Astro 596/496 NPA

Lecture 32

Nov. 9, 2009

Announcements:

- Problem Set 5 really due
- Preflight 6 posted, due next *Monday* noon

Last time: Gamma-Ray Bursts

Q: what are their key observed properties?

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

Gamma-Ray Burst Key Properties

- *observed rate* ~ 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 ~ 1 msec timescales!
- *energy spectra*: typically $\epsilon_{\rm peak} \sim few \times 100$ keV
- *fluence* $\mathcal{F}_\gamma = \int_{\rm burst} F_\gamma(t)\ dt$
  $\mathcal{F}_\gamma^{\rm BATSE} \sim 10^{-7} - 10^{-4}\ {\rm erg/cm^2}$

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 occurence in a galaxy

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
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: $\delta R_{\rm max}/R \geq \delta R/R \leq 1/2\ \delta L/L \sim 1/2$

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

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_{max}
then should be $\mathcal{F}_{\text{min}} = \mathcal{F}(d_{\text{max}})$, and $N(>\mathcal{F}_{\text{min}}) = 0$!
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_{max}, strong drop beyond

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

Cosmological GRB: infinite distribution
$\rightarrow$ 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...

The Great Debate

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

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* $z_{\mathrm{abs}} = 0.835$

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
$\rightarrow$ 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: $\alpha_{\mathrm{scint}} \sim 3 \times 10^{-6}$ arcsec

For source at $d = 1$ Gpc

afterglow size $R = \alpha_{\mathrm{scint}} d \sim 0.01$ pc ~ 10 light-days!

but transition seen after $1 - 2$ months

$\rightarrow$ afterglow region expanding at $v = c$!

GRBs are relativistic outflows!