Ultra-High Energy $\nu$
from
Gamma-Ray Bursts

Peter Mészáros
Pennsylvania State University
First Detection of GRB

- Vela 4a (US DoD) monitored nuclear (& cosmic!) explosions
- Vela 5a,b/6a,b det 73 GRB in 1969-79
Compton Gamma Ray Observatory (CGRO): 1991-2000

• 4 γ-ray detectors:
  - BATSE: 20keV-1MeV
  - OSSE: 0.05-10 MeV
  - Comptel: 0.8-30MeV
  - EGRET: 30MeV-20GeV

CGRO MAIN RESULTS:

• BATSE all-sky survey:
  1) GRB → isotropic distrib., implying cosmological distance
  2) Long (>2 s) & short (<2 s)
  3) Non-thermal γ- spectra
• Spectra are non-thermal (broken PL)
• $E_{pk} \sim 0.3$ MeV, most energy above it
• Flux extends $>10$ GeV in some GRB

**GRB Durations:**
Range: $t_\gamma \sim 10^{-3} - 10^3$ s
bimodal (short/long)
BeppoSAX: 1996-2002

- γ-ray wide-angle det. + XR NFI + UVO tel

- → 1st afterglow det!

- ~ 40 GRB XR/O/R afterglows det., and ↑

- Precise loc’n → host galaxy → redshift dist.

- → calibr. flux, energy

← GRB 970228 X-ray fading afterglow
GRB: basic numbers

- Distance: $0.35 \lesssim z \lesssim 4.5$ $\rightarrow D \sim 10^{28}$ cm
- Fluence: $F = \int flux.dt \sim 10^{-4} - 10^{-7}$ erg/cm$^2$
  $\sim 1$ ph/cm$^2$
- Energy output: $10^{53} (\Omega/4\pi) D_{28.5}^2 F_{-5}$ erg

  jet: $\Omega \sim 10^{-2} - 10^{-1}$ $\rightarrow E_{\gamma,\text{tot}} \sim 10^{51}$ erg

  $E_{\gamma,\text{tot}} \sim L_\Theta \times 10^{10}$ year $\sim L_{\text{gal}} \times 1$ year
- Rate(GRB) $\sim 1$/day $\rightarrow 10^{-6} (\Omega/2\pi)^{-1}$ /yr/gal
  (whereas Rate[SN] $\sim 10^7$ /yr $\sim 1$/s at $z \approx 1$)
Generic GRB model: Hyperaccreting BHs

- **Very, very fast jet**
  - **NS - NS merger**
  - **BH - NS merger**
  - **BH - WD merger**

- **0.01 M_☉ torus**
- **0.1 M_☉ torus**
- **1 M_☉ torus**
- **Few M_☉ torus**

- **NS/BH - He core merger after common envelope**
- **Collapse of rotating, collapsing "failed" supernova**

**Note:**
- Should also produce **Neutrinos**, Gravity waves

---

*Source: M. Ruffert, H.-Th. Janka, 1998*
Explosion $\rightarrow$ FIREBALL

- $E_\gamma \gtrsim 10^{51} \Omega_{-2} D^{2.28.5} F_{-5}$ erg
- $R_0 \sim c t_0 \sim 10^7 t_{-3}$ cm
  - Huge energy in very small volume
- $\tau_{\gamma\gamma} \sim (E_\gamma/R^3_0 m_e c^2) \sigma_T R_0 \gg 1$
  - Fireball: $e^\pm, \gamma, p$ relativistic gas
- $L_\gamma \sim E_\gamma/t_0 \gg L_{\text{Edd}} \rightarrow$ expanding ($v \sim c$) fireball
  
  (Cavallo & Rees, 1978 MN 183:359)

- Observe $E_\gamma > 10$ GeV ...but
  
  $\gamma\gamma \rightarrow e^\pm$, degrade 10 GeV $\rightarrow 0.5$ MeV?
  
  $E_\gamma E_t > 2(m_e c^2)^2/(1-\cos\Theta) \sim 4(m_e c^2)^2/\Theta^2$
  
  Ultrarelativistic flow $\rightarrow \Gamma \gtrsim \Theta^{-1} \sim 10^2$
  
  (Fenimore et al 93; Baring & Harding 94)
BH + accr. Torus $\rightarrow$ Jet

- Collapsar or merger $\rightarrow$ BH+accr.torus
- Nuclear density hot torus $\rightarrow$ $\nu\nu\rightarrow e^\pm$
- Hot infall $\rightarrow$ conv.
- Dynamo $\rightarrow$ $B\sim10^{15}$ G, twisted (thread BH?)
- $\rightarrow$ Alfvénic or $e^\pm p\gamma$ jet
- (Note: magnetar might do similar)
Jet emergence from star

- Num. simulations: (Aloy et al 00; Zhang, Woosley, McFadyen 02)
- So far: 2D, SR; jet first $v_h \lessapprox c$, then $v_h \rightarrow c$, in agreement with analytical calculations
- KH instability: variable power output, $\Gamma$
- Preliminary (num.) conclusion: jets emerge only from stars of $R_* \lessapprox 10^{11}$ cm; but larger stars not calculated numerically.
- Analytical estimates indicate larger radii may be possible (Meszaros, Rees 02, ApJ 556, L37)
- $\Gamma \gtrapprox 150$, → OK

Shocks in Fireball Outflow

- **Shocks** expected in any unsteady supersonic outflow (esp. in a non-vacuum environment)
- **Internal** shocks: fast shells catch up slower shells (unsteady flow)
- **External** Shock: flow slows down as it plows into external medium
- NOTE: “ext.” termination shock & internal shocks can be expected also while jet is still inside star
Shock Acceleration $\rightarrow$ Non-th. $\gamma$-Sp.

- Strong shocks accelerate charged particles $(e^\pm, p^+)$ $\rightarrow$ relativistic power law
- Post-shock turbulent dynamo $\rightarrow$ mag. fields
- $(e^\pm, B) \rightarrow e^\pm$ synchrotron, $(\gamma, e^\pm) \rightarrow$ Inv. Compton $\gamma$
- $\rightarrow$ broken power-law (non-thermal) $\gamma$-spectra from power-law $e^\pm$

[Other possibilities:
- magn. reconnect. $\rightarrow$ lin. accel. (Drenkhahn);
- wake-field accel. $\rightarrow$ lin. accel. (Chen et al)]
GeV-TeV photons from GRB

- Internal shocks: $\gamma\gamma \rightarrow e^\pm$, $\tau_{\gamma\gamma} \geq 1$ @ $E_\gamma \gtrsim \Gamma^2 \, 300$ GeV
  $\rightarrow$ pair cutoff in spectr
  $\implies$ get info about $r_{sh}$ (compactness, $\tau_{\gamma\gamma}$)
- In ext.shock, $\tau_{\gamma\gamma} \leq 1$ on GRB target $\gamma$;
- test if shock is int. or ext;
  test bulk Lorentz factor, shock accel efficiency, magnetic field in shock
  (max. $e^\pm$ energy? $\rightarrow$ size of accel region)

Baring 1999

![Graph showing energy distribution and attenuation with parameters](image)
Opacity of the Universe

- In ext. shock, $\tau_{\gamma\gamma} \leq 1$ for $>\text{TeV}$ on GRB target $\gamma$, but
- In Universe, $\tau_{\gamma\gamma} \geq 1$ for $>\text{TeV}$ on IR bgk $\gamma$ ($D \approx 100\text{Mpc}$) → test IR bgk spectral density,
- constrain early star formation rate & $z$-distr of SFR, LSS, cosmology
GeV-TeV γ & GW Facilities

Cherenkov Telescopes
0.1-5 TeV
← Water
Air →

HESS, VERITAS,..

Pair conv
20 MeV-300 GeV
←

Laser interf
Grav wave
Detector →

MILAGRO

GLAST

LIGO

P. Mészáros, NeSS02 9/19/02
CR’s & ν’s : sub-TeV to ZeV

- Universe opaque to $\gamma$ at $\epsilon_\gamma \gtrsim 10^{12}$ eV due to $\gamma \gamma \rightarrow e^\pm$ on IR background $\gamma$.
- Universe also opaque to $p$ at $\epsilon_p \gtrsim 10^{20}$ eV due to $p\gamma \rightarrow \pi^+ + \ldots$ on CMB.
- All $p$ of $\epsilon_p \lesssim 10^{19}$ eV lose directional information ($B_{\text{gal}}$).

- $\nu$ is only UHE witness from high z pointing back to its source!
“Thermal” Proton-Neutron Effects in GRB Fireball

- $p$-$n$ in f’ball move together while $t_{pn} > t_{exp}$ (rad. press. acts on $p$, elastic scattering couples $p,n$)
- $p$-$n$ decouple when $t_{pn} \gtrsim t_{exp}$ (also $\tau_{pn} \sim 1$, $v_{rel} \rightarrow c$) $\sigma_{pn} \rightarrow$ inelastic; occurs for $\Gamma \gtrsim \Gamma_{\pi} \sim 400$
  (Derishev et al 99; Bahcall, Meszaros 00; Fuller et al 00)
- Inelastic $pn \rightarrow \pi^{\pm} \rightarrow \mu^{\pm}, \nu_{\mu} \rightarrow e^{\pm}, \nu_{e}, \nu_{\mu}$
  $\epsilon_{\nu_{\mu}} \sim 5$-$10$ GeV
- **ICECUBE**: det @ $z \sim 1$, $R_{\gamma} \sim 7$/yr from all GRB, in coinc.w. $\gamma$ -rays
  (but only if larger PMT density)
- **GLAST**: $\pi^{0} \rightarrow 2\gamma$, $\epsilon_{\gamma} \sim 10$ GeV, det @ $z \sim 0.1$

(Bahcall & Meszaros 2000 PRL 85:1362)
Relativistic Proton Effects in GRB

- **Shocks**: internal & ext. rev. shocks: mildly relativistic $\rightarrow$ p-spectrum $N(E) \propto E^{-2}$
- Can reach $E_p \lesssim 10^{20}$ eV
  (& contr. to diff. CR flux: Waxman 95; Vietri 95)
- **Other obs. effects?**
  1) p-synchrotron $\gamma$; but $\rightarrow$ narrow param. space
    (Totani 98, Zhang & Mészáros 01)
  2) photo-hadronic $\gamma$’s
    (Böttcher & Dermer 98; Fragile et al. 02)
  3) photo-hadronic $\nu$’s
    (Waxman & Bahcall 97)
UHE $\nu$’s from $p\gamma$ collisions

- **Int. shocks**: $E_p > 10^{16}$ eV, coll. with $\sim 1$ MeV $\gamma$-rays,
  \[ \frac{dN_\gamma}{dE} \propto E^{-\beta}, \beta \sim 1,2 \]
  \[ \implies p\gamma \rightarrow \pi^\pm \rightarrow \mu^\pm, \nu_\mu \rightarrow e^\pm, \nu_e, \nu_\mu \quad (\Delta\text{-res.}) \]
  \[ \implies E_\nu \sim 5 \times 10^{14} \text{ eV} \Gamma_{300} (E_\gamma/1 \text{MeV})^{-1}, \]
  \[ E_\nu^2 \Phi_\nu \approx 10^{-9} (E_\nu/E_{\nu_b}) \text{ GeV/cm}^2 \text{ s sr} \]
  (Waxman, Bahcall 97; Rachen, Meszaros 98)

- **External shock**: $E_p > 10^{19}$ eV, coll. with $\sim 10$ eV $\gamma$’s,
  \[ \implies E_\nu \sim 5 \times 10^{17} - 10^{19} \text{ eV}, \]  
  (Waxman, Bahcall 00, Vietri 98)
  \[ E^2 \nu \Phi_\nu \approx 10^{-10} (E_\nu/10^{17} \text{eV})^\beta \text{ GeV/cm}^2 \text{ s sr} \]

- **Detect w.** **ICECUBE** (& test shock acc)
- **$p\gamma \rightarrow \pi^0 \rightarrow 2\gamma, E_\gamma \sim 0.1-1$ GeV $\rightarrow$ **GLAST**
Range of possible neutrino fluxes associated with the maximum energy CRs. "Transparent": source From which CRs escape after one interaction; “obscured”: where CRs are trapped, only ν’s escape. (from Halzen & Hooper 02)
TeV γ from bursting & choked GRB

- Collapsar: jet has termination shock and internal shocks, also while inside the star
- Int. shocks accel. protons to $E_p > 10^5$ GeV, which collide with thermal X-rays in jet cavity
- $E_{\gamma} \approx 2(2/1+z)$ TeV
  $F_{\gamma} \approx 10^{-5} E_{53}/D_{28}^2$ erg/cm²
  $N_\mu \approx 0.2$ /km² (avg., $R \approx 10^5$ /yr)
  $\sim 10$ /km² (rare, $R \sim 3$ /yr)
- $\gamma$-precursor in $\gamma$-bright GRB;
- $\gamma$-burst in $\gamma$-dark (choked)GRB
  → new “unseen” sources! e.g. “first” gen. (pop. III) stars?
Diffuse UHE $\nu$ from pop.III collapse

- At $z \sim 6-30(?)$: pop.III $\star$, $M_* \sim 30-300 \, M_\odot$, core coll.
  $\rightarrow M_{BH} \sim 15-150 \, M_\odot$
  $E_{iso} \sim 10^{54}-10^{56}(?)$ erg

- Buried jets $\rightarrow p\gamma \rightarrow \nu_\mu$, $\rightarrow \nu$-bursts, AMANDA/ICECUBE

- Escaping jets? $\rightarrow p\gamma \rightarrow \nu_\mu$
  $\rightarrow \nu, \gamma$-bursts, ICECUBE, Swift
  $\epsilon_\nu \sim 1-50$ TeV, $\epsilon_\gamma \sim 0.1-1$ MeV

- Detect highest $-z$ $\star$ form’n, get primordial IMF,
Prediction model-dependence & Detectability of GRB $\nu$

- $E_\nu \sim 100$ TeV are least model dependent
  (use observed MeV $\gamma$ & same shocks as accelerate $e^{\pm}$)
- $E_\nu \sim 1$ TeV: more model dependent,
  (also assume collapsar model, and $R_\star \approx 10^{11}$ cm)
- $E_\nu \sim 10^{17}$ eV: need assume reverse shock prompt opt flash is ubiquitous (?)
- $E_\nu \sim 5$ GeV: likely, but need special instr’pt
Other Implications of GRB $\nu$

- **Special relativity**: simultaneity of arrival of $\nu, \gamma$ tested to $\Delta t \lesssim 1 \text{ s} \left(10^{-3} \text{ s in short bursts}\right)$

- **Time delay due to $\nu_i$ mass**:
  \[ \Delta t (\nu_i) \sim 10^{-12} \left(\frac{D}{100 \text{Mpc}}\right) \left(\frac{E_{\nu_i}}{100 \text{TeV}}\right)^{-2} \left(\frac{m_{\nu_i}}{\text{eV}}\right)^2 \text{ s} \]
  (whereas for SN 1987a $\Delta t (\nu_i) \sim 10^{-8} \text{ s}$)

- **Vacuum oscillations**: at source exp. $N_{\nu_\mu} \sim 2N_{\nu_e}$, at observer exp. $\approx$ ratios, and upgoing $\tau$ appear.

- → sensitive to
  \[ \Delta m^2 \gtrsim 10^{-16} \left(\frac{E_{\nu_i}}{100 \text{TeV}}\right) \left(\frac{100 \text{Mpc}}{D}\right) \text{ eV}^2 \]
  (for $m_\nu \gtrsim 0.1 \text{ eV}$ due to finite pion life mixing is caused by decoherence rather than oscillation)
Summary

• GRB studied from radio to $\gtrsim$ GeV (so far)
• Working model (relat. fireball + shocks) works well (so far): will it continue to?
• Progress being made on central engine, progenitor
• Significant potential as cosmological tool
• TeV-EeV neutrino signals: new window
  - absorption & deflection-free UHE astrophys. probe
  - probe fund. interactions & accel. $\@ E_{cm} \gtrsim$ PeV
• More surprises expected!