

Gamma Ray Bursts: recent results and connections to very high energy Cosmic Rays and Neutrinos¹

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Abstract. Gamma-ray bursts are the most concentrated explosions in the Universe. They have been detected electromagnetically at energies up to tens of GeV, and it is suspected that they could be active at least up to TeV energies. It is also speculated that they could emit cosmic rays and neutrinos at energies reaching up to the $10^{18} - 10^{20}$ eV range. Here we review the recent developments in the photon phenomenology in the light of *Swift* and *Fermi* satellite observations, as well as recent IceCube upper limits on their neutrino luminosity. We discuss some of the theoretical models developed to explain these observations and their possible contribution to a very high energy cosmic ray and neutrino background.

1. Introduction

Gamma-ray bursts (GRB) are detected at an average rate of a one per day, lasting in gamma-rays from fractions of a second to tens of minutes. We know that these objects are distributed almost isotropically throughout the Universe, out to the largest cosmological distances yet sampled. Yet, while they are on, they far outshine all other sources of gamma-rays in the sky, including the Sun. They are, in fact, the most concentrated and brightest electromagnetic explosions in the Universe, the GRB prompt electromagnetic energy output during tens of seconds being comparable to that of the Sun over $\sim \text{few} \times 10^{10}$ years, or to that of the entire Milky Way over a few years. Their initial γ -ray emission is followed by an X-ray and an optical afterglow lasting for weeks, which during the first day can outshine the brightest quasars and active galactic nuclei in the Universe.

It is thought that GRB result as a consequence of a cataclysmic “end game” in the life of very evolved stars, where about a solar rest mass worth of gravitational energy is released in a matter of seconds or less within a small region of the order of tens of kilometers. This is likely to be the result of the collapse of the core of a massive star, or in some cases from the merger of two compact stellar remnants, either of these scenarios ultimately leading to a stellar mass black hole. Only a small fraction of this energy needs to be converted into electromagnetic

¹ Plenary talk at PASCOS 12, Mérida, Yucatán, Mexico, 2012; to appear in J.Phys. (Conf.Series)

radiation to satisfy the observations. It is thought that this conversion occurs through the dissipation of the kinetic energy of a collimated relativistic jet outflow, a “fireball”, whose bulk Lorentz factors are in the range of $\Gamma \sim 10^2 - 10^3$, expanding from the central engine which is powered by the gravitational accretion of surrounding matter into the collapsed core.

The generic scenario for the production of the observed non-thermal photons typically invokes synchrotron radiation and/or inverse Compton (IC) scattering by relativistic electrons which have been accelerated to a power-law distribution in the shocks expected in the optically thin regions of the outflow. These may be internal shocks, resulting in prompt γ -ray emission, and also external shocks at the termination of the relativistic outflow, which can explain many of the properties of the afterglows. Other mechanisms considered for the prompt emission are, e.g., magnetic dissipation or reconnection in the outflow, jitter radiation in shocks, or dissipative effects in the photosphere where the outflow transitions to optical thinness.

In the past few years, the *LAT* instrument on the *Fermi* spacecraft has shown that a substantial fraction of GRBs have photon spectra which extend at least to tens of GeV [1, 2]. These could be due either to leptonic mechanisms (such as the electron synchrotron or inverse Compton mentioned above), or they might be due to hadronic cascades. Various uncertainties hamper the analysis and modeling of these systems, including our the lack of knowledge about two important parameters of the outflow. These are the baryon load of the outflow, and the magnetic ratio σ between magnetic stresses and kinetic energy, which affect not only the bulk dynamics but also the mechanisms responsible for accelerating electrons and protons in the shocks or the dissipation region. It is the accelerated protons which could lead, in principle, to GRBs being luminous in cosmic rays and neutrinos. Under optimistic scenarios, they could be even more luminous in these particle channels than in the commonly observed MeV electromagnetic channels.

2. Electromagnetic phenomenology: MeV and sub-MeV

The prompt photon emission of GRBs, as documented already in the 1990s by the *Compton* (CGRO) satellite, shows often rapidly variable γ -ray light-curves, leading to a classification into “long” GRBs (LGRBs) whose γ -ray light curve lasts $2 \text{ s} \lesssim t_\gamma \lesssim 10^3 \text{ s}$, and “short” GRBs (SGRBs) for which $t_\gamma \lesssim 2 \text{ s}$, although the latter can be longer at softer energies. The first X-ray afterglows, lasting weeks or more, were discovered by the Italian-Dutch *Beppo-SAX* satellite in 1997, being acquired typically 8 hours after the initial γ -ray trigger. The NASA *Swift* satellite, launched in 2004, was designed to study afterglows within a minute after the trigger.

The *Swift* satellite has three instruments, covering the soft gamma-ray, the X-ray and the ultraviolet/optical ranges. The gamma-ray detector locates bursts to ~ 2 arcminute accuracy and the position is used to repoint the onboard X-ray and UV/O instruments, as well as being rapidly relayed to Earth so ground telescopes can follow the afterglows. Measurements of the redshift distance and studies of host galaxies are generally done with large ground-based telescopes which receive the alerts from the spacecraft. The average *Swift* burst detection rate is ~ 90 per year, of which approximately $\sim 90\%$ have detected X-ray afterglows, mostly among the longer GRBs. The shorter bursts, however, are harder to detect in X-rays, since often they fade rapidly below the X-ray sensitivity limit. With help from ground-based optical observations, about $\sim 60\%$ of *Swift* GRBs yield also an optical afterglow detection. One of the interesting findings of *Swift* was that the afterglow lightcurve has a complex structure. Often a fast decay is seen in the first 1000 s, followed by a shallow decay and then a re-steepening.

The long GRBs are found in the brightest regions of galaxies where intense star formation

occurs. Those which occur near enough are generally found in association with a (simultaneous) supernova of Type Ib or Ic (in more distant LGRB, the supernova is expected to be too faint to be detected). These facts support the view that LGRB are caused by the central core of a massive star collapsing to a compact object such as a black hole, or possibly a magnetar. LGRBs are extremely bright in both their gamma-ray prompt emission and their multiwavelength afterglow. This makes them unique tools for studying the high-redshift universe. For instance GRB 090423, at a redshift $z = 8.2$ is the source with the largest spectroscopically determined redshift. Such high redshift bursts provide information about the universe at a time when it was only a few percent of its current age, providing information about the process of re-ionization of the intergalactic medium and the chemical evolution of the universe. LGRBs also contribute to determining the star formation history of the Universe, since they are the endpoints of the lives of massive stars and their rate is approximately proportional to the star formation rate.

Previous to *Swift*'s launch the origin of short GRBs was very poorly constrained, since no afterglows had been detected to localize them. This changed in 2005 when *Swift* and *HETE-2* detected afterglows leading to a precise localization for several SGRBs, the total number by now being significant. Unlike long bursts, the evidence indicates that SGRBs originate in host galaxies with both low and high star formation rates, i.e. old and young stellar populations. These host properties are substantially different than those of long bursts, indicating a different origin, and, furthermore, nearby SGRBs show no evidence for simultaneous supernovae, both properties being very different than for long bursts. These results support the interpretation that SGRBs arise from an old population of stars and are probably due to mergers of compact binaries, such as double neutron stars or neutron star - black hole binaries. *Swift* observations have also revealed, in about 25% of SGRBs, long (~ 100 s) lightcurve tails with softer spectra than the first short prompt emission episode, which has a harder spectrum. The localization by *Swift* of short GRBs, if they are indeed compact binary mergers, could also help narrow the search window for gravitational waves from such binaries, which would lead to a great scientific payoff for gravitational physics, as well as for studies of progenitor stellar types and neutron star equations of state.

3. Electromagnetic phenomenology: GeV and above

The *Fermi* spacecraft, launched in late 2008, started detecting GRBs with two instruments, the Large Area Telescope (*LAT*, 20 MeV to > 300 GeV) and the Gamma-ray Burst Monitor (*GBM*, 8 keV to 40 MeV), which jointly cover more than seven decades in energy. The low energy *GBM* triggers on bursts at a rate of about 250 yr^{-1} , of which $\sim 80\%$ are LGRBs and $\sim 20\%$ are SGRBs, while the high energy instrument, *LAT*, detects bursts at a rate of $\sim 10 \text{ yr}^{-1}$. Of the latter, the *LAT* detects about twice as many at energies ≥ 100 MeV than it does at energies ≥ 1 GeV. An interesting and unexpected behavior is that in many cases the GeV emission starts with a noticeable delay after the MeV emission. E.g. in GRB 080916C, the GeV emission appears only in a second pulse, delayed by ~ 4 s relative to the first pulse (visible only in MeV); [3], see Fig. 3. Such a delay is present also in short bursts, such as GRB 090510 [4, 5], where it is a fraction of a second. Such a soft-to-hard spectral evolution is clearly seen in the brightest *LAT* bursts, and also to various degrees in most other weaker *LAT* bursts.

Perhaps the most exciting, or exotic, consequence of the observed delays between the *LAT* GeV emission and the *GBM* MeV emission is that it can be used to set robust constraints on effective field theory formulations of quantum gravity. In particular it rules out a first

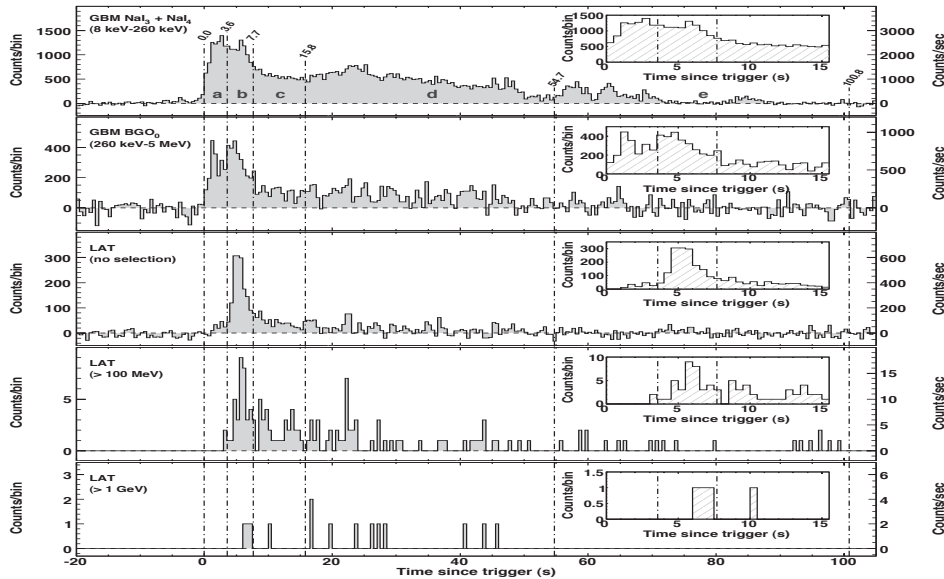


Figure 1. Light curves of GRB080916C with the *GBM* (top two curves) and *LAT* (bottom three curves)[3].

order dependence on $(E_\gamma/E_{\text{Planck}})$ of any Lorentz invariance violating (LIV) terms, using GRB 090510 data [4]. This result is robust, the limits getting even more stringent if there additional astrophysics causes for the delay, which indeed are expected.

In some burst, such as GRB 080916C, the broad-band gamma-ray spectra appear, to within statistical accuracy, as simple “Band” type (broken power law) functions in *all* time bins (similar to the spectrum in time bin [a] of Fig. 3). The absence of statistically significant evidence for a distinct second high energy spectral component in this and some other *LAT* bursts was initially puzzling, since naively such an extra component is expected from inverse Compton up-scattering or from hadronic cascades. However, subsequent observations, e.g. of GRB090510 [4, 5] and GRB 090902B [6], have shown a second hard spectral component, extending above 10 GeV, in addition to the common Band spectral component dominant in the 8 keV-10 MeV band. In some cases, such as GRB 090926A (Fig. 3), this second hard component also shows a downturn around a few GeV.

An exciting discovery by the *Fermi LAT* was the detection of GeV emission from two short bursts (GRB 081024B [8] and GRB 090510 [5]), whose general behavior (including a GeV delay) is qualitatively similar to that of long GRBs. The ratio of short to long GRBs is $\sim 10 - 20\%$, and while the statistics on short GRBs are still small, it appears that the ratio of the *LAT* energy fluence to the *GBM* fluence is $> 100\%$ for the short bursts as compared to $\sim 5 - 60\%$ for the long bursts. Thus, although fewer in number, future large ground-based Cherenkov such as *CTA* [9] and *HAWC* [10] may be able to detect short bursts.

A remarkable feature of both long and short GRBs is that the ≥ 100 MeV emission generally lasts much longer than the $\lesssim 1$ MeV emission. The flux of the long-lived *LAT* emission decays as a power law with time, which is more reminiscent of the smooth temporal decay of the afterglow X-ray and optical fluxes, rather than the variable temporal structure in the prompt keV–MeV flux.

Interestingly, the *LAT* detects only $\lesssim 10\%$ of the bursts triggered by the *GBM* which are in the common *GBM-LAT* field of view. This may be related to the fact that the *LAT*-detected GRBs, both long and short, are generally among the highest fluence bursts, as

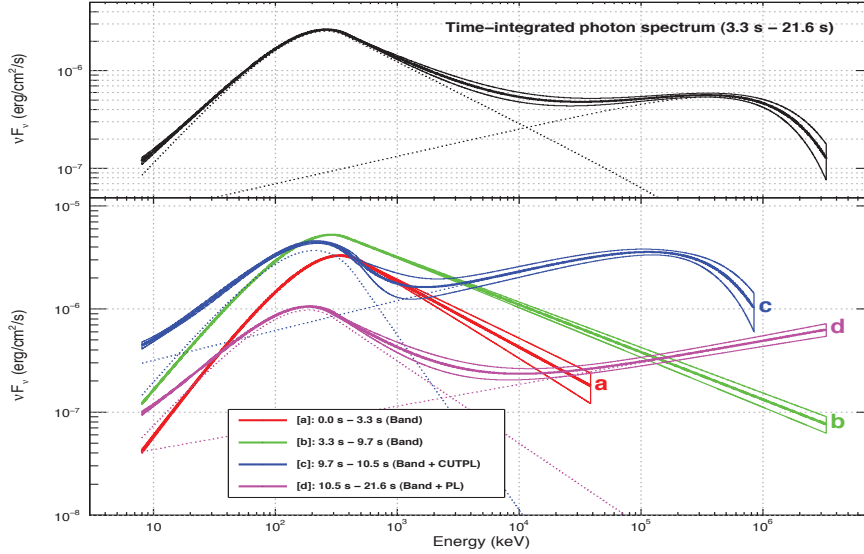


Figure 2. Spectra of GRB090926A from *Fermi* at four different time intervals, a= [0.0-3.3s], b= [3.3-9.7s], c= [9.7-10.5s], d= [10.5-21.6s] [7].

well as being among the intrinsically most energetic GRBs. For instance, GRB 080916C was at $z = 4.35$ and had an isotropic-equivalent energy of $E_{\gamma, \text{iso}} \approx 8.8 \times 10^{54}$ ergs in γ rays, the largest ever measured from any burst [3]. The long *LAT* bursts GRB 090902B [6] at $z = 1.82$ had $E_{\gamma, \text{iso}} \approx 3.6 \times 10^{54}$ ergs, while GRB 090926A [7] at $z = 2.10$ had $E_{\gamma, \text{iso}} \approx 2.24 \times 10^{54}$ ergs. Even the short burst GRB 090510 at $z = 0.903$ produced, within the first 2 s, an $E_{\gamma, \text{iso}} \approx 1.1 \times 10^{53}$ ergs [5].

4. Leptonic GRB Models

The standard scenario of the mechanics of a burst is that the rotating debris falling into the central black hole leads, via a shear or turbulent dynamo mechanism, to extremely strong magnetic fields, which couple the debris to the rotating black hole and, like super-strong rubber bands, extract the rotational energy of the black hole and pump it into a jet, which becomes highly relativistic and collimated into a 5-10 degree angular extent (a similar jet is possible if the central engine is a highly magnetized neutron star).

The energy of the jet is initially mainly in the kinetic energy of its motion, and as it moves away from the black hole, the initially large particle density in it decreases until at a “photospheric” radius the photon mean free path becomes larger than the jet dimension and the photons trapped in the jet can escape freely. However, if the jet energy is still mainly bulk kinetic energy at the photosphere, this escaping radiation would be weak, unless a substantial fraction of the bulk kinetic energy has been dissipated into random energy of charged particles and radiated. This can be achieved if the kinetic energy is dissipated beyond the photosphere in shocks, either internal shocks within the jet itself [11], or external shocks [12], as the jet is decelerated by external matter. Charged electrons bouncing across these shocks can then be accelerated via the Fermi mechanism to a relativistic power law energy distribution, and can produce a non-thermal photon spectrum via synchrotron or inverse Compton radiation, which approximates the observed Band type broken power law spectra. This is the “standard shock leptonic” model. The simple internal shock interpretation of the prompt MeV emission, however, has typically a low radiative efficiency, while the observed spectra sometimes disagree

with a straightforward synchrotron interpretation, which has motivated searches for alternative interpretations of the origin of the prompt MeV emission (see below).

The external shock is generally expected to be accompanied by a reverse shock, which can produce a prompt optical emission [13] at the time the jet deceleration begins. This has been detected in a number of bursts, with robotic ground-based telescopes such as ROTSE and others [14]. As the jet keeps decelerating by virtue of sweeping up increasing amounts of external matter, the bulk Lorentz factor of the shock decreases as a power law of the distance, and the resulting synchrotron radiation becomes a long lasting, fading X-ray, optical and radio afterglow [13], whose predicted detection allowed the first measurements of host galaxies and redshift distances [14]. The external shock interpretation of the late afterglow is quite robust overall. However, there is debate about some of the more detailed features seen in the first few hours of the afterglow by *Swift*, such as X-ray steep decays followed by a flat plateau and occasional large flares, and various proposed extensions of the basic external shock picture continue to be tested.

The above internal and external standard leptonic shock model is generally used also for interpreting the *Fermi* data on individual *Fermi* *LAT* bursts, e.g. [15, 16], etc. Broader formulations of the shock leptonic scenario attempting to cover *LAT* bursts in general were discussed by [17], where the GeV emission arises from a fast cooling forward shock, and by [18, 19], where the forwards shock is assumed to be slow cooling (referring to the ratio of radiative cooling time to jet dynamic time). In such models, it is argued that the external shock GeV emission would naturally start with a delay relative to the prompt MeV emission, assuming the latter arise from internal shocks (see also [20]).

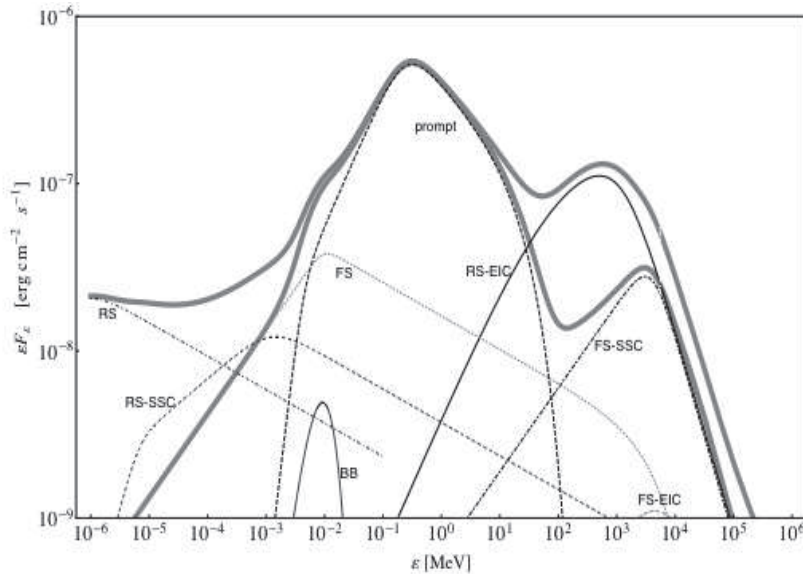


Figure 3. A magnetically dominated leptonic model, with parameters typical of *Fermi* *LAT* GRBs. The MeV Band spectrum is due to photospheric emission, there are no internal shocks, and the external reverse and forward shock upscatter the MeV spectrum into the GeV range [21].

However, taking into account the constraints provided by the *Swift* MeV and X-ray observations, it is clear that at least during the prompt emission, there must be an interplay between the shorter lasting mechanism providing the MeV radiation and the mechanism, or emission region, responsible for the bulk of the longer lasting GeV radiation [22, 21]. The interplay between the two regions involves a number of subtleties, and taking into account the spatial structure by means of multi-zone models, the inverse Compton scattering by an outer

shock of the MeV radiation from an assumed inner source of Band-like MeV photons can give rise to the right delays [23]. These studies avoid specifying a model of the prompt emission origin. If one assumes that this is due to an internal shock, that is open to critique because of its radiative inefficiency and sometimes inconsistent predicted spectra. This problem can be resolved if the prompt MeV Band spectrum is due to an efficient dissipative photosphere with an internal shock upscattering the MeV photons at a lower efficiency, giving the delayed GeV spectrum [22]. Alternatively, for a magnetically dominated outflow, where internal shocks are not expected, an efficient dissipative photospheric Band spectrum can be up-scattered by the external shock and produce the observed delayed GeV spectrum [21] (see Fig. 4).

5. Hadronic GRB Models

If GRB jets are baryon loaded, the charged baryons are likely to be co-accelerated in shocks, reconnection zones, etc., and hadronic processes would lead to both secondary high energy photons and neutrinos. Monte Carlo codes have been developed to model hadronic effects in relativistic flows, including p, γ cascades, Bethe-Heitler interactions, etc. E.g., one such code [24, 25] was used to calculate the photon spectra in GRBs from secondary leptons resulting from hadronic interactions following the acceleration of protons in the same shocks that accelerate primary electrons. The code uses an escape probability formulation to compute the emerging spectra in a steady state, and provides a detailed quantification of the signatures of hadronic interactions, which can be compared to those arising from purely leptonic acceleration. Spectral fits of the *Fermi* *LAT* observations of the short GRB 090510 were modeled by [25] as electron synchrotron for the MeV component and photohadronic cascade radiation for the GeV distinct power law component. More generally, calculations used an advanced version of the above code show that hadronic models can describe GRB spectra where a second, harder photon spectral component arrives later (Fig. 4 because of the time delay needed for hadrons to be accelerated to high energies and for cascades to develop. A prediction of such calculations is that the ν_μ spectrum is harder than that in the models assumed in the recent IceCube papers [26, 27], and satisfies the constraints posed by those papers. The neutrino light curve expected from the charged pion decays also shows a delay relative to the MeV photon light curve (Fig. 5).

Hadronic interactions can also have interesting implications for GRB prompt optical flashes, observed in some bursts. As discussed in [29], besides the usual Band MeV spectrum produced by leptonic mechanisms, the acceleration of hadrons leads to secondaries whose radiation results not only in a GeV component but also to prompt synchrotron radiation in the optical band. This could, in principle, explain the observed “naked eye” 5th magnitude optical flash of GRB 080319B discussed in [30].

In addition to photo-hadronic interactions, also hadronic binary collisions may be important, both for an efficient bulk kinetic energy dissipation and for shaping the photon spectrum. The baryons in a jet will be mainly protons (p) and neutrons (n), especially if heavy elements are photo-dissociated. The protons are coupled to the radiation during the acceleration phase but the neutrons are carried along only thanks to nuclear (p, n) elastic collisions, whose characteristic timescale at some point becomes longer than the expansion time. At this point the p and n relative drift velocity v approaches c , leading to the collisions becoming inelastic, $p + n \rightarrow \pi^+, \pi^0$, in turn leading to positrons, gamma-rays and neutrinos [31]. Such inelastic (p, n) collisions can also arise in jets where the bulk Lorentz factor is transversely inhomogeneous [32], e.g. going from large to small as the angle increases, as expected intuitively from a jet experiencing friction against the surrounding stellar envelope. In such cases, the neutrons from the slower, outer jet regions can diffuse into the faster inner regions, leading

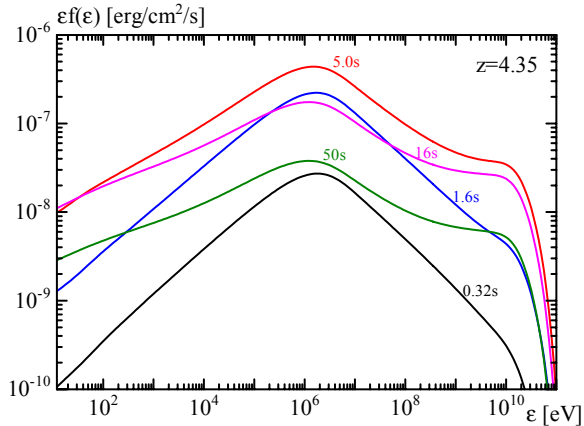


Figure 4. Hadronic GRB model Monte Carlo simulations: time evolution of the observable photon spectral radiation from hadronic cascades for typical *Fermi LAT* parameters, electron synchrotron producing a Band MeV spectrum and hadronic cascade secondaries producing the GeV spectrum as well as a low energy component [28].

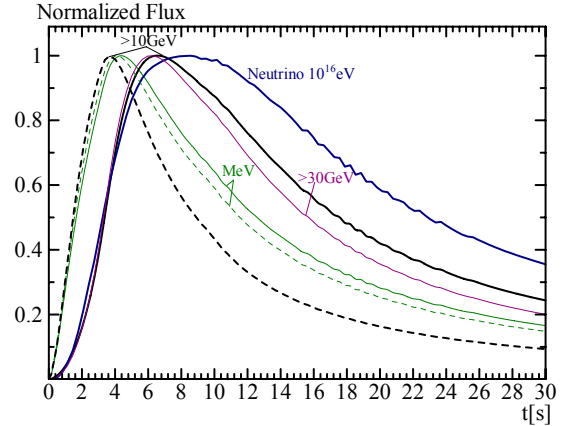


Figure 5. Monte Carlo photon and neutrino light curves of the same hadronic model (full lines) and a similar leptonic model (dashed lines) for a bright *Fermi-LAT* burst at $z = 4.35$, showing the expected delay between the MeV and GeV photon lightcurves and that of the neutrinos [28].

to inelastic (p, n) and (n, n) collisions resulting again in pions. An interesting consequence of either radial or tangential (n, p) drifts is that the decoupling generally occurs below the scattering photosphere, and the resulting positrons and gamma-rays deposit a significant fraction of the relative kinetic energy into the flow, reheating it [33]. Internal dissipation below the photosphere has been advocated, e.g. [34] to explain the MeV peaks as quasi-thermal photospheric peaks [35, 36], while having a large radiative efficiency. Such internal dissipation is naturally provided by (p, n) decoupling, and numerical simulations [33] indicate that a Band spectrum and a high efficiency is indeed obtained, which remains the case even when the flow is magnetized up to $\varepsilon_B = 2$ [37], while keeping the dynamics dominated by the baryons. These numerical results were obtained for nominal cases based on a specific radial (n, p) velocity difference, although the phenomenon is generic.

6. Cosmic rays from GRB

A GRB origin of extragalactic ultra-high energy cosmic rays (UHECR) at energies $10^{18.5} - 10^{20.5}$ eV is in principle possible, if the lower energy cosmic rays are provided by other, e.g. galactic sources, such as supernova remnants [38, 39]. This is because the maximum energy for a particle of shock accelerated particle of charge Z is $E \leq \beta Z e B R$, which is $\sim 10^{20}$ eV for a proton in a typical GRB shock. However, only the highest energy range can be supplied by GRB, mainly because the spectrum is expected to be $\propto E^{-2}$. This, combined with the low energy galactic component would yield approximately the observed $E^{-2.7}$ in the sub-GZK range. A steeper production spectrum in GRB, such as $E^{-2.7}$ or even $E^{-2.3}$, in amounts enough to explain the UHECR observations in the $10^{15} - 10^{18}$ eV range would be too energy demanding for a stellar collapse or merger GRB model, under usual intergalactic propagation conditions (c.f. [40]).

In the most common version of the GRB scenario the UHECR are considered to be protons accelerated in GRB internal shocks [38, 41], while another version attributes them to external shocks [39, 42]. An important caveat of the internal shock UHECR scenario is that it assumes that the GRB prompt gamma-ray emission is due to such internal shocks. Although this is the leading work-horse scenario, there is no strong proof so far for this (as there is for external shocks). In fact, there are problems with the radiative efficiency and the electrons synchrotron spectrum of internal shocks (see previous sections), which put internal shocks into doubt, at least in their simple form usually assumed for UHECR GRB models. (Such problems may be solved in alternative internal shocks or slow magnetic dissipation models [43]).

A relevant development is the evidence accumulating from the Pierre Auger Observatory on the depth of shower penetration, as well as on the fluctuations of this quantity and the muon content of the showers, which suggests that in the range $10^{18} - 10^{20}$ eV the UHECR chemical composition acquires an increasing contribution from heavy nuclei [44, 44]. In a baryonic GRB jet, where magnetic fields are dynamically sub-dominant, the pressure is provided by radiation, and this is expected to photo-dissociate any heavy elements down to p , n and He [45, 46]. However, if magnetic fields are dynamically dominant, they would provide the dominant pressure, the internal radiation field being lower, and in such GRB jets nuclei can survive [47, 48]. If GRB are the sources of UHECR, this is another argument suggesting that they are magnetically dominated.

7. High energy neutrinos from GRB

If protons are accelerated in GRB shocks, these would interact with the observed photons mainly near the \sim MeV peak energy in the GRB spectrum, chiefly through the Δ^+ resonance, $p\gamma \rightarrow \Delta^+$. The threshold condition to produce a Δ^+ is $E_p E_\gamma = 0.2\Gamma_i^2 \text{ GeV}^2$ in the observer frame, which corresponds to a proton energy of $E_p = 1.8 \times 10^7 E_{\gamma, \text{MeV}}^{-1} \Gamma_{300}^2 \text{ GeV}$. The short-lived Δ^+ decays either to $p\pi^0$ or to $n\pi^+$ $\rightarrow n\mu^+\nu_\mu \rightarrow ne^+\nu_e\bar{\nu}_\mu\nu_\mu$ with roughly equal probability. It is the latter process that produces high energy neutrinos in the GRB fireball, contemporaneous with the γ -rays [49]. The secondary π^+ receive $\sim 20\%$ of the proton energy in such an $p\gamma$ interaction and each secondary lepton roughly shares 1/4 of the pion energy. Hence each flavor (ν_e , $\bar{\nu}_\mu$ and ν_μ) of neutrino is emitted with $\sim 5\%$ of the proton energy. Using the standard internal shock model, as in [49], the neutrino spectrum has a spectral break at an energy $E_{\nu, b} \sim 10^{15}$ eV, where the neutrino production efficiency is high. This break is related via the Δ -resonance condition and the bulk Lorentz factor to the photon spectral break energy $E_{\gamma, b} \sim 1$ MeV of the Band spectrum. For a generic photon spectrum with slopes $dN(E_\gamma)/dE_\gamma \propto E_\gamma^{-1, -2}$ below/above $E_{\gamma, b}$, and protons with a spectrum $N(E_p) \propto E_p^{-2}$, the neutrino spectrum coincidentally has slopes $dN(E_\nu)/dE_\nu \propto E_\nu^{-1, -2}$ below/above $E_{\nu, b} \sim \text{PeV}$; for other photon and proton spectral slopes the neutrino slopes are different, but qualitatively similar. The fluxes of all three neutrino flavors (ν_e , ν_μ and ν_τ) are expected to be equal after oscillation in vacuum over astrophysical distances. The diffuse muon neutrino flux from GRB internal shocks in this scenario, using an average GRB photon luminosity, spectrum and bulk Lorentz factor as well as standard GRB occurrence statistics, is expected to be comparable or somewhat below the so-called Waxman-Bahcall (WB) diffuse neutrino flux for optically (neutrino) thin sources implied by the observed cosmic ray flux [50].

This GRB ultra-high energy neutrinos (UHENU) scenario, based on internal shocks, was used by [51] to predict a diffuse neutrino flux which scales with the MeV photon fluxes of GRBs detected by a spacecraft. This can be done having observed the photon spectra, and using these for predicting a neutrino flux (same duration as the photon burst) by assuming neutrino

production via the Δ -resonance, a proton spectrum $\propto E_p^{-2}$ and a relativistic proton energy scaling with the relativistic electron energy by a factor $f_p = 1/f_e = (\mathcal{E}_p/\mathcal{E}_e) \sim 10$, where the electron energy is assumed, due to the fast cooling, to be equal to the observed MeV photon energy. The neutrino spectral shape has a break which scales with observed photon spectral break, and thus using the actual MeV fluxes and spectra of GRBs measured by a spacecraft they predict a cumulative neutrino flux over the period of observations, say a year.

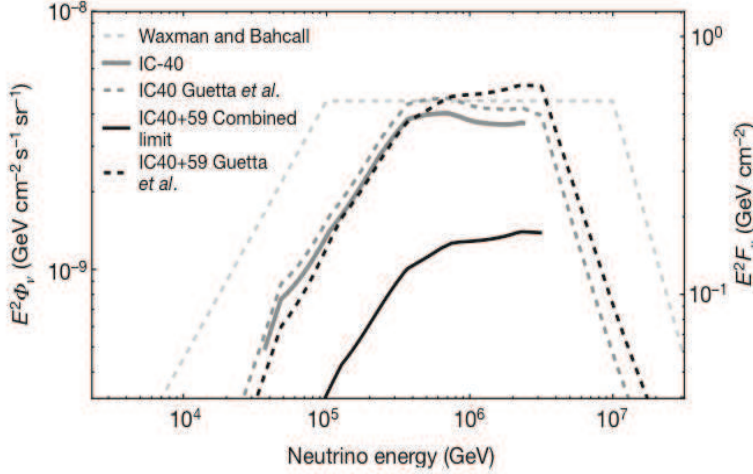


Figure 6. IceCube upper limits [27] for the 40-string array and the 40+59 string array on 190 GRBs localized by *Swift*, compared to an internal shock model [51] scaled to the photon luminosity (right y-axis). The data is a factor 3.7 below this model. The left y-axis is the diffuse flux calculated for 677 bursts/year, the WB limit is in light dashed lines.

Recently, the IceCube group has been analyzing the TeV-PeV UHENU data accumulated by the 40-string array and subsequently the 59-string array [26, 27], and comparing it to the GRB neutrino model flux expectations based on [51]. In the combined 40 and 59 string data (IC-40+59) they used 190 electromagnetically detected bursts (Fig. 6), with their specific photon spectral slopes and breaks to predict, modulo the factor $f_p = 10$, the predicted neutrino spectra, adding them all up. The predicted neutrino cumulative spectrum is shown in Fig. 6 for the 40 string array as the gray dashed (model) and gray solid (data) lines; and for the 40+59 string array as the dark dashed (model) and dark solid (data) lines; the original generic Waxman-Bahcall spectrum is shown by the very light gray dashed lines. It is seen that the IC-40+59 observed data fall a factor 0.27 below the predicted model neutrino flux. This means that this internal shock model over-predicts the data by a factor 3.7, assuming a proton to electron energy ratio of 10, interactions via the Δ -resonance and buck Lorentz factors in the usual range $\Gamma \sim 300 - 600$. Using similar assumptions but not using the spectral information, if these GRB supply the GZK cosmic ray flux, the implied neutrino flux is $2 - 3\sigma$ above the level allowed by the data. The conclusion is that either $f_p = (\mathcal{E}_p/\mathcal{E}_e)$ is significantly below 10, or the production efficiency of neutrinos is lower than was assumed - or the specific model as used can be largely ruled out. This is a major landmark, being the first time that a specific extragalactic astrophysical source model is being tested through neutrino observations, at this $\sim 95\%$ level of significance. IceCube is doing exciting astrophysics, and this is a major step towards testing a candidate astrophysical source of GZK cosmic rays.

There are two additional points in this connection. One is that in using the standard internal shock model to predict the expected neutrino flux [26, 27] made a number of simplifications. As discussed in [53], the neutrino production efficiency at all energies was assumed to be the same as that evaluated at the break energy, but integrating the efficiency over the actual photon spectrum below and above the break yields a total neutrino flux a factor five lower than that

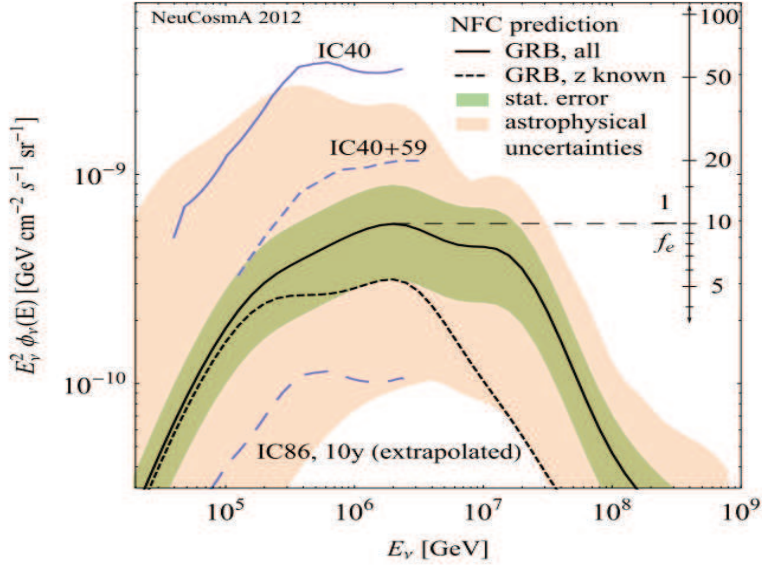


Figure 7. Predictions of the same internal shock model neutrino flux without several of the previous approximations (solid and dashed dark lines), compared to IC-40 and IC-40+59 data. The statistical error is given by the darker shaded region, the astrophysical uncertainties is given by the lighter shaded area [52].

used in the comparison with the data. Also, as discussed in [52, 54], including production not just via Δ -resonance but also via multi-pion and Kaon production, the spectrum is harder and this results in lower predicted fluxes at the lower energies sampled. Allowing for the statistical uncertainty, the $\pm 1\sigma$ limits of the predictions are calculated to be still below the current IC-40+59 data, with $f_p = 1/f_e = 10$ (see Fig. 7). Considering the range of variability of the various astrophysical parameters, it appears that at least several years of observations with the full array may be needed to reach conclusive results about the standard internal shock model. The other point is that internal shocks, in their standard form used above, have been known for a while to have some problems as far as efficiency and spectrum of the prompt γ -ray emission (see discussion in Sections 4 and 5). For this reason, alternative models of MeV photon production have been considered, and the neutrino fluxes and spectra from such models are still in the process of evaluation (e.g. [28]).

Acknowledgments

We acknowledge partial support from NASA NNX08AL40G, NSF PHY0757155 and Grant-in-Aid for Scientific Research No.22740117 from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan.

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