Astro 404
Lecture 34
Nov. 15, 2019

Announcements:

- **Problem Set 10 due today**
- **Problem Set 11 (penultimate!) due Fri 22**
- **No class meeting Friday Nov 22**

Last Time:

core-collapse supernovae: observations

*Q: types based on spectra?*

*Q: correlation with host galaxies?*

*Q: lessons for supernova origin?*

SN 1987A

*Q: why was this special? crown jewel?*

*Type I:* **hydrogen** totally or nearly *absent*

subclasses: Type Ia: silicon present, iron-peak elements

Types Ib and Ic: helium and oxygen present

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

*elliptical/early-type galaxies*: no/little ongoing star formation

- only have Type Ia explosions
- no progenitors seen to date–they must be faint!?!

*spiral and irregular galaxies*: star formation ongoing

- Type II are most numerous, Types Ib, Ic also found

**Supernovae have two distinct physical origins**

**massive stars explode** as Type II, Ib, Ic events

**white dwarfs explode** as Type Ia events

# Supernova 1987A

**explosion:** Feb 23, 1987, in Large Magellanic Cloud (LMC)
$d_{\rm LMC} \sim 50$ kpc – nearest (known) event in centuries

**spectrum:** shows hydrogen, thus Type II event → core collapse

**pre-explosion images**: $M \sim 18 - 20 M_\odot$ blue supergiant

**explosion energy**: baryonic ejecta have $1.4 \pm 0.6$ foe

**compact remnant:** no pulsar seen (yet) → a black hole instead?

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

## SN 1987A detected in neutrinos

first extrasolar (in fact, extragalactic!) $\nu$s

birth of neutrino astrophysics

demonstrates basic correctness of core-collapse picture

# Supernova Element Production

**supernovae are element factories**

massive stars make of the most abundant heavy elements
particularly the most tightly bound/stable

- some created during life of star
- but explosion partially or totally destroys nuclei near core
  compresses and heats them, then reassemble
  → ejected iron is entirely made in explosion!

supernova ejecta mix with interstellar matter
seeding it with heavy elements

- oxygen, magnesium, silicon, sulfur, calcium
- iron peak: iron, cobalt, nickel
- possibly: some of heaviest elements (up to uranium)

`www: supernova nucleosynthesis summarized`

*Q: how to test this?*

# Supernova Remnants and Nucleosynthesis

supernova explosions launch *blast wave*

- outer edge encounters interstellar matter
  sweeps up, compresses, heats
- interior hot, low density
- lasts for 100,000 yr, sometimes longer

hot bubble with thick shell: supernova remnant

young supernova remnants: X-ray emitters
old supernova remnants: glow from shocked atoms
spectra reveal heavy elements
`www: supernova remnants and element maps`

in some very young remnants: evidence for $^{44}\mathrm{Ti}$
*unstable–radioactive* half-life $t_{1/2}(^{44}\mathrm{Ti}) = 59$ yr
*Q: lesson?*

# Supernova Radioactivity

young supernova remnants show radioactive $^{44}$Ti
*decays exponentially* on timescale $t_{1/2}(^{44}\mathrm{Ti}) = 59$ yr
much shorter than lifetime of progenitor star!
cannot pre-date star! must have been made in it!

*direct proof of element synthesis in stars!*

in blizzard of nuclear reactions in massive stars
most nuclei produced are stable – and are us!
but many radioactive nuclei made, with wide range of half-lives
up to millions of years

we can see them if they emit photons ($\gamma$ decay)
example: $^{26}\mathrm{Al} \xrightarrow{0.7\ \mathrm{Myr}} {}^{26}\mathrm{Mg} + \gamma$
`www:` $^{26}$Al `sky map`

# Nucleosynthesis: Summary

cosmic production of elements combines all events and sources
where nuclear reactions occur
and the results are ejected into space

element origins: the story thus far:

- *intermediate-mass stars:* $0.9 M_\odot \lesssim M \lesssim 8 M_\odot$
  sources of carbon (C)
  ejected in planetary nebulae
- *high mass stars*: $M \gtrsim 8 M_\odot$
  sources of O, Si, Fe …
  ejected in supernova explosions

`www: circle of life cartoon`

**we are made of star-stuff** –Carl Sagan

# Nearby Supernovae: May We Have Another?

Today: ready for another SN!

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

candidates: Betelgeuse? Eta Carinae?

But don't get too close!
minimum safe distance: $\sim$ 8 pc
*Q: why would this ruin your whole day?*
*Q: should we alert Homeland Security today?*

# Supernova Threat

explosion produces *high-energy photons:*
extreme UV, X-ray, $\gamma$-rays
*ionizing radiation* – can tear apart atoms

we on Earth's surface: shielded by atmosphere
but: ionizing photons alter atmospheric chemistry
tears apart $N_2$ → highly reactive → destroys ozone $O_3$

this is bad.
no stratospheric ozone: UV from Sun unfiltered
you and I: wear hats and sunblock SPF 2000
species at bottom of food chain: no escape!
damage propagates up: could trigger biological mass extinction!

*Q: how can we identify a nearby supernova in the distant past?*

# Nearby Supernova Detection: Live Radioactivity

if supernova exploded in distant past
evidence on sky may be gone
have to look on Earth

if explosion near enough: blast wave engulfs the Earth
supernova debris literally rains on our heads
signature: newly-produced supernovae elements
- stable: *can't distinguish from terrestrial matter*
- live (not decayed) radioactivity: none found on Earth!
  if half-life less than Earth age: cosmic "green bananas" (unripe)

radioactive $^{60}$Fe found on Earth! half-life $t_{1/2} = 2.6$ Myr
- in deep ocean, in Antarctic snow, and on Moon too!
- signal 2–3 Myr ago
- a near miss!
- no mass extinction, but possible extinctions under investigation

# Supernova Discovery: The Future

SN1987A neutrinos pioneered **multimessenger astronomy:**
collecting signals from all fundamental forces

messenger: *neutrinos*
emitted from neutrinosphere → probe proto-neutron star

messenger: *gravitational radiation*
spoiler alert–ripples in space, propagate at $c$
created by rapid aspherical motions of large masses
should arise in collapse, escape immediately

messenger: *photons*
arise from photosphere once blast wave arrives there

# iClicke Poll: Messenger Choreography

a supernova explodes nearby, with little dust obscuration

In what order do we see the messengers?

given from first to last

A neutrinos, gravitational radiation, photons

B gravitational radiation, neutrinos, photons

C gravitational radiation, photons, neutrinos

D gravitational radiation and neutrinos tied, then photons

# Supernova Search Engines

modern telescopes (so far!) have *tiny* fields of view!
Hubble: single image $\sim 1$ arcmin $\times$ 1 arcmin $\sim 10^{-7}$ sky
priority has been to deeply study small regions of sky

But a revolution is coming...

**Large Synoptic Survey Telescope** `www: LSST`

- site: Cerro Pachón ridge, Andes mountains, Chile
- primary mirror diameter $D = 8.4$ m: large but not unusual
- field of view 10 $\text{deg}^2$ **enormous!**
  requires 3.2 Gigapixel camera!
  first telescope to have such a large field of view
- Illinois is LSST member; Astronomy, Physics, NCSA involved

*Q: why is such a large field of view useful? what does this allow?*

# Coming Soon–Cosmic Movie & Wallpaper

thanks to large field of view
LSST can **scan entire night sky** in a few days!
and then **repeat** this scan for ≈ 10 years

result: ≈ 1000 deep digital images of *every point* on the southern celestial sphere, spanning 10 years!

Strategy: *compare* images of *same* region

- some things won't show any change *Q: like?*
  *add* exposures to get *very* deep images
  "The Sky: The Wallpaper"
- other things *will* show change! *Q: like?*
  *subtract* exposures to find & monitor changes
  → reveal celestial variability over timescales ∼hours to years
  "The Sky: The Movie"
  ⇒ this has never been done on such a huge scale!

# LSST and Supernovae

*every year*, LSST expected to see:

- $\sim 300,000$ core-collapse supernovae!
  more than all discoveries in recorded history
  from 185 AD to present day
- nearly all supernovae in local Universe
- distant events out to $z > 1$

over 10-year LSST lifetime: *millions of supernovae!*
unusual events will still be numerous
and surprises likely!

opportunities for clever ideas on supernova discovery
classification, and science questions
see Director's Cut Extras for one idea

# The Central Object

in core-collapse supernovæ:
*most of progenitor mass ejected in wind or explosion*

but what about the central object – the star's core

*Q: properties before and during collapse?*

*Q: properties after collapse?*

*Q: what if pre-collpase star was rotating? spoiler–it was!*

*Q: what if pre-collapse star was magnetized?*

# The Ultra-Compact Remains

massive star collapse begins when iron core mass $> M_{\text{Chandra}}$
collpase accelerated during neutronization: $e^- + p \rightarrow \nu_e + n$
finally halted when core → degenerate

result: star core is degenerate gas of neutrons

Baade & Zwicky (1934 PNAS 5, 259):

> With all reserve we advance the view that a super-nova represents the transition of an ordinary star into a neutron star, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density. As neutrons can be packed much more closely than ordinary nuclei and electrons, the gravitational packing energy in a cold neutron star may become very large, and, under certain circumstances, may far exceed the ordinary nuclear packing fractions. A neutron star would therefore represent the most stable configuration of matter as such.

*Note: the neutron was only discovered by Chadwick in 1932!*

# Interlude: Pulsar Discovery

neutron stars studied from 1930's onward
but viewed as theoretical curiosity

even if they existed, too small to ever observe
since $L = 4\pi R^2 \sigma T^4$

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1968: Antony Hewish radio astronomy group in Cambridge UK
graduate student Jocelyn Bell [Burnell] notices variable radio sources

- pointlike, pulsing with regular periods $P \sim 1$ sec
- extraterrestrial, but no obvious counterparts for first discoveries

cosmic lighthouses! aliens? joking name LGM = little green men
named pulsars: pulsating stars

# Pulsars and Spin

now thousands of radio pulsars found
periods down to $P \sim 1\ \text{ms} = 10^{-3}\ \text{sec}$
`www: radio pulses sonified`

imagine pulsars are *spinning stars*
a challenge to remain stable with these spin periods

if mass $M$ and radius $R$
**escape speed** at surface: set by energy conservation

$$\frac{1}{2}mv_{\text{esc}}^2 - \frac{GMm}{R} = \frac{1}{2}mv_\infty^2 = 0 \tag{1}$$

$$v_{\text{esc}}^2 = \frac{GM}{R} \tag{2}$$

at equator, rotation speed $v_{\text{rot}} = \omega R = 2\pi R/P$

*Q: condition for stability?*

escape speed:

$$v_{\text{esc}}^2 = \frac{GM}{R} \tag{3}$$

equatorial rotation speed:

$$v_{\text{rot}} = \frac{2\pi R}{P} \tag{4}$$

stability: $v_{\text{esc}} < v_{\text{rot}}$:

$$\begin{aligned} \frac{GM}{R} &> \frac{4\pi^2 R^2}{P^2} \quad (5) \\ \frac{GM}{R^3} \sim G\rho_{\text{avg}} &> \frac{4\pi^2}{P^2} \quad (6) \\ \rho_{\text{avg}} &> \frac{3\pi}{GP^2} \sim 10^{14}\ \text{g/cm}^3 \quad (7) \end{aligned}$$

huge density! near that of nuclei!

Bell and Hewish suggest *pulsars are spinning neutron stars*
1974: Antony Hewish wins Nobel Prize for Physics

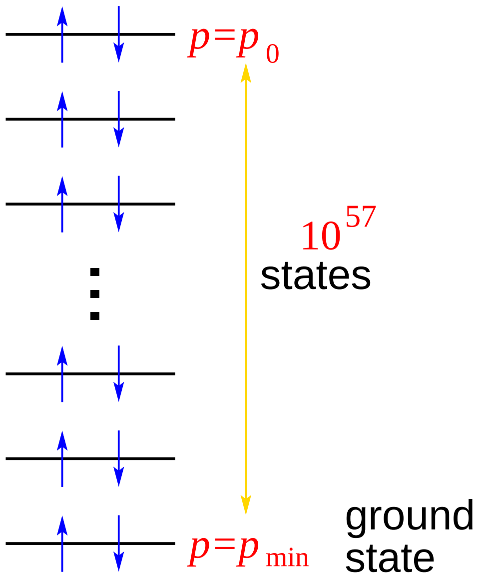
# Neutron Stars: Theory

consider *degenerate star made of neutrons*
closely related to white dwarfs: degenerate electron star

recall how degeneracy works:
Pauli: no two identical Fermions in same quantum state
Heisenberg: $\Delta x \ \Delta p \geq \hbar/2$,
so confinement to small region $\Delta x$
means high momentum $\Delta p$ and energy

Taken together:
a star made of identical Fermions
confined to stellar radius $R$
forms quantum states, max 2 per level: ↑↓

- the more particles added...
- the higher the last filled level
  the Fermi level, with Fermi momentum $p_0$



# Director’s Cut Extras

# 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
- compute all nuclear reactions and element production
- ejected material gives nucleosynthesis 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 $E_{\rm kin} \sim 1$ 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 $\tau_{\mathrm{nuke}} > \tau_{\mathrm{hydro}}$

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

resulting ejecta:
dominated by **$\alpha$-elements** $^{12}$C, $^{16}$O, ..., $^{44}$Ca
and iron-peak elements

# Cosmic Core-Collapse Supernovae

supernovae are rare: MW rate $r_{\mathrm{SN}} \sim (1-3)/\mathrm{century}$
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

$$F_\nu^{\mathrm{DSNB}} \sim \frac{\Gamma_{\mathrm{SN}} \mathcal{N}_\nu}{4\pi d_H^2} \sim 3 \text{ neutrinos cm}^{-2}\ \mathrm{s}^{-1} \tag{8}$$

*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 $\nu_e, \nu_\mu, \nu_\tau$ signal swamped by solar $\nu$s
- 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 $\sim 2$ of limits → should show up soon!
- *non*-detection sets limit on
  "invisible" SN which make only $\nu$ and BH!
- *detected* background will *measure* invisible SN rate!