Astro 596/496 NPA

Lecture 33

Nov. 11, 2009

Announcements:

- Preflight 6 due next *Monday* noon

Last time: the Distance Scale to Gamma-Ray Bursts

Q: what is this scale? how do we know?

Q: what are population studies? how are they useful for GRBs?

Q: what's difficult about quantifying burst timescale? spectra?

Q: how might you do it anyway?

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 $\Gamma_{\mathrm{Fermilab}}$?

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:

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

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 $\lambda_{\rm obs} = 1/\text{day}/\text{Universe}$
per galaxy we infer $\dot{N}_{\rm grb} = \dot{N}_{\rm grb}^{\rm iso} = \lambda_{\rm obs}/N_{\rm gal} \sim 3 \times 10^{-5}$ 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 $\rightarrow$ 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`