Astro 404

Lecture 33

Nov. 12, 2021

Announcements:

- **PS10 due today**
- **PS11 due next Friday**

Last time:

- deaths of massive stars in supernova explosions
- supernova explosions observed historically in our Galaxy
- supernova explosions observed now in other galaxies
- supernovae classified into different *types* based on *patterns of elements observed in their spectra*

Extragalactic Supernovae: Expectations

supernovae reach enormous luminosities
allows supernova discovery in other galaxies
out to cosmological distances

- allows many supernova observations despite low rate per galaxy
- provides data to guide and test supernova theories
- allows supernovae to be probes of cosmology

supernova observations:
star-forming vs non-star-forming galaxies

expectation: massive stars have short lifespans

- so they die in or near the star-forming regions of their birth
- thus: should *only see core-collapse explosions in galaxies with ongoing star formation* and in the star-forming regions of these galaxies

Q: how does this prediction compare to observations?

Extragalactic Supernovae: Observations

observations supernovae observed in **all** galaxy types!

- found in star-forming galaxies: spiral and irregular types
  in agreement with predictions for core-collapse explosions (yay!)

- but **not** always in star-forming regions of spirals

- also found in non-star-forming galaxies: ellipticals !?

`www: examples`

ω Conclude: Something is missing in our predictions!

Observed Supernovae: Properties and Correlations

spectra of supernovae show two classes
based on elements observed in the supernova aftermath
this is the material ejected in the explosion: **"ejecta"**

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

Supernova Types Correlated with Galaxy Types

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

- only have Type Ia explosions
- no progenitor stars seen before explosions–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 stars 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: $M(\mathrm{O}) \sim 2 M_\odot$ observed; $M(\mathrm{Fe}) = 0.7 M_\odot$
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 versus time: L vs t

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

• initially, powered by thermal energy, then adiabatically cool

• after ~ 1 month: powered by decay of ^{56}Ni:
radioactive ^{56}Ni made during the explosion
then decays $^{56}\text{Ni} \rightarrow {}^{56}\text{Co}\ e^+\ \nu_e \rightarrow {}^{56}\text{Fe}\ e^+\ \nu_e$
neutrinos escape, but the rest of the decay energy remains

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

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: $\langle E_\nu \rangle^{\rm obs} \sim 15$ 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}Ti
decays exponentially on timescale $t_{1/2}(^{44}\text{Ti}) = 59$ 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: $^{26}\text{Al} \xrightarrow{0.7\ \text{Myr}} {}^{26}\text{Mg} + \gamma$
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 $<$ 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!
- two pulses: one 2–3 Myr ago, another 7 Myr ago
- two nearby supernovae! very close–near misses!
- no mass extinction, but possible extinctions under investigation

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 $E_{\mathrm{kin}} \sim 1$ 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 $\tau_{\mathrm{nuke}} > \tau_{\mathrm{hydro}}$

- 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 $r_{\rm SN} \sim (1-3)$/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

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

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 $\rightarrow$ should show up soon!
- *non*-detection sets limit on
  "invisible" SN which make only ν and BH!
- *detected* background will *measure* invisible SN rate!