Astro 404
Lecture 31
Nov. 8, 2021

Announcements:

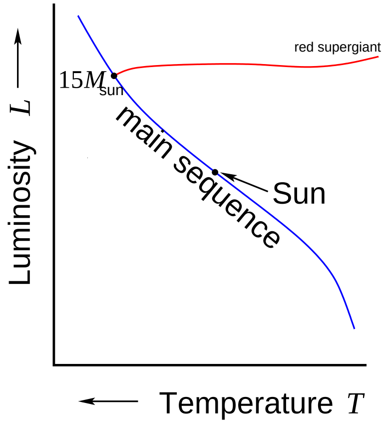
- **PS10 due Friday**
- **Exams Graded at last!** scores posted on Canvas
  solutions posted today

Last Time: core-collapse supernovae-prelude to explosions
Q: core-collapse progenitors: masses? lifetimes?
Q: main seq location HR diagram? evolution?
Q: nuclear burning phases? nucleosynthesis products?
Q: neutrino production–during which phases? Origin?
Q: evolution after main sequence? core structure?

massive stars: $8-10M_{\odot}$

"celebrities of the cosmos"

- live fast: high $T_{\mathrm{c}}, \rho_{\mathrm{c}}$
  $\rightarrow$ rapid nuclear burning
- die young:
  lifetimes $\sim few$ Myr
- we'll see: leave beautiful corpse



Massive Star Binarity

recall that most stars overall are in binaries

★ nearly 100% of massive stars are in binaries

★ often the binary companion is another massive star!

this fact will be important

after main sequence: repeated cycles of

- core contraction and ignition
- ash of last burning phase becomes fuel for next
- shell burning "remembers" earlier phases

develop "onion skin" structure: `www: pre-SN`

favors "α-elements" : tightly bound

$$\alpha = {}^{4}\text{He} = \boxed{2p\ 2n}$$

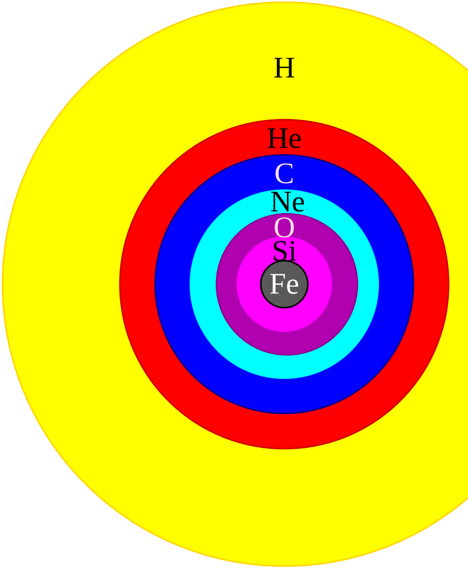
$${}^{12}\text{C} = \boxed{3\alpha}$$

$${}^{16}\text{O} = \boxed{4\alpha}$$

$${}^{20}\text{Ne} = \boxed{4\alpha}$$

$$\vdots$$

$${}^{40}\text{Ca} = \boxed{10\alpha}$$



Binding Energy Patterns

recall: binding energy B_i is
energy required to tear nucleus to protons and neutrons

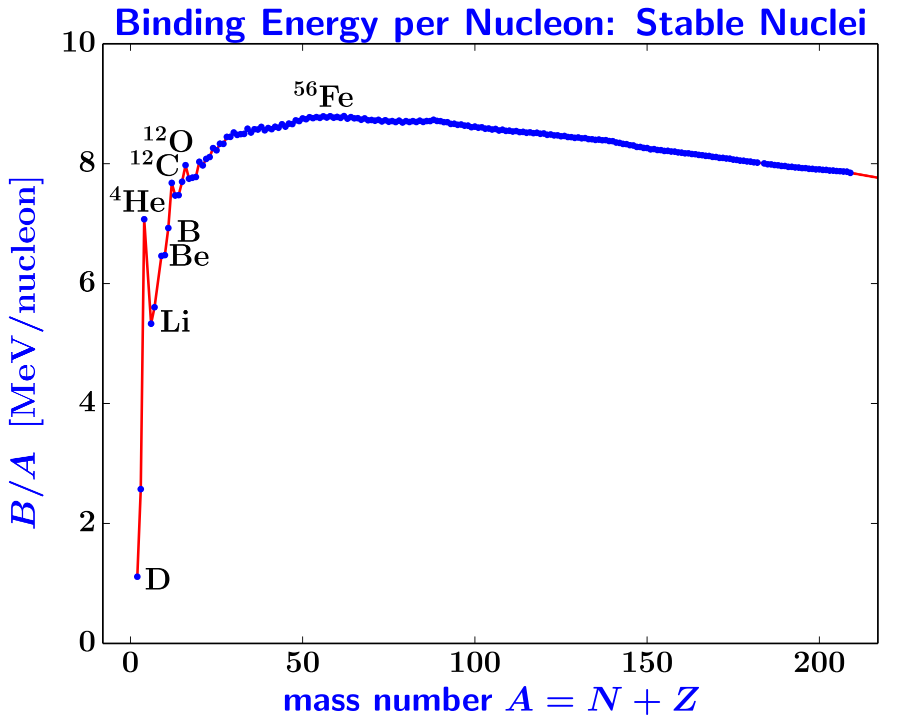
note that larger nuclei have large B_i,
but shared among more nucleons

consider: **binding energy per nucleon** B/A
Q: what does this represent physically?

Nuclear Stability: Binding Energy

For stable nuclei:

- sharp rise in B_i/A_i at low A
- local max at ^{4}He
- *no stable nuclei at $A = 5, 8$*
- lowest B/A for D, LiBeB
- *max B/A for middle masses:*
- **peak at** ^{56}Fe



Nuclear Equilibrium

nuclear reactions drive core to **equilibrium**
dominated by most stable nuclei possible
→ most tightly bound

max abundance → largest nuclear binding: “iron peak”

core dominated by iron and nickel

An now the end is imminent. *Q: why?*

Iron Core Evolution

can't burn Fe → degenerate core

support: e degeneracy pressure–core is iron white dwarf!

first time a massive star core is degenerate

stable briefly, but...

do burn Si in overlying shell

→ increase Fe core mass

Si burning lasts about 1 day, then

$M_{\text{core}} > M_{\text{Chandra}}$ → core unstable

$\searrow$ begins to collapse

Core Collapse

upon collapse: *iron core disintegrated by photons*
e.g., $^{56}\mathrm{Fe} \rightarrow 13\alpha + 4n$

huge density: electrons have high Fermi energy
→ favorable to get rid of them!

electrons capture onto protons $e^- + p \rightarrow n + \nu_e$
and onto nuclei $e^- + Z_A \rightarrow Z - 1_A + \nu_e$
"neutronization" or "deleptonization"

removes e and so reduces degeneracy pressure!

- accelerates collapse (positive feedback)
- also: releases ν_e

Collapse Dynamics

Freefall timescale for material with density ρ (PS4):

$$\tau_{\rm ff} \sim \frac{1}{\sqrt{G\rho}} \sim 446\ {\rm s}\sqrt{\frac{1\ {\rm g/cm^3}}{\rho_{\rm cgs}}} \lesssim 1\ {\rm sec}$$

but pre-supernova star very non-uniform density

Q: what does this mean for collapse?

inner core: homologous collapse $v \propto r$

outer core: quickly becomes supersonic $v > c_{\rm s}$

outer envelope: unaware of collapse

Q: what (if anything) stops collapse?

Bounce and Explosion

core collapses until $\rho_{\text{core}} > \rho_{\text{nuc}} \sim 3 \times 10^{14}\ \text{g/cm}^3$

repulsive sort-range nuclear force dominates: *"incompressible"*

details depend on equation of state of nuke matter

1. *core bounce* → proto neutron star born
2. *shock wave* launched
3. a miracle occurs
4. outer layers *accelerated*

   Demo: AstroBlaster™
5. successful *explosion* observed

   $\rightarrow v_{\text{ej}} \sim 15,000\ \text{km/s} \sim c/20!$

Why step 3? What's the miracle?

"prompt shock" fails:

do launch shock, but

- overlying layers infalling at high speed

→ violently collide with outgoing layers

- dissociate Fe → lose energy

outward shock motion stalls → "accretion shock"

"prompt explosion" mechanism fails

Q: how to revive explosion?

iClicker Poll: Supernova Neutrinos

We saw that the Sun is a confirmed source of neutrinos
in fact: a few percent of the Sun's luminosity (energy release)
is in neutrinos rather than light

Now consider a massive star, exploding as a supernova
and vote your conscience:

Which best describes a supernova's energy release?

A $< 1\%$ of energy released in neutrinos, $> 99\%$ in photons

B $\approx 50\%$ of energy released in neutrinos, $\approx 50\%$ in photons

C $> 99\%$ of energy released in neutrinos, $< 1\%$ in photons

Delayed Explosion Mechanisms

"delayed explosion" to revive:
neutrinos, 3-D hydro/instability, rotation effects?
some models do work, but controversial

Energetics:

$E_{\rm ejecta} \sim M_{\rm ej} v^2 \sim (10 M_\odot)(c/20)^2 \sim 10^{51}\ {\rm erg} \equiv 1\ {\rm foe}$

but must release gravitational binding energy

$$\begin{aligned} \Delta E &\sim -GM_\star^2/R_\star - (-GM_{\rm NS}^2/R_{\rm NS}) \\ &\simeq GM_{\rm NS}^2/R_{\rm NS} \sim 3 \times 10^{53}\ {\rm erg} = 300\ {\rm foe} \end{aligned}$$

Q: Where does the rest go?

⇒ SN calculations must be good to $\sim 1\%$
to see the minor optical fireworks

Supernova Neutrinos

two phases of neutrino emission during collapse and explosion:

1. **neutronization**
2. **thermal emission**

when electrons removed to make neutrons
neutronization neutrinos produced before collapse
emitted over < 1 sec, leave freely

during collapse: huge temperature $kT > m_e c^2$
thermal bath makes e^+e^- pairs
sometimes make thermal neutrinos $e^+e^- \rightarrow \nu\bar{\nu}$

Thermal Supernova Neutrinos

by far, thermal neutrinos have a larger luminosity
and larger energies than neutronization neutrinos
→ these are the bulk of the supernovae neutrino emission

thermal νs initially leave freely
but when proto-neutron-star formed
mean free path $\ell_\nu = 1/(n_{\rm nuc}\sigma_\nu)$
becomes small: $\ell_\nu \lesssim R_{\rm NS}$

Q: what happens to these thermal neutrinos?
Q: will they ever escape? if so, how?
Q: neutrino telescope time signature?

Supernova Neutrinos: Theory

when dense core has $\ell_\nu \lesssim R_{\rm NS}$: neutrinos trapped
proto-neutron star develops "neutrinosphere"
size set by radius where ~ 1 scattering to go: $r \sim \ell_\nu(r)$

inside r_ν: weak equilibrium → "neutrino star"

- both neutrinos and anti-neutrinos created
  for experts: all species $\nu_e, \nu_\mu, \nu_\tau \approx$ equally populated

neutrinos still leave, but must diffuse
emit neutrinos & energy (cool) over diffusion time
PS10: $\tau_{\rm diff} \sim few$ sec

Q: how to test this? how to find supernovae? where to look?
Q: how to identify progenitor (pre-explosion star)?

Supernovae Observed: Historical Supernovae

supernovae are rare:

- true rate: about $\sim$ 3/century in our Galaxy
- observed (naked-eye) rate: $\sim$ 0.5/century
  our Galaxy dims and obscures most supernovae!

Supernovae Discovery Strategy I:

look at written records in historical archives

try to match with known explosion remnants on sky

pro: get firsthand account!

con: ancient records often ambiguous
and no hope of learning about pre-supernova (progenitor) star

Supernova 1054

- July 4(!) 1054: event seen in Taurus
- no record in Europe, even though should have been visible
- “guest star” noted in Chinese astronomical records
- also possible hint in Anasazi (Pueblos) rock paintings
  `www: Anasazi drawing, Y1K`
- possible indications in artifacts from India
- Present-day: Crab Nebula (Messier 1)
  `www: present-day view: Y2K`
  one of the closest and best-studied supernova remnants!

Supernova 1572

reported extensively by Tycho Brahe: “Nova Stella” – new star

`www: sketch`

> On the 11th day of November in the evening after sunset ... I noticed that a new and unusual star, surpassing the other stars in brilliancy, was shining ... and since I had, from boyhood, known all the stars of the heavens perfectly, it was quite evident to me that there had never been any star in that place of the sky ...
>
> I was so astonished of this sight ... A miracle indeed, one that has never been previously seen before our time, in any age since the beginning of the world.
>
> – Tycho Brahe

Q: What did Tycho get right? Where was he wrong?

Tycho's Supernova

⋆ Tycho recorded brightness peaked after days
then visible for months

⋆ Searched for but did not find parallax
showed event had to be at a great distance
certainly beyond the Moon

⋆ dramatic challenge to Aristotelian/Ptolemaian worldview
celestial realm supposed to be perfect
and unchanging: "incorrubtible"
very different from "corruptible" terrestrial realm we live in
Tycho showed the heavens are changeable

`www: present-day Tycho image (X-ray)`

Extragalactic Supernovae

Supernova Detection Strategy II
since only a few per century per galaxy, *look at many galaxies!*
→ if monitor 100 Milky-Way-like galaxies,
expect to see $\sim few$ supernovae per year!

pro: much higher discovery rate
if know distance to galaxy, get distance to SN
can find events with little dust obscuration
can search for progenitor stars in archival images
con: don't know where or when a supernova will occur
must monitor many galaxies over a long time
farther away → less able to resolve details

this has been incredibly successful:
most of our SN knowhow comes from extragalactic events

`www: extragalactic supernovae`

Observed Supernovae: Properties and Correlations

spectra of supernovae after explosions show two classes

Type I: **hydrogen** totally or nearly *absent*
in spectrum and thus ejecta
subclasses: Type Ia: silicon present, iron-peak elements
Types Ib and Ic: helium and oxygen present

Type II: **hydrogen present** in spectrum and ejecta

Q: how could we understand this?

host galaxies show correlation with type

elliptical/early-type galaxies: no/little ongoing star formation
- only have Type Ia explosions
- no progenitors identified

spiral and irregular galaxies: star formation ongoing
- supernovae found in star-forming regions
- Types Ib, Ic, and II all found
- progenitors have masses $8 - 50 M_\odot$
- Type Ib and Ic progenitors:
  evidence of winds, Wolf-Rayet stars

Q: how could we understand this?

Supernova 1987A

Supernova Discovery Strategy III: get lucky!
very nearby event goes off in modern age

explosion: Feb 23, 1987, in Large Magellanic Cloud (LMC)
$d_{\mathrm{LMC}} \sim 50$ kpc – nearest (known) event in centuries
spectrum: shows hydrogen, thus Type II event → core collapse
pre-explosion images: progenitor $M \sim 18 - 20 M_\odot$
star was blue supergiant

explosion energy: baryonic ejecta have 1.4 ± 0.6 foe
compact remnant: no pulsar seen (yet) → a black hole instead?

ejecta: $M(\mathrm{O}) \sim 2M_\odot$ observed; $M(\mathrm{Fe}) = 0.7M_\odot$
also N, Ne, Mg, Ni; also molecules and dust formation

light echoes: outburst reflections off surrounding material
allow for 3-D reconstruction of pre-explosion environment!

SN1987A: Light Curve

light curve: luminosity L vs t

`www: 1987A bolometric (all-wavelength) light curve`

- initially, powered by thermal energy, then adiabatically cool

- after ~ 1 month: powered by ^{56}Ni decay:

$^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co}\ e^+\ \nu_e \rightarrow {}^{56}\mathrm{Fe}\ e^+\ \nu_e$ (PS6)

Q: how can you test that this is the power source?

- really: decay to excited state $^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co}^* \rightarrow {}^{56}\mathrm{Co}^{\mathrm{gs}} + \gamma$
  ^{56}Co de-excitation γs seen at 0.847 MeV and 1.238 MeV
  but: seen earlier than expected for onion-skin star
  Q: what does this mean?

SN 1987A Neutrino Signal

SN 1987A detected in neutrinos

first extrasolar (in fact, extragalactic!) νs

birth of neutrino astrophysics

Reliable detections: water Čerenkov

- Kamiokande, Japan
- IMB, Ohio, USA

observed $\sim$ 19 neutrinos (mostly $\bar{\nu}_e$) in 12 sec

`www: ‘‘neutrino curve’’`

detected $\sim few$ hrs before optical signal

Q: Why?

Q: what info–qualitative and quantitative–do the νs give?

Qualitatively

neutrino detection demonstrates basic correctness of core-collapse picture

Quantitatively

ν time spread: probes diffusion from protoneutron star

ν flux, energies: $\langle E_\nu \rangle^{\text{obs}} \sim 15$ MeV

$\Rightarrow$ -neutrino energy release $\mathcal{E}_{\bar{\nu}_e} \sim \mathcal{E}_\nu/6 \sim 8 \times 10^{52}$ erg

Q: why divide by 6?

$\Rightarrow$ $\mathcal{E}_\nu \sim 4 \times 10^{53}$ erg

$\Rightarrow$ observational confirmation:
by far, most ΔE released in νs

$\Rightarrow$ basic core collapse picture on firm ground!

Also: signal probes ν & particle physics

`www: 2002 Nobel Prize in Physics: Masatoshi Koshiba`

Nearby Supernovae: May We Have Another?

Today: ready for another SN!

for event at 10 kpc, Super-K will see ~ 5000 events
gravity waves?

candidates: Betelgeuse? Eta Carinae?

But don't get too close!

- minimum safe distance: ~ 8 pc
  Q: why would this ruin your whole day?
  Q: should we alert Homeland Security today?

Core-Collapse Nucleosynthesis

recall: hard/impossible for simulations
to make make imploding supernova explode

but we still want to know what nucleosynthesis to expect

ideally: have one self-consistent model
- pre-supernovae evolution
- detailed explosion
- ejected material gives nuke yields

Q: in practice, how can we proceed?
Q: how to calibrate the "cheat"?
Q: which results/elements most likely reliable?
Q: which results/elements most uncertain?

Supernovas Nucleosynthesis–As Best We Can

real supernovae do explode:

- most ($\gtrsim$ 90%) material ejected
- compact remnant (neutron star, black hole) left behind

nucleosynthesis simulation strategy:
pick ejecta/remnant division: “**mass cut**”
force ejection of region outside cut
  either inject energy (“thermal bomb”)
  or momentum (“piston”)
  or extra neutrinos (“neutrino bomb”)

calibrate: demand blast with $E_{\text{kin}} \sim 1$ foe
  and ejected iron-peak match SN observation
still: uncertain! → particularly in yields of heaviest elements

Explosive Nucleosynthesis

as shock passes thru pre-SN shells

compress, heat: explosive nucleosynthesis

burning occurs if mean reaction time $\tau_{\text{nuke}} > \tau_{\text{hydro}}$

similar processes, products as before, but also freezeout behavior

- largest effects on inner shells/heaviest elements
- little change in outer shells

resulting ejecta:

dominated by α-**elements** ^{12}C, ^{16}O, ..., ^{44}Ca

and iron-peak elements

Cosmic Core-Collapse Supernovae

supernovae are rare: MW rate $r_{\rm SN} \sim (1-3)$/century
but the universe is big: $N_{\rm gal} \sim 4\pi/3\ d_H^3 n_* \sim 10^9$ observable
bright ($L_* \sim L_{\rm MW}$) galaxies out to horizon

so: all-sky supernova rate inside horizon $\Gamma_{\rm SN} \sim 1$ event/sec!
more careful estimate: closer to $\Gamma_{\rm SN} \simeq 10$ events/sec!
Q: what makes the careful estimate higher?

These events are all neutrino sources!
if $\mathcal{E}_{\nu,\rm tot} \sim 300$ foe & mean neutrino energy $\langle\epsilon\rangle_\nu \sim 3T_\nu \sim 15$ MeV
then *per species* $\mathcal{N}_\nu \sim 2 \times 10^{57}$ neutrinos emerge
gives all-sky neutrino flux per species

$$F_\nu^{\rm DSNB} \sim \frac{\Gamma_{\rm SN}\mathcal{N}_\nu}{4\pi d_H^2} \sim 3 \text{ neutrinos cm}^{-2}\text{ s}^{-1} \tag{1}$$

Q: how does this compare to solar neutrinos?
Q: how to detect it? what if we don't? what if we do?

Diffuse Supernova Neutrino Background

cosmic core-collapse SNe create diffuse neutrino background
isotropic flux in all species (flavors and antiparticles)

at energies $E_\nu \lesssim 10$ MeV, lost:
- for regular ν_e, ν_μ, ν_τ signal swamped by solar νs
- even for $\bar{\nu}$, backgrounds too high (radioactivity, reactors)

Detection Strategy:
look for $\bar{\nu}_e$ at 10–30 MeV
- SN signal dominates sources & background in this window
- detect via $\bar{\nu}_e p \rightarrow n e^+$: KamLAND

Not seen so far:
- signal within factor ~ 2 of limits → should show up soon!
- *non*-detection sets limit on
  "invisible" SN which make only ν and BH!
- *detected* background will *measure* invisible SN rate!