luminosity, and lifespan
- determines the final fate of the star

stellar luminosities: (power, wattage, energy output)

- span huge range from $10^{-4} L_{\mathrm{Sun}}$ to $10^{6} L_{\mathrm{Sun}}$
- set by mass $L \propto M^3$: low (high) mass $\Rightarrow$ low (high) L

stellar lifespans

- lifetime τ is time to use up fuel: $E_{\mathrm{fuel}} = L\ \tau$
- but stars powered by fusion: mass is fuel! $E_{\mathrm{fuel}} \propto M$
- lifespan $\tau \propto E_{\mathrm{fuel}}/L \propto\ M^{-3}$
  low (high) mass $\Rightarrow$ long (short) lifespan
  if many stars born together: high M die first, low M remain

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* $L \to$ not much light produced
- *low temperature* $\to$ emission mostly in infrared, not visible

recall $L \propto M^4$: lower mass $\to$ 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:
a star's 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:

$$^{4}\text{He} + {}^{4}\text{He} + {}^{4}\text{He} \rightarrow \text{carbon} + \text{energy} \tag{1}$$

He ash → fuel to make C: cosmic recycling!

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

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

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”**
  ultra-dense, inert stellar cinder
  masses $(0.5 - 1.4)M_{\rm Sun}$, always $<$ 50% of initial star mass

- $>$ 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%$c > v_{\mathrm{esc}}$, 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
  around 90% of initial star mass
  high-mass stars major source of oxygen up to uranium

- explosion heats, stirs up interstellar gas

- leftover cinder: **neutron star or black hole**
  neutron stars: masses $(1.4 - 3) M_{\mathsf{Sun}}$
  black hole masses: we will see!

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

Finding Cosmic Supernovae

Massive star appearance (luminosity, temperature) doesn't change over last several 100,000 years of lifespan
→ cannot when massive stars will die in supernovae explosions

Observational Strategy:
- monitor many many galaxies
  → **survey** wide area of sky
- observe each every few days: repeatedly **scan**
- look for appearance, brightening, and disappearance of supernovae
- huge amounts of data → huge challenge to process

powerful computers and huge digital cameras make this possible
e.g., can digitally "subtract" before/after images
→ difference shows what's changed: SN
`www: SN search teams`

Supernovae Observed Across the Universe

Results thus far:

⋆ supernovae seen out to great distances → early times
star birth indeed occurred in the past, not just now!

⋆ in fact, birthrate *much* higher in the past!

⋆ also: SN as standard candles give very interesting result ...
will provide most direct evidence for bizarre dark energy!

Coming Soon: LSST!

Vera Rubin Telescope
location: Cerro Pachón, Chile
telescope: 8 meter diameter
camera: 3200 Megapixel
field of view: $10\,\mathrm{deg}^2 = 100\times$ full moon

dedicated to one project: **Legacy Survey of Space and Time(LSST)** scan mode: monitor $20,000\,\mathrm{deg}^2 =$ *entire southern sky*

about to begin! first light expected mid-2023!

Lineup of Dark Matter Suspects

~~hot gas~~

~~cold gas~~

black holes
neutron stars
white dwarfs
“failed stars” – “Jupiters,” brown dwarfs
} compact objects

neutrinos

relic particles from big bang

compact objects arising from star formation
are small → easy to miss
but Einstein taught us a way to find them!

Director’s Cut Extras

Anticipated LSST Results

Deep *maps* of the *unchanging* sky will show

- stars in Milky Way
- nearby and distant galaxies
- the large scale structure of the Universe
- surprises we have not anticipated

But scanning will reveal, for the first time
movies of the entire (southern) sky
→ we will see anything that changes over 10 year survey time

- comets & asteroids in solar system
- variable stars
- supernovae (and other explosions: novae, gamma-ray bursts, other?)
- surprises we have not anticipated

Predictions (Dr. Amy Lien, UIUC PhD & BDF):
▷ DES: about 5000 supernovae per year! out to 4000 Mpc!
▷ LSST: about 500,000 supernovae per year! to $>$ 4000 Mpc!