Astro 596/496 NPA
Lecture 32
April 17, 2019

Announcements:

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

Last Time: core-collapse explosions

Today:

- the next Galactic supernova
- core-collapse supernova nucleosynthesis
- Gamma-Ray Bursts: a detective story

Nearby Supernovae: May We Have Another?

Today: ready for another SN!

for a core-collapse SN at 10 kpc:

- $\sim 1000 - 6000$ neutrino events in largest detectors
  Super-K, DUNE, JUNO
- gravitational waves likely emitted, target for LIGO-Virgo
  Q: what is needed for gravity wave emission?

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

theory: predicts *nucleosynthesis yields in ejecta and winds*

simulations only starting to achieve baryonic explosions

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 impatiently 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 ($\gtrsim 90\%$) of star's massn ejected
- compact remnant (proto-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! $\rightarrow$ 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 $\tau_{\rm nuke} > \tau_{\rm hydro}$

similar processes, products as before, but also freezeout behavior
- largest effects on inner shells/heaviest elements
- little change in outer shells

Q: net result–dominant supernova products?

Core Collapse Nucleosynthesis: Theory vs Observation

Theory: predicted ejecta dominated by

- **α-elements** ^{12}C, ^{16}O, ..., ^{44}Ca
  made by assembling the ^{4}He from hydrogen burning
  and favored by tight binding
- and iron-peak elements from *nuclear statistical equilibrium*

Observations

- individual supernova remnants confirm these basic patterns!
- can also see integrated effects of all Galactic supernovae
  Q: how?

`www: Solar System Abundances`

Where do we stand in the big picture?

Gamma-Ray Bursts

Gamma-Ray Bursts: Discovery

historical context: in late 1960's: *Cold War*
Nuclear Test Ban treaty–no explosions in atmosphere or space
US military: *Vela* satellites to monitor for air blast γ-rays
discovered signals at a huge rate: 10–20/year!
huge worry but quickly realized events are
extraterrestrial and indeed extrasolar

1973: Los Alamos *Vela* Group finally went public
"Observations of Gamma-Ray Bursts of Cosmic Origin"
Klebesadel, Strong, & Olsen 1973 ApJL 182, L85

hundreds (!) of different theories proposed over the decades

Gamma-Ray Bursts in the Compton Era

major advance: *Compton Gamma-Ray Observatory* 1991-2000
Burst And Transient Source Experiment (BATSE)
monitored all sky for ≈ 9 years, found:

- *event rate*: 2704 BATSE bursts seen
  $\rightarrow \sim 300$ events/yr $\rightarrow$ 1 GRB/day!
- *no repeat events* from same direction
- *duration* (time above background): ~ 0.1 sec to $\sim 10^2$ sec
- time history (*lightcurves*): highly nonuniform
  some highly variable: 100% modulation on < 0.1 sec timescales!
  but others fairly smoothly varying
  `www: BATSE lightcurve sampler`
- *energy spectra*: typically $\epsilon_{\rm peak} \sim few \times 100$ keV
- *sky locations* only known to within $\sim 1^\circ$
  $\rightarrow$ too big a region to quickly search with telescopes
  $\rightarrow$ no counterparts seen at any other wavelengths!

What are they?!?

GRB Mystery: Clues from Physics

a measure of burst intensity is *time-integrated flux* $\equiv$ **fluence**

$\mathcal{F}_\gamma = \int_{\rm burst} F_\gamma(t)\ dt$

BATSE observed fluences: $\mathcal{F}_\gamma^{\rm BATSE} \sim 10^{-7} - 10^{-4}\ {\rm erg/cm^2}$

for an isotropic source with luminosity $L^{\rm iso}(t)$ at distance d

flux is: $F_\gamma(t) = L^{\rm iso}(t)/4\pi d^2$

and so fluence is

$$\mathcal{F}_\gamma = \frac{\int L^{\rm iso}(t)\ dt}{4\pi d^2} = \frac{E_\gamma^{\rm iso}}{4\pi d^2} \quad (1)$$

solve for $E_\gamma^{\rm iso} = 4\pi d^2 \mathcal{F}_\gamma$

key question: **what is typical burst distance d?**

Q: what are characteristic distance scales to try? min, max?

Q: what goes into this decision?

GRB Energetics

distance scale to GRBs crucial

- determines energetics, but more deeply
- encodes origin

to fix numbers: total emitted energy *just in gamma rays*

$$E_\gamma^{\rm iso} = 1.2 \times 10^{34} \ {\rm erg} \ \left(\frac{d}{1 \ {\rm pc}}\right)^2 \ \frac{\mathcal{F}_\gamma}{10^{-4} \ {\rm erg/cm}^2} \qquad (2)$$

- *at Galactic scales*, $d \sim 10$ kpc:
  $E_\gamma^{\rm iso} \sim 10^{42}$ erg $\sim 10^{-9}$ foe
- *at cosmological distances* $d \sim 3$ Gpc:
  $E_\gamma^{\rm iso} \sim 10^{53}$ erg ~ 100 foe $\sim 1/20 \ M_\odot c^2$!!

Q: what are implications if bursts are in our Galaxy?
Q: what if they are cosmological?

GRB Distance Scale and Sources

most models have either GRBs very local or very distant

Galactic models:
$\sim$ all observed bursts within our Galaxy

energetics requirements modest $\rightarrow$ neutron stars?

event rates high: many sources needed to give
$\sim$ daily, non-repeating event rate
bursts a very common, frequent occurrence in a galaxy

this was the favored model pre-BATSE

GRB Distance Scale and Sources

Galactic models: (favored pre-BATSE)
$\sim$ all observed bursts within our Galaxy
energetics requirements modest $\rightarrow$ neutron stars?
event rates high: many sources needed
bursts a very common, frequent occurrence in a galaxy
compare: novae (accreting white dwarfs) $\sim$ 50 events/yr
Galactic population, similar rate

Cosmological models:
bursts come from other galaxies, typically very distant:
substantial fraction of max distance $\sim d_H$ *energetics* requirements enormous! $\gg$ SN baryonic energies
event rates low: only 1 GRB/day/observable Universe
bursts a very rare occurrence in a galaxy

rate per galaxy $\sim 3 \times 10^{-5}$ GRB/century

compare: core-collapse supernova rate $\sim few/$century

Q: what information (from BATSE alone) would discriminate the Galactic vs cosmo pictures?

Implications of Variability

GRBs can be highly variable, with $\delta F/F \sim 1$
on the smallest observable timescales, $\delta t \sim 1$ msec

but if entire signal varies, has to reflect
coordinated behavior of *entire source*
i.e., source luminosity has $L = F_{\rm surface} A_{\rm emit}$
and so $\delta L/L \sim \delta A_{\rm emit}/A_{\rm emit} \sim 2\delta R_{\rm emit}/R_{\rm emit}$

in time δt, max change in emitting region $R_{\rm emit}$
is $\delta R \leq \delta R_{\rm max} = c\ \delta t$
and so given observed variability, can put *upper limit*
on source size: $\delta R_{\rm max}/R \geq \delta R/R \leq 1/2\ \delta L/L \sim 1/2$

$$R_{\rm emit} \lesssim 2R_{\rm max} = \frac{c\ \delta t}{2} \simeq 6 \times 10^7\ \text{cm} = 600\ \text{km} \ll R_\oplus, R_\odot$$

emitting region must be *tiny*!
compact source required – neutron star?! black hole?!

Implications of Fluence Distribution

consider "standard candle" approximation
all bursts have same intrinsic γ energy output E_γ
for burst at distance d, observed fluence is $\mathcal{F} = E_\gamma/4\pi d^2$
and so $d(\mathcal{F}) = \sqrt{E_\gamma/4\pi\mathcal{F}} \propto \mathcal{F}^{-1/2}$
fluence distribution probes source *spatial distribution*

for uniform spatial (number) density $n_{\rm grb}$ of GRB sources
within distance d, number of bursts $N(< d) = 4\pi/3\ n_{\rm grb} d^3 \propto d^3$
so number $N(> \mathcal{F})$ of bursts with fluence $> \mathcal{F}$ is

$$N(> \mathcal{F}) = 4\pi/3\ n_{\rm grb} d(\mathcal{F})^3 \propto d(\mathcal{F})^3 \propto \mathcal{F}^{-3/2}$$

Q: what is $N(> \mathcal{F})$ if no sources beyond some $d_{\rm max}$?
Q: what if GRB also have some intrinsic E_γ distribution?
Q: what would be $N(> \mathcal{F})$ for Galactic GRB models?
Q: what would be $N(> \mathcal{F})$ for cosmological GRB models?

for infinite (Euclidean, static) distribution of sources:
$N(>\mathcal{F}) \propto \mathcal{F}^{-3/2}$ for all fluence $\mathcal{F}$
if standard candles, but with distribution "edge" at $d_{\rm max}$
then should be $\mathcal{F}_{\rm min} = \mathcal{F}(d_{\rm max})$, and $N(>\mathcal{F}_{\rm min}) = 0$!
if intrinsic E_γ distribution ("luminosity function")
then a *range* of $\mathcal{F}$ for each d
but still: $N(>\mathcal{F}) \propto \mathcal{F}^{-3/2}$ inside $d_{\rm max}$, strong drop beyond

Galactic GRB: finite distribution
$\longrightarrow$ expect break/turnover in fluence distribution

Cosmological GRB: infinite distribution
$\longrightarrow$ expect $N(>\mathcal{F}) \propto \mathcal{F}^{-3/2}$ out to edge of observable U
(but also cosmological redshifting effects)

`www: observed fluence distribution`
- shows $N(>\mathcal{F}) \propto \mathcal{F}^{-3/2}$ for highest $\mathcal{F}$
- but breaks, and is lower for much of observed range

$\Rightarrow$ most simply fit in Galactic model

Implications of Sky Distribution

GRB positions not well-determined by gamma-ray data (BATSE) localized to $\sim 1^\circ$

But for > 4700 bursts, *sky distribution* of events carries important information

Q: expected distribution in Galactic model (very nearby, all-Galaxy)?

Q: expected distribution in cosmological model?

Observed GRB Sky Distribution

`www:  BATSE sky distribution`

isotropic to very high precision
  no correlation with Galactic plane

much more simply explained in cosmological model
thanks to Cosmological Principle

in Galactic model: very difficult to avoid anisotropy
- either sources *very* close: $d \ll$ disk scale height ~ 100 pc
- or sources in Galactic "halo"
  spherical configuration, much larger than $R_\odot \sim 10$ kpc
  ... but must avoid signal from M31...

Director's Cut Extras

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

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

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!