Astro 404

Lecture 32

Nov. 10, 2021

Announcements:

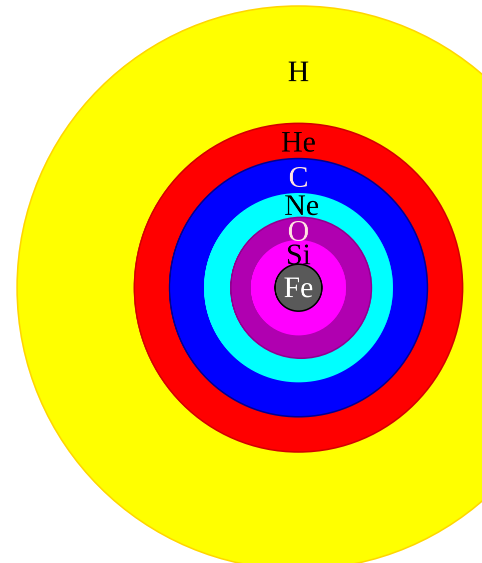
- **PS10 due Friday**
- Office hours:
  Instructor – today 10:50 to noon, or by appointment
  TA: Thursday 2:30–3:30pm

Last Time: deaths of massive stars
core collapse and supernova explosions!
a lot happens in a short time!
important to keep in mind the essentials

Q: key events after pre-collapse formation of iron core?
Q: what remains after the explosion?

Massive stars $\gtrsim 8 M_\odot$ evolve to form

- *iron core*: inert–a *white dwarf!*
  surrounded by burning shells
  in "onion skin" structure
- Si burning shell adds to iron core mass
  until $M_{\text{core}} > M_{\text{Chandra}}$: **core collapses!**
  star implodes
- during collapse, core converted to neutrons
- collapse halts when neutron core is dengenerate
  birth of hyperdense **proto neutron star**
  large production of neutrinos
- overlying layers "bounce" on core
  imposion becomes explosion
- with help of neutrinos, **most of star ejected**
  at intial speeds up to $v \sim c/20$!



Q: questions? how to test?

Supernovae Observed: Historical Supernovae

supernovae are rare:

- true rate: about $\sim 3/\text{century}$ in our Galaxy
- observed (naked-eye) rate: $\sim 0.5/\text{century}$
  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)`

Supernova Warning: Theory vs Observation

How can we know a massive star will explode? Does it give a warning?

Theory

stellar models have long predicted:
after core helium burning, stellar envelope decoupled from core in red supergiant phase, lasting $> 100,000$ years
unchanged during all of the late phases of evolution
implying: *no (optical) warning by looking at star!*

Supernova Warning: Observation

Observations

- *some* SN ("Type IIn") surrounded by thick shells of gas close to star – ejected a few years before explosion
- some stars have luminous outbursts that look like supernovae but a star remains afterwards, such as Eta Carinae

implying: likely some stars **do** give a warning!

- Great Dimming of Betelgeuse

  Betelgeuse in 2019 dimmed dramatically–an omen?

  `www: Great Dimming`

∞ *Q: other ways to know a SN will happen?*

Core-Collapse Supernova Warning: Neutrinos

all core-collapse explosions lead to
a huge burst of **neutrino radiation**

with current neutrino detectors, the neutrino flux from a core-collapse supernova would be

- strongly detected from anywhere in our Milky Way Galaxy
  the burst will be huge! Can even tell direction!
- weakly detected in our next nearest galaxy M31 (Andromeda)
  only a few events seen–confirms neutrino emission, but not details

This provides a guaranteed warning!
and a notification system has been set up:
the Supernova Early Warning System `www: SNEWS`

Extragalactic Supernovae

Supernova Detection Strategy II

since only a few per century per galaxy, *look at many galaxies!*
$\rightarrow$ 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 $\rightarrow$ 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?

iClicker Poll: Extragalactic Supernova Expectations

All responses count! But go for bragging rights.

In which galaxies should we find core-collapse supernova explosions?

A galaxies with ongoing star formation (spiral, irregular)

B galaxies with little/no ongoing star formation (elliptical)

C both (a) and (b)

D none of the above

host galaxies show correlation with type

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

- supernovae found in star-forming regions
- Type II are most numerous, Types Ib, Ic also found
- progenitors discovered, with masses $8 - 50 M_\odot$
- Type Ib and Ic progenitors:
  evidence of winds, Wolf-Rayet stars
  as expected–explains lack of hydrogen in spectrum

Q: how could we understand these trends?

Supernovae Have Two Distinct Physical Origins

massive stars explode as Type II, Ib, Ic events
as expected, progenitors have high mass
consistent with expectations of our basic theory
of advanced burning followed by core collapse
core-collapse supernovae

but this picture can't explain the Type Ia events
in galaxies without star formation $\rightarrow$ no massive stars!
stellar populations are old, long-lived
and so we are forced to conclude...

some long-lived stars explode as Type Ia events
origin must be low/intermediate mass stars
but these have hydrogen while main sequence and giants
$\rightarrow$ suggests *exploding white dwarf!* somehow exceeds M_{chandra}
requires a binary partner. stay tuned...

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)
$d_{\rm LMC} \sim 50$ kpc – nearest (known) event in centuries
spectrum: shows hydrogen, thus Type II event $\rightarrow$ core collapse
pre-explosion images: $M \sim 18 - 20 M_{\odot}$ blue supergiant
explosion energy: baryonic ejecta have 1.4 ± 0.6 foe
compact remnant: no pulsar seen (yet) $\rightarrow$ a black hole instead?
ejecta: $M({\rm O}) \sim 2 M_{\odot}$ observed; $M({\rm Fe}) = 0.7 M_{\odot}$
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:

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

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 ~ 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`

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
  $\rightarrow$ 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 $^{44}\mathrm{Ti}$
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 (γ decay)
example: $^{26}\mathrm{Al} \xrightarrow{0.7\ \mathrm{Myr}} {}^{26}\mathrm{Mg} + \gamma$
p `www:` ^{26}Al `sky map`

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, γ-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 $\rightarrow$ highly reactive $\rightarrow$ 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" (un-ripe)

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

supernova discovery pioneered **multimessenger astronomy:** collecting signals from all fundamental forces

messenger: *neutrinos*
emitted from neutrinosphere $\rightarrow$ 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 ~ 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 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
  $\rightarrow$ reveal celestial variability over timescales $\sim$hours to years
  "The Sky: The Movie"
  $\Rightarrow$ 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

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! $\rightarrow$ 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 $\tau_{\rm nuke} > \tau_{\rm hydro}$

- 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 $\bar{\nu}_e p \to n e^+$: KamLAND

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