GAMMA-RAY BURSTS
and
GRAVITATIONAL WAVES

Peter Mészáros
Pennsylvania State University
COSMOLOGICAL GRB:

BASIC NUMBERS

- **Distance:** \(0.4 \lesssim z \lesssim 4.5\)  
  \(0.008 \lesssim z \lesssim 5 - 15?\)  
  \(\rightarrow D \sim 10^{28} \text{ cm} - 10^{29} \text{ cm}\)

- **fluence** \(F = \int \text{flux} \cdot dt \sim 10^{-4} - 10^{-7} \text{ erg cm}^{-2}\)  
  \(\sim 1 \text{ ph cm}^{-2}\)  
  \(\sim \text{ Crab /sec (\gamma-rays)}\)

\(\rightarrow\) **Energy Output:** \(10^{54}(\Omega/4\pi)D_{28.5}^{2}F_{4} \text{ erg}\)  
\(\sim M_{\odot}c^{2}(\Omega/4\pi) \sim \text{solar rest mass in \gamma-rays}\)  
\((\sim \text{supernova } \nu\bar{\nu}, \text{GW energy, BUT: in photons!})\)

Note: collimation \(\Omega \sim 10^{-2} \rightarrow E_{\gamma}(\text{isotr}) \lesssim 10^{52} \text{ erg}\)  
\(E_{\gamma}(\text{isotr}) \sim 10^{51} \text{ erg} \sim L_{\odot} \times 10^{10} \text{ years}\)  
\(\sim L_{\text{GAL}} \times 1 \text{ year}\)

- **Rate** \(\sim 1/\text{day}\) observed at Earth  
  \(\rightarrow \text{only } 10^{-6}(\Omega/4\pi)^{-1} \text{ events/yr/galaxy}\)  
  (i.e., could be \(\sim 10^{4}\) times rarer than supernovae)
DURATION DISTRIBUTION

BATSE 4B Catalog

NUMBER OF BURSTS

$T_{50}$ (seconds)

$0.001 \quad 0.01 \quad 0.1 \quad 1.0 \quad 10.0 \quad 100.0 \quad 1000.$

(≤ 2 s) "SHORT" $\rightarrow$ "LONG" (≥ 2 s)

Kouveliotou et al. 93, 98
GRB: Signature of a BH birth?

- **BATSE**: $\gtrsim 3500$ GRB, + SMM, PVO, Venera, etc
  $\gtrsim 4000$ BHs? (≫ # quasars or MXRB, so far)

- "Long" bursts ($t_b \gtrsim 2$ s): $\sim 2/3$ of total
  (localized by Beppo-SAX: $\gtrsim 40 \rightarrow \sim 30$ redshifts)
  $\rightarrow$ massive stellar collapse ("collapsar") $\rightarrow$ BH?

- "Short" bursts ($t_b \lesssim 2$ s): $\sim 1/3$ of total
  (*not* with Beppo-SAX, but: **HETE-2, Swift**)
  $\rightarrow$ compact merger (NS-NS, NS-BH) $\rightarrow$ BH?

- **Observation channels**:
  - **EM**: (TeV?) GeV, MeV, keV, O, IR, sub-mm, R
  - Neutrinos? $\lesssim 10^{19}$ eV, TeV, GeV
  - Cosmic Rays? $\lesssim 10^{20}$ eV
  - Gravitational waves?
  * NS-NS, NS-BH $\rightarrow$ excellent GW sources
  * Collapsars $\rightarrow$ weaker GW sources. (?)
Hyperaccreting Black Holes

NS - NS merger

very, very fast jet

BH - NS merger

0.01 M☉ torus

0.1M☉ torus

BH - WD merger

1M☉ torus

few M☉ torus

NS/BH - He core merger after common envelope

"collapsar" = rotating, collapsing "failed" supernova ("hypernova")

astro-ph/9810357

Woosley, Macfadyen, Fryer...
NS-NS/NS-BH → MERGER → BH + DEBRIS TORUS

Mészáros & Rees 77 ApJL
Paczynski 78 ApJL
Fryer, Woosley 98 ApJL

EVACUATED FUNNEL
OPT. THICK SLOW WIND

FAST FIREBALL

OPT. LOW

P+_-, e+_-, \pi^0, \gamma

BARYONS n, p, \pi, e

EVACUATED FUNNEL
OPT. THICK SLOW WIND

BARYONS n, p, \pi, e
Aloy et al., astro-ph/9911098
SHOCKS
in relativistic fireball outflow: unavoidable fact of life

Ejecta shells w/ \( x \neq \nu \) velocities \( \Delta \nu \approx (\gamma) \)

Progenitor star (binary)

"INTERNAL" shock \( \Pi_{sh,i} \)

"EXTERNAL" shock (deceleration)


\( \epsilon_{sh,i} < \epsilon_{sh, due} \)
- **BUT:** \( \gamma \)-emission could be due to **INTERNAL shocks** \((e^- \text{ or } e^-e^+ \text{ synch} + IC)\)


which would be followed by an external shock

![Graph showing the relationship between different shock types and emissions](image)

- **Multi-\( \lambda \) “Simultaneous” Flash** \(\text{ALSO expected from INTERNAL shocks}\) \((e^- \text{ or } e^-e^+)\)


![Graph showing different emission profiles](image)
AFTERGLOW of a GRB

(evolution of a GRB remnant, or GRBR)

adiabatic: \( \rho_{extr} r^3 \Gamma^2 \sim \text{const.} \rightarrow \Gamma \propto r^{-3/2} \propto t^{-3/8} \);

radiative: \( \rho_{extr} r^3 \Gamma \sim \text{const.} \rightarrow \Gamma \propto r^{-3} \propto t^{-3/7} \)

\( B \propto t^{-p} \), \( \nu_{\text{max}}(\text{sy}) \propto t^{-q} \), \( F_{\nu_{\text{max}}} \propto t^{-a} \), \( F_{V_{\text{obs}}} \propto t^{-b} \)

Rees & Mészáros '92 MNRAS 258, P41

Spectral Softening in Time:

\( \ell F_{\nu} \) vs. \( \ell \nu \) vs. \( t \)

\( \ell F_{V_{\text{obs}}} \) vs. \( t^{-b} \) vs. \( t_{\text{obs}} \)
The bright source in the field is the new X-ray source

1SAX J0501.7+1146

associated with the Gamma Ray Burst GRB 970228 IAUC 6576.

1SAX J0501.7+1146, has been detected by the MECS and LECS at the same position (R.A. = 5h01m44s, Decl. = +11o46'.7, equinox 2000.0; estimated error radius 50''). This position lies at the edge of the reported BeppoSAX WFC error box (IAUC 6572). The source flux is (2.8 +/- 0.4) x 10E-12 erg cmE-2 sE-1 in the MECS (2-10 keV) and (4.0 +/- 0.6) x 10E-12 erg cmE-2 sE-1 in the LECS (0.5-10 keV). The field was observed again on Mar. 3.734, and a source was detected at a position consistent with the previous one, but at a flux level lower by a factor of 20.

This page is maintained by Lucio Angelo Antonelli and Fabrizio Fiore.

GRB 970228 : BeppoSAX team

FADING X-RAY AFTERGLOW \( \geq 1997 \)
Fig. 1.— The Afterglow of GRB 970228 in the $\gamma$, X, O and IR bands

Wijers, Rees & Mészáros '97, MNRAS 288, L51, (using models from

JETS: GRB 990510

Light-curve steepening $\rightarrow$ Jet edge seen?

- $t_0 = 1.57$ days
- $F(t) \sim \frac{(t/t_0)^{-2.40}}{1 + (t/t_0)^{0.76-2.40}}$

Days after UT May 10.36743

Jet candidates:
GRB 980703, 990123, 990510, 991216, ...
$\Delta S_L \geq 10^{-2}$
Sample of 17 GRB w. jet breaks (or limits on...)

$\gamma$-ray fluence ($\propto E_{\text{iso}}$)

Inverse beaming factor $\Gamma_j^2 \left( \frac{E_{\text{iso}}}{\frac{E}{\text{iso}}} \right)^{-1}$

Closer to standard candle

Note: requires $\Gamma_j \propto \text{top-hat}^2$? ($\Gamma_j \neq f(\theta)$ for $\theta < \theta_j$)

Frail et al., astro-ph/0102282
New & Future GRB Experiments

- **HETE-2**: launched Nov 5'00
  GBM Fregate: 6-400 keV,
  WXM: 2-25 keV, $\theta \lesssim 10'$,
  SXC: 0.5-10 keV, $\theta \sim 30''$
  currently (Dec.) engineering & testing phase; but:
  detected $\&$ (several) GRB (seen by IPN etc., others as well)
  expect 20-30 GRB/yr localized & followed

- **Swift**: launch exp. 2003
  BAT: 10-150 keV CdZnT, $\theta \sim 1 - 4'$;
  XRT: 0.2-10 keV CCD, $\theta \sim 1''$;
  UVOT: 170-650 nm, $\theta \sim 0.5''$
  expect 300 GRB/yr localized & followed

- **GLAST**: launch exp. 2005
  - LAT: 20 MeV-300 GeV, $\theta \sim 0.15$ deg (10 GeV)
    pair-conversion modules + calorimeter,
  - GBM: 10 keV - 30 MeV, CsI and BGO
  expect 200-300 GRB/life of mission
Swift Overview
Catching Gamma Ray Bursts on the Fly

Capabilities
- ~1000 GRBs studied over a three-year period
- 0.3-2.5 arc-second positions for each GRB
- Multiwavelength observatory (gamma, X-ray, UV, and Optical) to monitor afterglows
- 20-70 s reaction time
- Five times more sensitive than BATSE
- Six colors covering 170-650 nm spectroscopy from 0.2 to 150 keV
- UV and optical spectroscopy with R ~ 300-600
- Capability to directly measure redshift
- Results publicly distributed with seconds

Swift

PGS 2003
The Swift Gamma Ray Burst Explorer

Catching Gamma Ray Bursts on the Fly

PI: Neil Gehrels
Lead University Partner: Penn State
Countries Involved: USA, Italy, UK
Spacecraft Partner: Spectrum Astro

Goddard Space Flight Center
Penn State University
Leicester University
Mullard Space Science Laboratory
Osservatorio Astronomico di Brera
Los Alamos National Laboratory
University of California, Berkeley
Instituto di Fisica Cosmica, Milano
Princeton University
Sonoma State University, California
University of California, Santa Barbara
Centre d'Etudes Nucleaires, Saclay
Agenzia Spaziale Italiana (ASI)
Università di Roma
Osservatorio Astronomico di Roma

NRAO
GLAST

LAT: 2.0 MeV-300 GeV
θ ~ 0.15 deg (10 GeV)

GBM: 10 keV - 30 MeV
C/I ≈ 500

→ 200-300 GRB/mission
OTHER INTERESTING

( M O R E  S P E C U L A T I V E ,
A N D  S O  F A R  U N C O N F I R M E D )

GRB SIGNALS:

1. UHE COSMIC RAYS $\lesssim 10^{20}$ eV
2. UHE NEUTRINOS $\lesssim 10^{18}$ eV
3. GRavitational WAVES $\lesssim 10^{3}$ Hz
UHE Cosmic Rays

- Internal & external *reverse* shocks mildly relativistic
  → CR particle en. sp. \( N(E_p) \propto E_p^{-2} \)

- Can reach \( E_p \sim 10^{20} E_{p,20} \, \text{eV}, \) if
  \( \xi_B / \xi_c > 0.02 \Gamma_{300}^2 E_{p,20}^2 L_{75,52}^{-1}, \quad \Gamma > 130 E_{p,20}^{3/4} \Delta t_{10 \text{ms}}^{-1/4} \)

- CR energy input at \( E_p \sim 10^{20} \, \text{eV} \)
  \( E^2 (d\bar{n}_{CR}/dE)_{z=0} \sim 10^{44} \zeta \, \text{erg/Mpc}^3 \text{yr} \sim \text{obs. value} \)
  \( (\zeta \sim 1 - 8); \) Waxman 95, PRL75,386; Vietri 95 ApJ 453,883

- Can entire \( \gtrsim 10^{20} \, \text{eV} \) CR flux be from GRB?
  No: Stecker 00 APPh 14,207; Farrar & Piran a-ph/0010379
  Yes: Waxman 00,NucPhS 87,345; Dermer, a-ph/0005440; a-ph/0010564
  also: Waxman&Bahcall a-ph/9807282; Mannheim etal a-ph/9812398

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![Graph](image)

Fig. 1.— The UHECR flux from GRB expected in a cosmological model, compared to the Fly's Eye, Yakutsk and AGASA data. 1σ flux error bars are shown. The highest energy points are derived assuming the detected events (1 for Fly's Eye and Yakutsk, 4 for AGASA) represent a uniform flux over the energy range \( 10^{20} \, \text{eV} - 3 \times 10^{20} \, \text{eV} \). (Waxman, Neutrino 2000, hep-ph/0009152)
TeV Neutrinos from $p\gamma$ in Bursting and Stifled Fireballs

- Previous neutrino mechanisms & energies:
  - $p, n$ inelastic collisions $\rightarrow \epsilon_\nu \sim 1 - 5$ GeV
  - $p, \gamma$ ($\epsilon_\gamma \sim$ MeV, int. shock) $\rightarrow \epsilon_\nu \gtrsim 500$ TeV
  - $p, \gamma$ ($\epsilon_\gamma \sim$ eV, ext rev sh.) $\rightarrow \epsilon_\nu \gtrsim 10^{18}$ eV
  - ... and, new mechanism ...

- $p, \gamma$ ($\epsilon_\gamma \sim$ keV, stifled fireball) $\rightarrow \epsilon_\nu \sim$ TeV

Mészáros & Waxman 01, astro-ph/0103275

- $\epsilon_\nu \gtrsim 2 \left( \frac{1+z}{2} \right)^{-1} \left( \frac{r_{12}^2 t_2}{E_{53}} \right)^{1/4}$ TeV.

$F_{\nu_\mu} \approx F_{\bar{\nu}_\mu} \approx F_{\nu_\tau} \sim \frac{E/8}{4\pi D_L^2} = 10^{-5} \frac{E_{53}}{D_{28}^2}$ erg/cm$^2$

avg.: $N_\mu \approx \frac{P_0}{E_0} \frac{E/4}{4\pi D_L^2} = 0.2 \frac{E_{53}}{D_{28}^2}$ km$^{-2}$ in km$^3$ det. (ICECUBE) $\rightarrow 10^{-5}$ km$^{-2}$

$N_{\mu, bkg} \sim 3 \times 10^{-5} (\theta/\text{deg})^2 t_2$ km$^{-2}$

- Measure TeV $\nu$ precursor in individual succesful GRB bursts (whether $\gamma$-detected or not)
  - and measure TeV $\nu$ from choked (failed) GRB
  - constrain envelope size (progenitor), high-$z$ IMF
AMANDA

Depth
- surface
- 50 m
- snow layer
- 60 m
- 810 m
- 1000 m
- 1150 m
- 1500 m
- 2000 m
- 2350 m

AMANDA as of 2000
Eiffel Tower as comparison
(true scaling)

AMANDA-A (top)
AMANDA-B10 (bottom)

zoomed in on

Optical Module
- HV divider
- pressure housing
- PMT
- silicon gel
- light diffuser ball

zoomed in on one optical module (OM)

AMANDA : $\frac{1}{25}$ km$^3$

ICECUBE : 1 km$^3$ ....
SC. W. SUR

BASED ON

**BAT**: 300 GRB/yr w. 5x BATSE sensit. w. at least \( \theta \leq 1' - 4' \) position (\( m_{55} \))

Spectra \( \Gamma \sim 20 \) (10-150 keV)

FOV: 2.5 sq.

**XRT**: 100-300 /yr w. \( \theta \sim 0.3" - 2.5" \) position (\( m_{70} \))

\( F \geq 2 \times 10^{-6} \text{erg/cm}^2/\text{keV/s} \) (10^4 s)

Spectra \( \Gamma \sim 20 \) (0.2-10 keV)

FOV: 23' x 23'

**UVOT**: 100-300 /yr 6-color photon. 170-650nm

\( 1.5 < z < 5 \) (\( M_{V} < 24 \) \( \times 10^{3} \))

\( \sim 4 \text{m from quasar} \)

Spectra \( \Gamma \sim 300 - 600 \) \( M_{V} \leq 17 \)

\( \sim 10^{3} \text{E resolution} \)

\( \theta \leq 0.5' \) position

FOV: 17' x 17', \( f/13, 30 \text{cm} \), ap.

\( M_{V} \leq 21 \) (10^6) GROtSE, SLOTIS: 18, 19
Quantum gravity effects? In some models of string quantum gravity and in loop quantum gravity, expect vacuum dispersive effects for EM waves,

\[ \nu = c \left[ 1 \pm \chi (E_\gamma / E_{QG}) \right], \]

where \( \chi \sim 1 \), \( E_{QG} \sim \mathcal{O} (E_{Pl}) \sim 10^{19} \) GeV.

Figure of merit \( \phi \equiv (D/c\Delta t)(E_\gamma / E_{QG}) \)

BATSE: \( \phi \sim 10^{-2}\Delta t_{-3} \), sensitive to \( E_{QG} \gtrsim 10^{-2} E_{\text{Planck}} \)

GLAST: \( \phi \sim 10\Delta t_{-3} \), sensitive to \( E_{QG} \lesssim 1 - 10E_{\text{Planck}} \)

Amelino-Camelia et al. 98, Nature 393, 763;

Gambini & Pullin 99 PRD 59,124021
Fig. 1.—The figure shows the integral event rate of binary coalescences with characteristic strains greater than $h_c$. The three models are a fit to the GRB rates with a constant comoving rate and $z = 1$ spectral index (solid line), a fit to the GRB rates with a comoving rate proportional to $r(z) \propto t(z)^2$ (dashed line), and a constant event rate of $10^{-7} h^{-3}$ Mpc$^{-3}$ yr$^{-1}$ (solid with points). The strain scales as $h_0 \mu_5^{1/2} M_{50}^{1/3} f_{50}^{1/6}$. The estimated LIGO sensitivity $h_{3\text{ yr}}$ is shown by the vertical solid line, and the sensitivity improvement from using coincidences with GRBs is shown by the vertical dashed line.

Kochanek & Piran 1993  Apr 4, 17, 17
(Binary point mass quadrup. estimate)
GW FROM DNS MERGER

Fig. 16. Same as Fig. 15 but for Models O and o.

Fig. 19. Gravitational waveforms, $h_+$ and $h_\times$, for Models M and O, respectively, as functions of time.

Ruffert & Janka

Fig. 18. Gravitational-wave luminosity as a function of time for the off-center collision Models O and o, compared with the result from Centrella & McMillan (CM, 1993, Fig. 11).
GW from COLAPSAR

Fig. 8.— Comparison of the characteristic wavetrain for black hole ringing to the mean noise in enhanced LIGO interferometers (broad-band configuration). The two tracks for each source show the change in strain as the parameter $\alpha_{\text{ring}}$ [which apportions signal power between $m = 0$ and $m = 2$ modes; cf. Eq. (31)] varies from 0 to 1. The tracks begin at the upper right dark circles and evolve downwards and to the left. The open circles indicate the half way point in time of the evolution. Notice that the wavetrain associated with collapsars quickly falls to its minimum value; this is because the accretion starts out strong but is quickly reduced. The Population III waves are computed assuming the energy emission parameter $\varepsilon = 0.1$ [an optimistic choice, but not excessively so; cf. Eq. (26)] and $T_{\text{thump}} = 0.1$ seconds (indicating a fairly clumpy flow). The collapsar track assumes that $\varepsilon = 0.5$ (an extremely optimistic choice) and $T_{\text{thump}} = 0.5$ seconds (indicating a very clumpy flow). ($\varepsilon = 1$)

Fryer, Holz & Hughes, astro-ph/0106113
FIG. 6: Comparison of source strength to noise magnitude for several astrophysical gravitational-wave sources. The heavy black bands are the various incarnations of LIGO interferometers: initial (top, solid), advanced in wide band configuration (bottom, solid), advanced in narrow band configuration (bottom, dotted). The meaning of the various source markers included here is described in the text. (Figure adapted by Kip Thorne for our use, from Ref. [18].)
Fig. 2.— The center panel shows points indicating the peak flux and redshift for 5000 GRBs selected from the SFR distribution with the BATSE flux cutoff; the asterisks are GRB970508, GRB971214, and GRB980703. The left panel shows the number of GRBs per year in each peak flux range, divided into 20 evenly spaced logarithmic bins. The dot-dash vertical line shows the BATSE flux cutoff. The histogram in the bottom panel shows the expected number of bursts per year in each redshift range, divided into 30 evenly spaced logarithmic bins. The total number of bursts is generated by setting the number in each model equal to the number per year seen by BATSE, corrected for BATSE's effective coverage of 48.3 percent of the sky. In left and bottom panels, the solid histogram is the SFR model, and the dashed histogram is the CCD model. The dotted line in the left panel is the BATSE catalog.

(Krumholz et al. 98) ApJL 504, 181
<table>
<thead>
<tr>
<th>Event</th>
<th>Rate obs ( (\text{dy}^{-1}) )</th>
<th>Rate occur ( (\text{yr}^{-1} \text{Gal}^{-1}) )</th>
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<tbody>
<tr>
<td>DNS, BH/NS</td>
<td>( 3 \times 10^{-3} )</td>
<td>( 10^{-7} - 3 \times 10^{-5} )</td>
</tr>
<tr>
<td>COLL (1,2)</td>
<td>( 4 \times 10^{-7} - 4 \times 10^{-5} )</td>
<td>( 10^{-5} - 10^{-3} )</td>
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<tr>
<td>HE/BH</td>
<td>( 10^{-1} - 4 \times 10^{-3} )</td>
<td>( 3 \times 10^{-7} - 10^{-4} )</td>
</tr>
<tr>
<td>WD/BH</td>
<td>( 10^{-2} - 5 \times 10^{-1} )</td>
<td>( 3 \times 10^{-9} - 10^{-7} )</td>
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Ap 526:152
(Fryer, Woosley, Hartmann 99)

\[
\begin{align*}
\text{Gpc:} & \quad h_c \sim 2 \times 10^{-23} & h_0/\text{M}_\odot & \frac{1}{2} & \frac{1}{3} & \frac{1}{6} & (\text{GHz/DL}) \left( \text{Hz} \right) \left( \text{GHz} \right) \left( \text{DL} \right) \\
\text{GF:} & \quad h_{\text{coll}} \sim 2 \times 10^{-22} & h_0/\text{M}_\odot & \text{h.o.s} \ldots \ldots & (\text{GHz/DL}) & \frac{5}{6} & \left( \text{GHz} \right) & \left( \text{DL} \right)
\end{align*}
\]

**GRB Rates (Swift, expected)**

<table>
<thead>
<tr>
<th>( z )</th>
<th>DL (Gpc) ( (h_0 = 0.65) )</th>
<th>( \sigma_{\text{GRB}} )</th>
<th>#/yr</th>
<th>( h_{\text{coll}} ) ( (2 \text{kHz}) ) ( (\text{optimistic}) )</th>
<th>( h_{\text{DNS}} ) ( (1000 \text{kHz}) ) ( (\text{conservative}) )</th>
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<td>( 2 \times 10^{-24} )</td>
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<td>0.3</td>
<td>1.7</td>
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<td>15</td>
<td>( 2 \times 10^{-22} )</td>
<td>( 2 \times 10^{-23} )</td>
</tr>
<tr>
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<td></td>
<td>( \text{few} )</td>
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<tr>
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<td>3</td>
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<td>( 2 \times 10^{-22} )</td>
<td>( 2 \times 10^{-22} )</td>
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