Astro 596/496 NPA

Lecture 33

April 19, 2019

Announcements:

- **Preflight 6 due today** preflights finished!
- **Problem Set 6 due next Friday** penultimate!

Last Time: Gamma-Ray Bursts (GRBs)

Q: what are their key observed properties?

Q: what are implications of Galactic vs extragalactic GRB origins?

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...

The Great Debate

1995: Debate of Cosmo vs Galactic GRB models
"The Distance Scale to Gamma-Ray Bursts"
Bodhan Paczynski (cosmo) vs *Don Lamb* (Galactic)

75th anniversary of 1920 Curtis-Shapley debate
on "the Scale of the Universe" (are galaxies cosmological?)

strong arguments made by both
my read of community sentiment then: heavily cosmo
but no overwhelming consensus
  and puzzlement of cosmo energy requirements

key test needed: direct distance info for one or more GRB

Experimentum Crucis: GRB Afterglows

Recall: until 1997, no GRB seen at non-γ wavelengths
$\rightarrow$ can't identify source location, revisit after burst

1996–2002: *BeppoSAX* (Italian, Dutch, ESA)
- one instrument detected GRBs in γ-rays
- another detected X-rays in same field, arcmin resolution

GRB 970228: first *BeppoSAX* GRB event
- X-ray **afterglow** seen
- then optical afterglows found by ground-based telescopes
- after faded, distant galaxy seen as host!

GRB 970508: position found rapidly $\rightarrow$ afterglow still bright
- optical spectrum $\rightarrow$ absorption lines $\rightarrow$ *redshift* $z_{\rm abs} = 0.835$

Gamma-Ray Bursts are cosmological!

Afterglows Observed

GRB afterglows have revolutionized the field
many observed now, in all wavelengths from X-ray to radio

2004–present: NASA *Swift*
• gamma-ray instrument (BAT) for GRB detection
• telescope for afterglows: UV, Optical (UVOT)
`www: UVOT afterglows`

general afterglow behavior:
• spectrum a powerlaw in ν
• dimming an inverse powerlaw in time

redshifts usually obtained and/or host galaxy identified
galaxies are always gas-rich = star-forming ("late type")
where resolved: GRB is in *star-forming region*
$\Rightarrow$ GRBs connected to star-formation

Afterglow Scintillation: Beaming

GRB radio afterglows can be measured very sensitively
$\longrightarrow$ can follow some for > 1 year

observed radio afterglows:
• strong variations for first $\sim$ 1–2 months
• then smooth decay with time

key idea: fluctuations not due to GRB or its environment
but rather **scintillation**= *"twinkling"* in Milky Way

GRB afterglow: apparent angular size grows with time

- at early times: source angular size small
  single light path fluctuates in non-uniform interstellar MW
- at late time: source disk larger $\rightarrow$ average over paths
- dividing scale: $\alpha_{\rm scint} \sim 3 \times 10^{-6}$ arcsec

For source at $d = 1$ Gpc
afterglow size $R = \alpha_{\rm scint} d \sim 0.01$ pc ~ 10 light-days!

but transition seen after $1-2$ months
$\rightarrow$ afterglow region expanding at $v = c$!

GRBs are relativistic outflows!

GRB Populations: Timescales and Hardness

GRB lightcurves show wide diversity
$\longrightarrow$ difficult to characterize succinctly...but worth trying

timescale duration to see photon signal *over background*
depends on GRB fluence $\longrightarrow$ distance, and detector sensitivity
largest confusion near background level so to avoid
use $T_{90} \equiv$ time interval for 90% of signal
or $T_{50} \equiv$ time interval for 50% of signal
`www:` **BATSE T_{90} distribution**

GRB detailed γ spectra not available in BATSE
only broadband "colors"

hardness ratio of fluence in high- vs low-energy bands
a GRB "color index"
interesting to look at distribution and correlate with T_{90}
`www:` **T_{90}--hardness correlation**

GRB Populations: Two Classes

BATSE bursts show:

- clear bimodal separation in timescale
  separation at $T_{90} \simeq 2$ sec
- less clear but bimodal separation in hardness
- groups in each are *correlated* $\rightarrow$ **two GRB populations**
  - ⋆ **short-hard bursts**
  - ⋆ **long-soft bursts**

Also note:
afterglows (almost) exclusively seen for the long-soft bursts
so only long-soft bursts have confirmed association with active star formation

few short-hard bursts afterglows, host galaxies found
but many are in elliptical galaxies,
and not in active star-forming regions

How Relativistic are Bursts?

burst energy density is enormous
from know burst energies, timescales $\rightarrow$ huge photon energy density at source
ε_γ so high that $\gamma\gamma\rightarrow e^+e^-$ efficient
$\rightarrow$ photons should create pairs $\rightarrow$ rapidly thermalize
...but GRB emission nonthermal

cure: highly relativistic outflow
Lorentz factor $\Gamma = 1/\sqrt{1 - v^2/c^2}$
nonstandard symbol to avoid confusion with γ-rays

if $\Gamma \gg 1$:
- blueshifting $\rightarrow$ smaller rest-frame photon energies
- to avoid thermalization: need $\Gamma \gtrsim 100$ **!**

bursts are ultrarelativistic!
Q: for comparison, what is $\Gamma_{\rm LHC}$?

GRB Afterglows: Beaming

several lines of evidence point to beamed burst geometry
$\longrightarrow$ relativistic outflow confined to cone: opening angle θ

special relativity: light source with Γ
has emission confined to region of angle $\sim 1/\Gamma$

thus: GRB emission initially highly collimated (radial photons!)
$\longrightarrow$ observer initially sees only small part of emitting region

but as burst decelerates, larger emitting region seen

Q: what happens when $1/\Gamma > \theta$?

if outflow is in jet of angle θ

then when $1/\Gamma > \theta$, photons more isotropic than jet

$\longrightarrow$ more photons directed away from observer

$\longrightarrow$ substantial sudden decrease in afterglow brightness

afterglow lightcurves: show slope change "breaks"

imply significant beaming: $\theta \sim few \times 1^\circ$

$\longrightarrow$ fraction of solid angle:

$$f_{\rm beam} \equiv \frac{\Omega_{\rm beam}}{4\pi} = \frac{1}{2}(1 - \cos\theta) \approx \theta^2/2 \sim \frac{1}{300} \qquad (1)$$

Q: what does this imply for GRB properties? what changes, doesn't?

Implications of Beaming: Event Rate, Energetics

given $f_{\rm beam} = \Omega_{\rm beam}/4\pi \sim 1/300 \ll 1$:

- we only see bursts aimed right at us
- energy output is highly anisotropic

energetics

typical *isotropic* energy output $E_\gamma = E_\gamma^{\rm iso} = 4\pi d^2 \mathcal{F} \sim 100$ foe
but this was an *overestimate*: correct value is

$$E_\gamma = \Omega d^2 \mathcal{F} = f_{\rm beam} E_\gamma^{\rm iso} \simeq 1 \text{ foe}$$

rate per galaxy

from observed burst rate of $\lambda_{\rm obs} = 1$/day/Universe
per galaxy we infer $\dot{N}_{\rm grb} = \dot{N}_{\rm grb}^{\rm iso} = \lambda_{\rm obs}/N_{\rm gal} \sim 3\times10^{-5}$ GRB/century
but this was an *underestimate*, since $\lambda_{\rm obs} = f_{\rm beam}\lambda_{\rm tot}$, so:

$$\dot{N}_{\rm grb} = \frac{\lambda_{\rm tot}}{N_{\rm gal}} = \frac{1}{f_{\rm beam}} \dot{N}_{\rm grb}^{\rm iso} \simeq 10^{-3} \text{ GRB/century} \sim 0.1\ \dot{N}_{\rm SN}$$

Long GRBs and Supernovae

hints of 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 $\rightarrow$ no H, He I, Si II; lines all broad consistent with relativistic ejecta

all GRB-linked supernovae are Type Ic

very massive star, winds/companion remove outer layers

...but not all Type Ic 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 simulati`

Short-Hard Bursts: Status Before 2017

short-hard bursts:

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

What are the astrophysical sources?
neutron star mergers with other neutron stars or black holes
`www: Illinois Shapiro group GR merger simulation`

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