Astro 596/496 NPA
Lecture 34
April 22, 2019

Announcements:

- **Problem Set 6 due Friday** penultimate!

FYI: two new GRBs discovered since we last met
long burst yesterday, short this morning

Last time: gamma-ray bursts pre-LIGO

- *Q: evidence that bursts are cosmological?*
- *Q: burst timescale distribution and implications?*
- afterglows and host galaxies *Q: trends?*
- bursts are not isotropic *Q: beaming implications?*

The GRB Story Thus Far

GRBs are cosmological

- isotropic sky distribution
- afterglows with distances are extragalactic and often $z > 1$

GRBs show two populations based on timescale and spectra

- long $\gtrsim 2$ sec + soft (lower high/low energy flux ratio)
- short + hard

afterglow host galaxies

- long/soft events mostly found in star-forming galaxies
  directly tied to star formation
- short/hard events also in ellipticals, or in outskirts
  implies delay between progenitor birth and GRB

GRB Relativistic Beaming

bursts born with Lorentz factor

$$\Gamma = \frac{1}{\sqrt{1 - v^2/c^2}} \gtrsim 100$$

implies blueshifting and beaming of flux
in forward cone $\theta \sim 1/\Gamma$

as burst slows, Γ drops → more isotropic

beaming implications:
- true GRBs rate $\gg$ observed rate
- energy requirements $\ll E_{\mathrm{iso}}$ isotropic estimate

Long GRBs and Supernovae

evidence for supernova association with long-soft bursts:

- given beaming; long-soft burst energetics, rate in line with supernova blasts
- long-soft bursts found in regions of active star formation

direct evidence: supernova outbursts seen in GRB afterglows!

- SN 1998bw seen in unusually low-energy GRB 980326
- SN 2003dh seen in "vanilla" GRB 030329
- supernova spectra derived → no H, He I, Si II; lines all broad consistent with relativistic ejecta

all GRB-linked supernovae are Type Ib and Ic: no hydrogen!
very massive star, winds/companion remove outer layers
...but not all Type Ib/c make GRBs

Collapsar Model

How does a supernova make a GRB?

collapsar model (Woosley)

- very massive progenitor, rapid rotation
- black hole formed in core, ang momentum → accretion disk
- relativistic jet created, punctures star `www: jet simulation`

What makes the jet?

magnetohydrodynamic effects in GR?

`www: Illinois Shapiro group GR magnetohydrodynamic collapse simulat`

Short-Hard Bursts: Status Before 2017

short-hard bursts:

- fewer bursts seen: $\sim 30\%$ of BATSE catalog
  farther? intrinsically fainter? both?
- few afterglows seen, often not in star-forming regions
  and many seen in elliptical galaxies
  → come from older population

What are the astrophysical sources?

neutron star mergers with other neutron stars or black holes

- neutron star "kicks": up to $\sim few \times 100$ km/s at explosion
  → ejected from disk
- gravitational inspiral time long
  → mergers not connected to star formation
- possible sources of gravitational radiation

GW 170817 and GRB 180817A

GW 170817

LIGO: first gravitational wave events discovered
were BH-BH mergers $\sim 30 M_\odot$ binaries

August 17, 2017: event seen by LIGO-Virgo

gravitational wave signal detected for $\sim$ 100 sec

`www:  observed gravitational radiation signal`

- longest gravitational wave duration seen to date
- inspiral phase, frequency increases until out of bandpass
  gravity waves did not observe coaelscence
- initial mass estimates: $0.86 - 2.26 M_\odot$ → neutron stars!

Whodunit?

Where did the event occur?

luminosity distance:
based on gravity wave strain amplitude $h \propto 1/D$:
$D_L = 40 \pm 8$ Mpc – very nearby! *Q: implications for followup?*

localization crude: 31 deg^2 region
- done via delay times and triangulation
- signal not seen by Virgo (dead zone)

GRB 170817A

Fermi/GBM detected gamma ray burst
- ~ 2 sec after LIGO signal
- duration ~ 2 sec
- hard-ish spectrum
- with some evidence of another gamma outburst 2 sec later

Swift: behind Earth during event

isotropic energy: 2 orders of magnitude smaller
than any other GRB with measured distance
Q: implications?

with gamma-rays localization drastically improved!
launched EM followup at other wavelengths

EM Counterpart

LIGO+*Fermi* location errorbox searched by many telescopes
prioritized by nearby star-forming galaxies with high stellar mass

electromagnetic event discovered independently by many groups
blue point source in outskirts of elliptical galaxy NGC 4993
`www: discovery images`

distance: 40 Mpc, consistent with gravity waves!

EM emission much brighter than known short GRB afterglows

implications:

- off axis view of GRB jet
- lower-energy EM emission not from jet
  but fron central engine: **kilonova/macronova**

Neutron Star Mergers and Gamma-Ray Bursts

production: two scenarios (at least)

- binary massive stars, neutron stars survive explosions
- in star cluster, single neutron stars gravitationally settle to center, then become bound

evolution:

orbit inspiral - decay via gravity wave emission

known progenitor: binary pulsar

orbit decay observed, matches gravitational wave prediction

Nobel Prize 1993: Hulse and Taylor

fate:

coalescence: hypermassive neutron star? black hole?

gravitational wave amplitude rises to burst

then decays in “ringdown”

Kilonova/Macronova

theory predictions for binary neutron star merger outcome
merger matter sorted by angular momentum

- **central object:** lowest angular momentum matter
- **black hole**, or
  rotationally supported **hypermassive neutron star**
- magnetized, spinning → **relativistic magnetized jet**

- **accretion disk:** drives hot, low-density wind
  of expanding neutron star matter: expected EM signal!

- **dynamically ejected matter**: $v \sim 0.10 - 0.3c$
  expanding neutron star matter: expected EM signal!

key question:
What happens to decompressing neutron star matter?

Beyond the Iron Peak

Beyond the Iron Peak

`www: Solar Abundances`

if all heavy elements made only in
burning to nuclear statistical equilibrium
then should follow Fe peak, fall dramatically at high A
→ would have much less of the very heavy elements

How to synthesize nuclei with $A >$ iron peak?
- Coulomb barrier $\propto Z^2$ prohibitive
- fusion reaction *not* exothermic

Yet silver, gold, lead, uranium, ... all exist!
→ nature has found a way

Q: Suggestions?

Solution: **neutrons**

- no Coulomb barrier
- capture reactions occur even at small thermal speeds

Today: nuclear physics of n capture processes

Then: astrophysical sites for appropriate conditions

Neutron Capture Processes

To see basic physics:

(1) “let there be neutrons”

(2) assume a heavy “seed” nucleus (e.g., ^{56}Fe)

(3) ignore charged particle rxns (Coulomb suppressed)

Q: if add n to seeds, expect...?

`www: chart of nuclides`

Neutron capture physics set by competition

- neutron capture $n + (A, Z) \rightarrow (A + 1, Z) + \gamma$
- β decay $(A, Z) \rightarrow (A, Z + 1) + e^- + \bar{\nu}_e$

Two regimes (BBFH 1957; Cameron 1957):

capture rate $\gg$ decay rate

$\Rightarrow$ rapid capture: $\boxed{\textit{r}\text{-process}}$

decay rate $\gg$ capture rate

$\rightarrow$ slow capture: $\boxed{\textit{s}\text{-process}}$

Detective story:

- do these limiting cases occur? (*Yes!*)
- what are astrophysical sites?

n Capture Rates

n-capture cross sections:

typically, $\sigma \propto 1/v$

- enhanced at low energies!
- $\sigma v = \langle \sigma v \rangle = const$ → T-indep!
- fails for magic nuclei:

  tightly bound → small σ

Implications?

The s-Process: Basic Physics

slow n capture: $\Gamma_{n\gamma} \ll \Gamma_\beta$

$\Rightarrow$ path in chart of nuclides:

follow n-rich edge of β-stability

`www:` s`-process path`

for isobar A

$$\frac{dn_A}{dt} = -\langle\sigma v\rangle_A n_n n_A + \langle\sigma v\rangle_{A-1} n_n n_{A-1} \qquad (1)$$

except for seed (e.g., ^{56}Fe)

$$dn_{\text{seed}}/dt = -\langle\sigma v\rangle_A n_n n_{\text{seed}} \qquad (2)$$

Q: what behavior expected for n_A*?*

put neutron exposure: $d\tau = n_n(t)\ v_T\ dt$
(= time-integrated n flux = n "fluence")
where $v_T = \sqrt{2kT/\mu_n}$, $\mu_n = m_n m_A/(m_n + m_A)$.
Then

$$\frac{dn_A}{d\tau} = -\sigma_A n_A + \sigma_{A-1} n_{A-1} \tag{3}$$

where $\sigma_A = \langle \sigma v \rangle_A / v_T$: thermal n capture cross section

evolution is another example of *self-regulating* equation
→ expect abundance driven to equilibrium, $dn_A/dt = 0$
⇒ $\sigma_A n_A = \sigma_{A-1} n_{A-1}$

$$\frac{n_A}{n_{A-1}} = \frac{\sigma_{A-1}}{\sigma_A} \tag{4}$$

⇒ the "local approximation"
only holds for non-magic nuclei
⇒ good between magic numbers

Solar Abundances and the s-Process

For elements beyond Fe peak:
plot $N_A \sigma_A$ vs A
if *s*-process reaches equilibrium, predict flat curve
Transp: $N_A \sigma_A$ *plot*

for adjacent nuclides, local approximation excellent
between magic N: good
but globally, fails
$\Rightarrow$ need distribution of τ

Roughly: exponential distribution of τ needed
i.e., imagine series of n bursts of different intensities
Q: how does nature do this?

The s-Process: Characteristic Scales

typically, $\langle \sigma v \rangle \sim 3 \times 10^{-17}$ cm^3/s
capture timescale $\tau(n) = 1/(n_n \langle \sigma v \rangle)$
if $\tau(n) > \tau_\beta^{\rm min} \sim 10$ yr shortest lifetime on *s* path
$\Rightarrow n_n < 10^8$ neutrons cm^{-3}

but also must pass through $N = 61$*: no stable nuclei!*
but ${}_{61}{}^{107}$Pd: $\tau_{107} \sim 10^7$ yr
`www: s-process path`
can't decay first:
$\tau(n) < \tau_{107} \quad \rightarrow \quad \Rightarrow n_n > 10^2$ neutrons cm^{-3}

cf reactor: $n_n \sim 10^7$ cm^{-3}

Q: Guesses as to astrophysical site?

s-Process: Astrophysical Site

Intermediate mass stars: $\sim 3 - 8\ M_\odot$
recall–after main seq:
1. H shell burn → RGB
2. He ignition → core He burn
3 He shell burn → asymptotically approach RGB again
"asymptotic giant branch" = AGB
HR diagram sketch

On AGB:
two burning shells: H, He
instability → thermal pulses (TP)

TP-AGB stars observed to have
- C/O > 1 – "carbon stars"
- high *s*-process! – "S-stars"

s-Process: The Crown Jewel

technetium seen in AGB stars (Merrill 1952)

Transp: *Tc lines*

no stable isotopes!

longest-lived $\tau(^{98}\mathrm{Tc}) = 6$ Myr

$\Rightarrow$ 1st direct evidence for ongoing nucleosynthesis in stars!

$\Rightarrow$ *s*-process must occur in AGB!

$\boxed{s\text{-process occurs in pulsing AGB stars}}$

Q: where did the stars get the neutrons? the seeds?

AGB neutron sources:

- ^{13}C from CNO cycle: $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$
- ^{14}N from CNO cycle burnt to $^{14}\mathrm{N}(\alpha, \gamma)^{18}\mathrm{F}(\beta)^{18}\mathrm{O}(\alpha, \gamma)^{22}\mathrm{Ne}$ then $^{22}\mathrm{Ne}(\alpha, n)^{25}\mathrm{Mg}$

occurs in intershell region

n created during, between pulses

⇒ repeated n exposure of different intensities

⇒ can fit observed exposure distribution

...but now can make detailed, realistic models

in context of stellar evolution