Are gamma-ray bursts the sources of ultra-high energy cosmic rays?

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Contents

- Introduction
- Simulation of sources
- Multi-messenger astronomy with gamma-ray bursts (GRBs):
  Neutrinos, gamma-rays, cosmic rays
- Combined source-propagation model
- Summary
Cosmic messengers

Physics of astrophysical neutrino sources = physics of cosmic ray sources
Cosmic ray observations

- Observation of cosmic rays: **need to accelerate protons/nuclei somewhere**
- The same sources should produce neutrinos:
  - in the source (pp, p\(\gamma\) interactions)
  - Proton (E > 6 \(10^{10}\) GeV) on CMB ⇒ GZK cutoff + cosmogenic neutrino flux

Where do these come from?

In the source: \(E_{p,\text{max}}\) up to \(10^{12}\) GeV?

GZK cutoff?
Example: IceCube at South Pole. Detector material: \(~ 1 \text{ km}^3\) antarctic ice

Completed 2010/11 (86 strings)

Recent major successes:

- Constraints on GRBs
- 28 events in the TeV-PeV range
  - *Science* 342 (2013) 1242856

- Neutrinos established as messengers of the high-energy universe!

http://icecube.wisc.edu/
http://antares.in2p3.fr/
Neutrinos in the TeV-PeV range

~ 11 events of atmospheric origin.
The rest: Galactic? Extragalactic?

Where do these come from?

Prompt atmospherics?
Directional information: Clustering?
Isotropic/from Galactic plane/Galactic center?

Why no events > PeV?
Which source class? More than one?
⇒ Requires more statistics

No correlation with GRBs! however: if to be correlated with sources of UHECR, large $\Gamma$ and $B$ required
⇒ GRB???

(WW, PRD 88 (2013) 083007)

Equatorial

TS=2log(L/L0)

Science 342 (2013) 1242856
The two paradigms for extragalactic sources: AGNs and GRBs

- Active Galactic Nuclei (AGN blazars)
  - Relativistic jets ejected from central engine (black hole?)
  - Continuous emission, with time-variability

- Gamma-Ray Bursts (GRBs): transients
  - Relativistically expanding fireball/jet
  - Neutrino production e.g. in prompt phase
    
    (Waxman, Bahcall, 1997)

Cosmic Rays: 100 years of mystery

Using data from the IceCube Neutrino Observatory, astrophysicists Nathan Whitehorn and Pete Redl searched for neutrinos coming from the direction of known GRBs. And they found nothing.

Their result, appearing today in the journal Nature, challenges one of the two leading theories for the origin of the highest energy cosmic rays.

Nature 484 (2012) 351
Internal shock model

(Source: SWIFT)

Engine (intermittent)

"Isotropic equivalent energy"

Observable: Light curves

(Simulation by M. Bustamante)

\[ \Gamma \sim 200-1000 \]

Prompt phase

Collision of shells
⇒ Shocks
⇒ Particle acc.
Fermi shock acceleration

- Fractional energy gain per cycle: $\eta$
- Escape probability per cycle: $P_{\text{esc}}$

- Yields a non-thermal power law spectrum
  \[ \sim E^{-(P_{\text{esc}}/\eta+1)} \]
- $P_{\text{esc}}/\eta \sim 3/((\chi-1))$ in shock acc., where $\chi$ is the compression ratio of the shock
- $\chi \sim 4$ for a strong shock $\Rightarrow P_{\text{esc}}/\eta \sim 1$ and $E^{-2}$ is the typical “textbook” spectrum
Simulation of cosmic ray and neutrino sources

(focus on proton composition …)
Cosmic ray source
(illustrative proton-only scenario, pγ interactions)

If neutrons can escape:
Source of cosmic rays

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

If neutrons can escape:
Source of cosmic rays

Neutrinos produced in ratio $(\nu_e : \nu_\mu : \nu_\tau) = (1:2:0)$

$p + \gamma_{\text{CMB}} \rightarrow \Delta^+ \rightarrow \text{Cosmogenic neutrinos}$

$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} \nu + \pi^+ & 1/3 \text{ of all cases} \\ p + \pi^0 & 2/3 \text{ of all cases} \end{cases}$

$\pi^+/\pi^0$ determines ratio between neutrinos and high-E gamma-rays

$\pi^0 \rightarrow \gamma + \gamma$

High energetic gamma-rays;
typically cascade down to lower E

Cosmic messengers
\( \Delta (1232) \)-resonance approximation:

\[
p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} 
  n + \pi^+ & 1/3 \text{ of all cases} \\
  p + \pi^0 & 2/3 \text{ of all cases}
\end{cases}
\]

- Limitations:
  - No \( \pi^- \) production; cannot predict \( \pi^+ / \pi^- \) ratio (Glashow resonance!)
  - High energy processes affect spectral shape (X-sec. dependence!)
  - Low energy processes (t-channel) enhance charged pion production

- Solutions:
  - SOPHIA: most accurate description of physics
    - Mücke, Rachen, Engel, Protheroe, Stanev, 2000
      - Limitations: Monte Carlo, slow; helicity dep. muon decays!
  - Parameterizations based on SOPHIA
    - Kelner, Aharonian, 2008
      - Fast, but no intermediate muons, pions (cooling cannot be included)
      - Fast (~1000 x SOPHIA), including secondaries and accurate \( \pi^+ / \pi^- \) ratios

from:

Source simulation: \( p\gamma \) (particle physics)
Dashed arrows: kinetic equations include cooling and escape

Input $\Rightarrow$ Object-dependent:

\[
\begin{align*}
N'_\gamma(E') & \quad N'_p(E') & \quad B'
\end{align*}
\]

Q(E) [GeV\(^{-1}\) cm\(^{-3}\) s\(^{-1}\)] per time frame
N(E) [GeV\(^{-1}\) cm\(^{-3}\)] steady spectrum
Secondary spectra ($\mu$, $\pi$, K) loss-steepeend above critical energy

$$E'_c = \sqrt{\frac{9\pi\epsilon_0m^5c^7}{\tau_0e^4B'^2}}$$

- $E'_c$ depends on particle physics only ($m$, $\tau_0$), and $B'$
- Leads to characteristic flavor composition and shape
- Very robust prediction for sources? [e.g. any additional radiation processes mainly affecting the primaries will not affect the flavor composition]

From the source to the detector: UHECR transport

- **Kinetic equation for co-moving number density:**
  \[
  \dot{Y}_p = \partial_E (H E Y_p) + \partial_E (b_{e^+e^-} Y_p) + \partial_E (b_{p\gamma} Y_p) + \mathcal{L}_{CR}
  \]

  - Expansion of Universe
  - Pair production (Blumenthal, 1970)
  - Photohadronics (Hümmer, Rüger, Spanier, Winter, 2010)
  - CR inj. (z-dep!)

  [here \(b=-dE/dt=E t^{-1}_{\text{loss}}\)]

- **Energy losses**
  \(\Rightarrow\) UHECR must from our local environment
  \(
  \sim 1 \text{ Gpc at } 10^{10} \text{ GeV, }
  \sim 50 \text{ Mpc at } 10^{11} \text{ GeV}
  \)
- Prediction depends on maximal proton energy, spectral index $\gamma$, source evolution, composition
- Can test UHECR beyond the local environment
- Can test UHECR injection independent of CR production model $\Rightarrow$ constraints on UHECR escape

(courtesy M. Bustamante; see also Kotera, Allard, Olinto, JCAP 1010 (2010) 013)
Transition between Galactic (?) and extragalactic cosmic rays at different energies:

- **Ankle model:**
  - Injection index $\gamma \sim 2$ possible
  - Transition at $> 4$ EeV

- **Dip model:**
  - Injection index $\gamma \sim 2.5$-2.7 (how?)
  - Transition at $\sim 1$ EeV
  - Characteristic shape by pair production dip

Figure courtesy M. Bustamante; for a recent review, see Berezinsky, arXiv:1307.4043
Multi-messenger physics with GRBs
Multi-messenger physics

Model-dependent prediction

- GRB stacking

Properties of neutrinos really understood?

Satellite experiments (burst-by-burst)

Partly common fudge factors: how many GRBs are actually observable? Baryonic loading?

Robust connection if CRs only escape as neutrons produced in $p_{\gamma}$ interactions

- Ahlers, Gonzalez-Garcia, Halzen, Astropart. Phys. 35 (2011) 87

CR experiments (diffuse)

Neutrino telescopes (burst-by-burst or diffuse)

Question:

(energy budget, ensemble fluctuations, ...)

GRB stacking

- Idea: Use multi-messenger approach (BG free)

  GRB gamma-ray observations
  (e.g. Fermi, Swift, etc)

  Predict neutrino flux from observed photon fluxes event by event

  Observed: broken power law
  (Band function)

  E$^{-2}$ injection

  (Example: ANTARES, arXiv:1307.0304)
Gamma-ray burst fireball model: IC-40+59 data meet generic bounds

Generic flux based on the assumption that GRBs are the sources of (highest energetic) cosmic rays (Waxman, Bahcall, 1999; Waxman, 2003; spec. bursts: Guetta et al, 2003)

- Does IceCube really rule out the paradigm that GRBs are the sources of the ultra-high energy cosmic rays?
Analytical recomputation of IceCube method (CFB):

- \( c_{\pi} \): corrections to pion production efficiency
- \( c_S \): secondary cooling and energy-dependence of proton mean free path (see also Li, 2012, PRD)
**Quasi-diffuse prediction**  
**(NeuCosmA model)**

- Numerical fireball model cannot be ruled out yet with IC40+59 for same parameters, bursts, assumptions

- "Fudge" factors:
  - Baryonic loading (energy in protons vs. electrons) $\Rightarrow 10^2$?
  - Total number of GRBs in observable universe $\Rightarrow$ chosen to be 667/year

"Astrophysical uncertainties":
- $t_v$: 0.001s ... 0.1s
- $\Gamma$: 200 ... 500
- $\alpha$: 1.8 ... 2.2
- $\epsilon_e/\epsilon_B$: 0.1 ... 10

Neutrinos-cosmic rays

Properties of neutrinos really understood?

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Baryonic loading?

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CR experiments (diffuse)

Neutrino telescopes (burst-by-burst or diffuse)

Model-dependent prediction

\( \gamma \)

GRB stacking

? (energy budget, ensemble fluctuations, …)


Ahlers, Gonzalez-Garcia, Halzen, Astropart. Phys. 35 (2011) 87
The “neutron model”

- If charged $\pi$ and $n$ produced together:

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ & 1/3 \text{ of all cases} \\ p + \pi^0 & 2/3 \text{ of all cases} \end{cases}$$


Consequences for (diffuse) neutrino fluxes

Fit to UHECR spectrum

Ahlers, Gonzalez-Garcia, Halzen, Astropart. Phys. 35 (2011) 87
CR escape mechanisms

Optically thin (to neutron escape)

- One neutrino per cosmic ray
- Protons magnetically confined

Optically thick (to neutron escape)

- Neutron escape limited to edge of shells
- Neutrino prod. relatively enhanced

Direct proton escape (UHECR leakage)

- pγ interaction rate relatively low
- Protons leaking from edges dominate
A typical (?) example

- For high acceleration efficiencies: \( R'_L \) can reach shell thickness at highest energies (if \( E'_{p,\text{max}} \) determined by \( t'_{\text{dyn}} \))

- UHECR from optically thin GRBs will be direct escape-dominated

(Baerwald, Bustamante, Winter, Astrophys.J. 768 (2013) 186)

\[ \Gamma = 300, \ t_v = 0.01 \ s, \ T_{90} = 10 \ s, \ \eta = 1, \ \varepsilon_e/\varepsilon_B = 1, \ f_e = 0.1, \ \alpha_\gamma = 1, \ \beta_\gamma = 2, \ \varepsilon_{\gamma,b} = 1 \ \text{keV}, \ \text{and} \ z = 2. \]
Combined source-propagation model

... as a first step towards completely self-consistent picture
GRB source model:

\[ E_{\gamma,\text{iso}}, f_e^{-1}, \Gamma, \ldots \]

- Determines prompt neutrino and injected cosmic ray spectrum (including composition, \( E_{\text{max}} \), spectral index)

Cosmic ray propagation:

- Cosmological distribution of sources; number of sources (normalization) \( N \)

- Determines observed cosmic ray (incl. GZK cutoff) and cosmogenic neutrino spectra

Use multi-messenger picture (norm. to obs. UHECR flux) to measure \( f_e^{-1} \)
Gamma-ray observables?

- Redshift distribution
  \[ \frac{d\dot{N}}{dz} \sim (1+z)^\alpha \]
  Star formation rate

\[ \frac{d\dot{N}}{dz} = F(z) \frac{\mathcal{E}(z) \rho_*(z) dV/dz}{\langle f_{\text{beam}} \rangle} \frac{1}{1+z} \]

- Total number of observable bursts
  \[ \dot{N} = \int_0^\infty \frac{d\dot{N}}{dz} dz \]
  - Can be directly determined (counted)!
  - Order 1000 yr\(^{-1}\)

- Provides information about cosmic distribution of sources as well (\(\alpha\))

- Cosmic ray leakage (dashed) can evade prompt neutrino bound with comparable $f_e^{-1}$:

(Baerwald, Bustamante, Winter, arXiv:1401.XXXX)
Dip-model transition requires extremely large baryonic loadings (bol. correction!):

- Combined source-prop. model fit
  (cosmic ray dip model transition, $\alpha_p \sim 2.5$)

(Baerwald, Bustamante, Winter, , arXiv:1401.XXXX)
Parameter space?
[ankle model, high acceleration efficiency]

- **Neutron model**
  - Ruled out by current stacking bounds on prompt neutrinos (dark gray)

- **Diffusive escape**
  - Remaining parameter space requires extremely large (unrealistic?) baryonic loadings

(Baerwald, Bustamante, Winter, arXiv:1401.XXXX)
What if: Neutrinos decay?

Decay hypothesis: $\nu_2$ and $\nu_3$ decay with lifetimes compatible with SN 1987A bound

- Reliable conclusions from flux bounds require cascade ($\nu_e$) measurements!

Baerwald, Bustamante, Winter, JCAP 10 (2012) 20
Summary

- GRB explanation of UHECR still possible (plausible?) in “ankle model“ for UHECR transition
- Neutron model for UHECR escape already excluded by current neutrino data
- Future neutrino bounds will strongly limit parameter space where pion production efficiency is large
- Possible ways out:
  - GRBs are not the exclusive sources of the UHECR
  - Extremely large baryonic loadings + direct/diffusive escape [applies not only to internal shock scenario …]
  - Model too simple? Do the cosmic rays and neutrinos come from different collision radii?
Backup
- $z \sim 1$ “typical” redshift of a GRB

- Peak contribution in a region of low statistics
  - Ensemble fluctuations of quasi-diffuse flux

(Baerwald, Hümmer, Winter, Astropart. Phys. 35 (2012) 508)
Not only normalization, but also uncertainties depend on assumptions:

- Internal shock model, target photons from synchrotron emission/inverse Compton from Fig. 3 of IceCube, Nature 484 (2012) 351; uncertainties from Guetta, Spada, Waxman, Astrophys. J. 559 (2001) 2001

- Internal shock model, target photons from observation, origin not specified from Fig. 3 of Hümmer et al, PRL 108 (2012) 231101

- Dissipation radius not specified (e.g. magnetic reconnection models), target photons from observation, origin not specified from Fig. 3 of He, Murase, Nagataki, et al, ApJ. 752 (2012) 29

(figure courtesy of Philipp Baerwald)
The challenge: need high enough $E_p$ to describe observed UHECR spectrum

- The acceleration efficiency $\eta$ has to be high
- Can evade the “one neutrino per cosmic ray” paradigm

(Baerwald, Bustamante, Winter, Astrophys. J. 768 (2013) 186)
The local GRB rate can be written as

\[ \dot{n}_{\text{GRB}} = \frac{1}{\text{Gpc}^3 \text{yr}} \frac{\dot{N}_{\text{tot}} \ [\text{yr}^{-1}]}{968} \frac{1}{f_z} \]

where \( f_z \) is a cosmological correction factor:

| SFR model                        | \( \alpha \) | \( f_z \) | \( \dot{n}_{\text{GRB}} \big|_{z=0} \) [Gpc\(^{-3}\) yr\(^{-1}\)] |
|----------------------------------|--------------|-----------|---------------------------------|
| Hopkins & Beacom (2006)         | 1.2          | 25.15     | 0.08                            |
|                                  | 0.0          | 5.65      | 0.35                            |
| Wanderman & Piran (2010)        | 0.0          | 7.70      | 0.26                            |
| Madau & Porciani (2000)         | 0.0          | 9.89      | 0.21                            |
| SF1                              | 0.0          | 14.42     | 0.14                            |
| SF2                              | 0.0          | 14.36     | 0.14                            |
| SF3                              | 0.0          |           |                                 |
Impact factors

\[ \gamma \]

\[ \dot{N}, E_{\gamma,\text{iso}} \]

\[ \frac{1}{f_e} \times \frac{1}{f_{\text{thresh}}} \times f_\pi \]

\[ \frac{1}{f_z} \times f_{\text{CR}} \times f_{\text{bol}} \]

(Baerwald, Bustamante, Winter, to appear)

Same. Focus on \(1/f_e\) in following

Baryonic loading

Depends on model for UHECR escape

\[ \sim \frac{f_\pi}{f_{\text{CR}} \times f_{\text{bol}}} \]
Required UHECR injection

- Required energy ejected in UHECR per burst:

\[ E_{[10^{10},10^{12}]}^{[10^{10},10^{12}]} = 10^{53} \text{ erg} \cdot \frac{\dot{\varepsilon}_{[10^{10},10^{12}]}^{[10^{10},10^{12}]} \cdot 968 \text{ yr}^{-1}}{N_{tot}} \cdot f_z \]

\[ \sim 1.5 \text{ to fit UHECR observations} \]

\[ \sim 5-25 \]

- In terms of \( \gamma \)-ray energy:

\[ E_{[10^{10},10^{12}]}^{[10^{10},10^{12}]} = f_{\text{CR}} \frac{f_{\text{bol}}}{f_e} E_{\gamma, \text{iso}} \]

Baryonic loading \( f_e^{-1} \sim 50-100 \) for \( E^{-2} \) inj. spectrum (\( f_{\text{bol}} \sim 0.2 \), \( E_{\gamma, \text{iso}} \sim 10^{53} \) erg, neutron model (\( f_{\text{CR}} \sim 0.4 \))

[IceCube standard assumption: \( f_e^{-1} \sim 10 \)]
IceCube method … normalization

- **Connection $\gamma$-rays – neutrinos**

\[ \frac{1}{8} \left( 1 - (1 - \langle x_{p\rightarrow\pi} \rangle) \right) \frac{\Delta R}{\lambda_{p\gamma}} \int_{1\,\text{keV}}^{10\,\text{MeV}} \frac{\text{d}E_{\gamma}}{E_{\gamma}} F_{\gamma}(E_{\gamma}) \]

- **Optical thickness to $p\gamma$ interactions**:

\[ \frac{\Delta R}{\lambda_{p\gamma}} = \left( \frac{L_{\gamma}^{\text{iso}}}{10^{52}\,\text{erg}\,\text{s}^{-1}} \right) \left( \frac{0.01\,\text{s}}{t_{\text{var}}} \right) \left( \frac{10^{2.5}}{\Gamma_{\text{jet}}} \right)^4 \left( \frac{\text{MeV}}{\epsilon_{\gamma}} \right) \]

[in principle, $\lambda_{p\gamma} \sim 1/(n_\gamma \sigma)$; need estimates for $n_\gamma$, which contains the size of the acceleration region]

(Description in arXiv:0907.2227; see also Guetta et al, astro-ph/0302524; Waxman, Bahcall, astro-ph/9701231)
Example:

\[ F_\gamma(E_\gamma) = \frac{dN(E_\gamma)}{dE_\gamma} = f_\gamma \times \left\{ \begin{array}{ll} \left( \frac{\epsilon_\gamma}{\text{MeV}} \right)^{\alpha_\gamma} \left( \frac{E_\gamma}{\text{MeV}} \right)^{-\alpha_\gamma} & \text{for } E_\gamma < \epsilon_\gamma \\ \left( \frac{\epsilon_\gamma}{\text{MeV}} \right)^{\beta_\gamma} \left( \frac{E_\gamma}{\text{MeV}} \right)^{-\beta_\gamma} & \text{for } E_\gamma \geq \epsilon_\gamma \end{array} \right. \]

First break from break in photon spectrum (here: E^{-1} \Rightarrow E^{-2} in photons)

Second break from pion cooling (simplified)