Astro 596/496 NPA

Lecture 31

Nov. 6, 2009

Announcements:

- Problem Set 5 due today ... but Monday okay too

Today:

- products of core-collapse supernovae
  nucleosynthesis
  diffuse neutrinos
- Gamma-Ray Bursts

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")

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 nuke"
burn if $\tau_{\rm nuke} > \tau_{\rm hydro}$
similar processes, products as before, but also freezeout behavior
• largest effects on inner shells/heaviest elements
• little change in outer shells

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

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 flew to monitor for blast γ-rays
found 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**

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

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

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

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

and so fluence is

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

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

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*

$$E_\gamma^{\rm iso} = 1.2 \times 10^{34} \ {\rm erg} \ \left(\frac{d}{1 \ {\rm pc}}\right)^2 \ \frac{\mathcal{F}_\gamma}{10^{-4} \ {\rm erg/cm2}} \qquad (3)$$

- *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 occurance in a galaxy

this was the favored model pre-BATSE

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 occurance in a galaxy
$\rightarrow$ since $n_{\rm gal} \sim 10^{-2}\ {\rm Mpc}^{-2}$, observable volume $V_{\rm obs} \sim 4\pi/3\ d_H^3$
and $N_{\rm gal} \sim n_{\rm gal} V_{\rm obs} \sim 10^9$ galaxies
$\rightarrow$ per galaxy, burst rate is $\sim 10^{-9}$ GRB/day $\sim 3 \times 10^{-5}$ GRB/century
compare: core-collapse supernova rate $\sim few$/century

pre-BATSE, this was seen as extravagant and hard to imagine

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