GRB history

Discovered 1967 Vela satellites

classified!

Published 1973!

Ruderman 1974 Texas: More theories than bursts!
Burst diversity

\[ E_{\text{peak}} \sim 300 \text{ keV} \]

Non-thermal spectrum

In some thermal contrib.

Short time variability down to ms

\[ 10^{-2} \text{ } - \text{ } 10^3 \text{ s} \]

Often substructure
Bimodal distribution

Short: \( t < 2 \text{ s} \) \( t_{\text{mean}} \sim 0.2 \text{ s} \) \( \frac{1}{4} \) Hard

Long: \( t > 2 \text{ s} \) \( t_{\text{mean}} \sim 35 \text{ s} \) \( \frac{3}{4} \) Soft

Fig. 1
\[ \sim 1 \text{ burst/day} \]

**Isotropic distribution:**

1. Cosmological
2. Distant halo contribution > 100 kpc
Beppo/SAX satellite

First GRB afterlow: GRB970228
First with redshift: GRB970508
z=0.835 from absorption lines

GRBs are cosmological!!

Energies $10^{50}-10^{54}$ erg/s if isotropic
Prompt phase

t $\sim 10 \text{ - } 1000$ s

rapid variability milli sec – sec

Gamma-rays

Both short and long bursts

Afterglow

t $\sim 100$ s – years

X-rays, optical, radio

smooth evolution, often power law decay

Until SWIFT only long, now also short
Relativistic expansion?

Photon-photon pair production

\[ \gamma + \gamma \rightarrow e^+ + e^- \quad h\nu > 2m_e c^2 \]

\[ \tau_{\gamma\gamma} \approx \sigma_T n_\gamma R \approx \sigma_T f_p \frac{L}{4\pi R^2 c m_e c^2 R} \]

\[ R \approx c \Delta t \quad L = 4\pi D^2 F / \Delta t \]

\[ \tau_{\gamma\gamma} \approx \frac{\sigma_T f_p F D^2}{(\Delta t c)^2 m_e c^2} \approx 3 \times 10^{14} f_p \frac{F}{10^{-6}} \left( \frac{\Delta t}{10^{-2} \text{s}} \right) \]

\[ \tau_{\gamma\gamma} \gg 1 \quad \text{thermalisation: black-body!} \]
Consequences of relativistic expansion

If relativistic, i.e., $\Gamma \gg 1$

$$\nu_{obs} \approx \Gamma \nu_{em}$$

Observed MeV photons become X-rays in rest frame: No pair production

$$f_p \propto \Gamma^{-2\alpha} \ll 1$$
Consequences of relativistic expansion II

\[ t_1^{\text{obs}} = t_1^{\text{em}} + (D - r_1)/c \]

\[ t_2^{\text{obs}} = t_2^{\text{em}} + (D - r_2)/c \]

\[ dt^{\text{obs}} = dt^{\text{em}} - dr/c = dt^{\text{em}} - V dt^{\text{em}}/c = dt^{\text{em}} (1 - V/c) \]

\[ dt^{\text{obs}} = dt^{\text{em}} (1 - \beta) \]

\[ \Gamma^2 = \frac{1}{(1 - \beta^2)} = \frac{1}{(1 + \beta)(1 - \beta)} \approx \frac{1}{2(1 - \beta)} \quad \text{if } \beta \approx 1 \]
Consequences of relativistic expansion III

\[ dt^{obs} = \frac{dt^{em}}{2 \Gamma^2} \]

1. Observer sees everything slower compared to comoving frame

\[ dt^{em} = 2 \Gamma^2 dt^{obs} \]

2. Size of object is NOT \( c t^{obs} \) but \( c t^{em} = 2 c t^{obs} \Gamma^2 \)

3. Solves compactness problem!

\[ \tau_{\gamma \gamma} \propto \Gamma^{-2(\alpha+1)} \]

\[ \alpha \approx 2 \quad \Rightarrow \quad \tau_{\gamma \gamma} \propto \Gamma^{-6} \]
Interstellar scintillations

Size larger than scintillating elements $> 10^{17}$ cm
Needs relativistic expansion
Baryon loading

\[ E = \Gamma M c^2 \]

\[ M \approx 5 \times 10^{-6} \left( \frac{\Gamma}{10^3} \right)^{-1} \left( \frac{E}{10^{52} \text{erg s}^{-1}} \right)^{-1} M_o \]
Anatomy of a GRB

See Piran 1999; Mészáros 2002 (ARAA) for reviews
Temporal Variability
Prompt burst scenarios

- **Internal Shocks**
  - many colliding shells
  - Complex, Long Lasting Engine

- **External Shocks**
  - irregular surrounding
  - Simple “Explosive” Engine

Sari
Jet steepening

Relativistic aberration

Correct for opening angle gives total energy. Nearly constant $\sim 10^{51}$ ergs

Close to 'normal' supernova energy! $\theta \sim 5$-10 degrees
Beaming $\Delta \Omega \sim 0.03$. Only one of 100-500 GRBs seen by us

1-3 GRBs observed per day. Total rate 100-1000 per day

1 GRB per $10^5 - 10^6$ years per galaxy

Compare 1-2 SNe per galaxy per 100 years, i.e. 1 GRB / $10^3 - 10^4$ SNe
SN 1998bw = GRB 980425

Type Ic supernova  \( z=0.0085 \) in ESO 184-G82  Radio:  \( \Gamma \sim 2 \)
Optical: Expansion velocity \( \sim 60,000 \) km/s  \( M(^{56}\text{Ni}) \sim 0.7 \) M\(_{\odot}\)
\( E \sim 10^{48} \) erg/s, low compared to 'normal' GRBs
No H or He in spectrum. Exploding Wolf-Rayet star

Sollerman et al
$z = 0.17$. Starforming dwarf galaxy

'Normal' gamma-ray burst energy

Type Ic spectrum after $\sim 1$ month

Spectrum identical to SN 1998bw

Hjorth et al 2003
Bump in light curves

GRB 011121

Bump at ~ 1 month well fitted with SN 1998bw supernova light curve
Collapsar model

Collapse of a very massive star (M > 30 MO).
Needs compact progenitor, i.e., no H envelope = Wolf-Rayet star
Fast rotation gives accretion disk + jets.
Electromagnetic energy extraction?
Collapsar model II

Jet accretion disk black hole

MacFadyen & Woosley

log density (g cm$^{-3}$)
Jet propagation

Model 2A

Stellar radius $\sim 10^{11}$ cm, $V \sim 50,000$ km/s, $t \sim 20$ s
Highly variable Lorentz factor source for internal shocks for the prompt burst

Difficult to get millisecond bursts  Main candidate: Long bursts
Jet expansion in circumstellar medium gives afterglow
Progenitor: Close binary neutron star system. Energy loss by gravitational waves give spiral-in and merger within $\sim 10^8$ years. Final merger within $\sim$ millisecond.
Merger sequence

Merger $\rightarrow$ accretion disk

$T \sim 10^{10}$ K

Energy loss by neutrinos

Energy conversion by

$$\nu + \bar{\nu}_e \rightarrow e^- + e^+$$

Pair plasma expands into ISM

All in milliseconds

No supernova in afterglow expected

Excellent candidate for short bursts
Short bursts with SWIFT

GRB 050509B, 050709, 050724

all short

X-ray afterglows!!

GRB 050709, 050724 also optical afterglows

\[ z = 0.16 - 0.25 \]

\[ E \sim 10^{50} \text{ ergs} \ll \text{Long} \]

Two in ellipticals, one in a starforming galaxy

No supernova signature

All consistent with merging neutron star system. Could also be NS + BH