Astro 596/496 NPA
Lecture 31
April 15, 2019

Announcements:

- **Preflight 6 due Friday** last preflight!
  group discussion question 6(b): either the two options will do

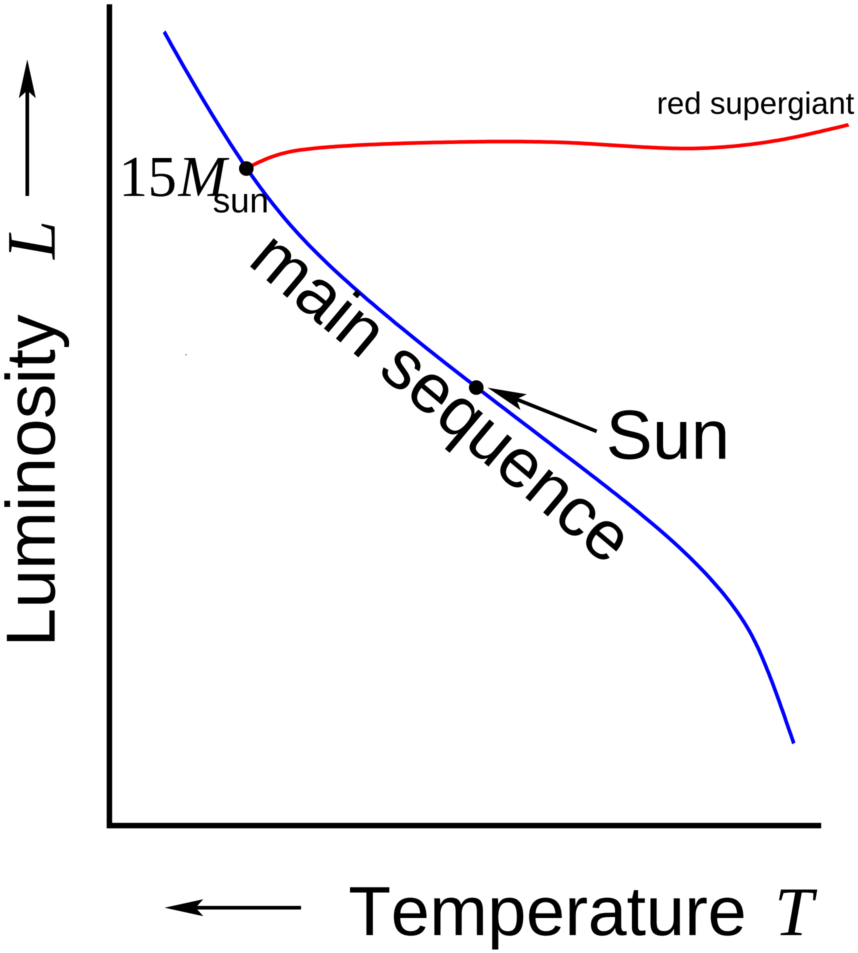
Last Time: core-collapse supernovae-prelude to explosions

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?


red supergiant
$15M_{\text{sun}}$
main sequence
Sun
Luminosity L
Temperature T

Collapse Dynamics

Freefall timescale for material with density ρ (PS6):

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

but pre-supernova star very non-uniform density

Q: what does this mean for collapse?

inner core: homologous collapse $v \propto r$

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

outer envelope: unaware of collapse

Bounce and Explosion

core collapses until $\rho_{\rm core} > \rho_{\rm nuc} \sim 3 \times 10^{14}$ 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$^{\rm TM}$
5. successful *explosion* observed
   $\rightarrow v_{\rm ej} \sim 15,000$ km/s $\sim c/20$!

Why step 3? What's the miracle?
"prompt shock" fails:
do launch shock, but
- overlying layers infalling

→ ram pressure $P = \rho v_{\mathrm{in}}^2$
- dissociate Fe → lose energy

shock motion stalls → "accretion shock"
"prompt explosion" mechanism fails

Q: what needed to revive explosion?

Delayed Explosion Mechanisms

"delayed explosion" to revive:
neutrinos, 3-D hydro/instability, rotation effects?
some models not work, but controversial

Energetics:
$E_{\rm ejecta} \sim M_{\rm ej} v^2 \sim (10 M_\odot)(c/20)^2 \sim 10^{51}\ {\rm erg} \equiv 1\ {\rm Bethe} = 1\ {\rm foe}$
but must relase grav binding

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

Q: Where does the rest go?
$\Rightarrow$ 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**

neutronization neutrinos produced before collapse
emitted over < 1 sec, leave freely

during collapse: thermal νs still produced, initially leave freely
but core → nuke density:
- very high $T \sim 4 - 8$ MeV $\sim 10^{10}$ K
- very high $n_\nu \sim T^3$

neutrino mean free path $\ell_\nu = 1/(n_{\rm nuc}\sigma_\nu)$ becomes small
i.e.: $\ell_\nu \lesssim R_{\rm NS}$

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

Supernova Neutrinos

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”

- all species ν_e, ν_μ, ν_τ and $\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau \approx$ equally populated
- ν_e have extra charged-current interactions
  slightly different T_ν and r_ν

neutrinos still leave, but must diffuse
emit neutrinos & energy (cool) over diffusion time
$\tau_{\rm diff} = 3r^2/\ell_\nu \sim 10$ s

Q: how to test this?

Supernova 1987A

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

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

ejecta: $M(\text{O}) \sim 2 M_\odot$ observed; $M(\text{Fe}) = 0.7 M_\odot$
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:

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

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

- really: decay to excited state $^{56}\text{Ni} \rightarrow {}^{56}\text{Co}^{*} \rightarrow {}^{56}\text{Co}^{\text{gs}} + \gamma$
  ^{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 achieve baryonic explosion

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 $\tau_{\mathrm{nuke}} > \tau_{\mathrm{hydro}}$

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

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

These events are all neutrino sources!
if $\mathcal{E}_{\nu,\mathrm{tot}} \sim 300$ 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

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

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!