Gamma Ray Bursts as Neutrino Sources

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Gamma-ray burst sources appear to fulfill all the conditions for being efficient cosmic ray accelerators, and being extremely compact, are also expected to produce multi-GeV to PeV neutrinos. I review the basic model predictions for the expected neutrino fluxes in classical GRBs as well as in low luminosity and choked bursts, discussing the recent IceCube observational constraints and implications from the observed diffuse neutrino flux.

1. Introduction

Gamma-Ray Bursts (GRBs) have been postulated to be sources of very high energy (TeV to PeV) neutrinos since at least 1997. This is based on the realization that these objects may be good sites for accelerating ultra-high energy cosmic rays (UHECRs), while having an extremely high photon luminosity which provides ideal target photons for photohadronic interactions. The observed electromagnetic radiation is typically interpreted in terms of shock-accelerated relativistic electrons undergoing synchrotron and inverse Compton losses. The standard fireball shock model of GRBs (e.g.) leads to estimates for the shock region size \( R \), comoving magnetic field strength \( B' \) and comoving photon density \( n'_\gamma \) which provide the basis for arguing that GRBs should also be sources of both UHECRs and very high energy neutrinos. The prediction that GRBs could be strong neutrino sources has served as one of the science goals motivating the building of the IceCube, ANTARES and the planned KM3NeT Cherenkov neutrino detectors.

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2. GRB model and variants

GRBs are thought to be caused by a cataclysmic event at the end of the life cycle of some massive stars, such as the collapse of the fast-rotating central core of stars more massive than $\sim 28M_\odot$ (giving rise to so-called “long GRBs of gamma-ray durations $\gtrsim$ few seconds); or the merger of two neutron stars or a neutron star and a stellar mass black hole, which themselves resulted from the previous core collapse of somewhat less massive stars (giving rise to so-called “short GRBs, gamma-ray durations $\lesssim$ few seconds). This is the central engine which can provide the huge energy needed to power the GRB emission which, while lasting only seconds, equals roughly the total luminous output emitted by the Sun over $10^{10}$ years, or that emitted by the entire galaxy over a hundred years, and is detectable out to the farthest reaches of the Universe.

The collapse or merger results in the liberation of a gravitational energy of order $E_{\text{grav}} \sim GM^2/r \sim 10^{54}$ erg on a very short timescale, in a region whose dimensions $r_0$ are of order of tens of kilometers, leading to a fireball of photons, $e^\pm$ pairs, magnetic fields and baryons. This fireball, which is initially extremely optically thick, expands most easily along the rotation axis, driven by the radiation pressure. The expansion is highly relativistic, characterized by bulk Lorentz factors of the fireball plasma of order $\Gamma \sim 10^2 - 10^3$, as inferred from the observation of multi-GeV photons. This requires the fireball to have a small baryon load $M_0 c^2$ compared to the fireball energy $E_0$, i.e. a high dimensionless entropy $\eta = E_0/M_0 c^2 \sim 10^2 - 10^3$. The actual outflow is inferred, from observations of the light-curves to be collimated into jets of opening angle $\theta_j \sim 0.1$, which reduces the fireball energy requirements to $O(10^{51}$ erg).

In the standard fireball model, if the inertia is dominated by the baryon load, the Lorentz factor grows as $\Gamma \propto r$ by converting internal into bulk kinetic energy, up to $\Gamma_f \approx \eta \approx \text{constant}$, at $r_s \gtrsim r_0 \eta$ after which the ejecta coasts. Beyond a photospheric radius $r_{\text{ph}}$ where the ejecta becomes optically thin to Thompson scattering the fireball quasi-thermal gamma-rays can escape freely. For $r > r_s$ however, most of the fireball energy is kinetic, rather than in the form of photons, and the spectrum is quasi-thermal, contrary to most of the observed burst spectra.

The most widely accepted paradigm for producing the $\gamma$-ray spectrum seen in the majority of GRBs is referred to as the standard fireball shock model, which naturally produces a non-thermal spectrum, and also increases the efficiency by tapping the large reservoir of expansion kinetic energy. Collisionless shocks are expected outside the photosphere, where the ejecta is optically thin, leading to Fermi acceleration of particles to a relativistic power law distribution, leading to broken power-law synchrotron and inverse Compton spectra. Two types of shocks are expected: internal shocks at $r_{\text{in}} \approx r_{\text{ph}}$ caused by variations in the ejecta Lorentz

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*Most of the liberated $E_{\text{grav}} \sim 10^{54}$ erg, however, escapes as a $\sim 10$ s burst of $\sim 10 - 30$ MeV thermal neutrinos, as in supernovae, and as gravitational waves.*
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Fig. 1. Top: schematic evolution of the bulk Lorentz factor for a GRB baryonic outflow. Bottom: the tree main emission zones from which gamma-rays are detectable.

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shock synchrotron spectrum at high energies were considered, and in fact, evidence for low energy quasi-thermal emission compatible with a photosphere has been detected in a number of bursts. More recently, it has been confirmed that considering the joint effects of a photosphere-like quasi-thermal spectrum together with a Band broken power-law non-thermal spectrum results in fitted slopes which are compatible with a synchrotron interpretation. The latter could be a shock outside the photosphere.

An alternative view of the origin of the prompt $\gamma$-ray emission, which similarly addresses the low energy slope issue and in addition also the efficiency issue, is that the entire prompt emission arises in a dissipative photosphere (as opposed to a passive, adiabatic photosphere). The low energy slope is hard because it is self-absorbed, while the high energy slope is a power law due to comptonization, e.g. The dissipation could be due to internal shocks at or below the photosphere, or else it could be due to magnetic field reconnection or it could be due to collisional effects following the decoupling of protons and neutrons below the photosphere. In this case the high energy photon power law slope extension is due to upscattering of the thermal photons by relativistic positrons from pion decay following $pn$ collisions.

3. VHE neutrinos from GRBs

The co-acceleration of ions is natural in models where electrons are accelerated (as inferred from the gamma-ray observations), if besides electrons the ejecta contains also baryons. The latter is expected in a stellar core collapse or merger event, where the mass density is close to nuclear. The detailed model fits indicate that the baryon load is small but non-negligible, as inferred from termination bulk Lorentz factors $\Gamma_T \sim E_0/M_0c^2 \sim 10^2 - 10^3$. In such scenarios, VHE neutrino production in the shock or acceleration zones is expected from $p\gamma$ interactions. Other scenarios where the stress-energy is dominated by $e^\pm$ or magnetic fields (which could have much fewer or no baryons, as in pulsar models) are possible, and would imply negligible neutrino production. However, such models would naturally be associated with much larger bulk Lorentz factors than those inferred from observations. In such models the flow further out may decelerate due to pair drag or it may pick up more baryons, but such scenarios involve more free parameters and are not widely considered in model fits. Models where the stress-energy is largely magnetic which do have small but appreciable baryon loads have been considered, e.g., which lead to observationally acceptable final Lorentz factors, and having baryons, also fulfill a necessary condition for being potential neutrino sources.

The most straightforward prediction for VHE neutrino production is that associated with internal shocks. This was initially based on a simplified internal shock, with given fixed shock radius parameterized by the total gamma-ray energy, Lorentz factor and outflow time variability, and approximating the photon spectrum as an average-slope Band broken power law, using the $\Delta$ resonance approximation for the
photohadronic interaction. This simplified model was adopted to make the first predictions of an expected diffuse VHE neutrino background, assuming a relativistic proton to electron luminosity ratio $f_p = f_e^{-1} = L_p/L_e$ and taking $L_\gamma \simeq L_e$, for a given a set of electromagnetically observed bursts. Using 215 bursts with known $\gamma$-ray fluences, the first IceCube observations with 40 strings and later 56 strings were compared to the diffuse flux predicted by this a simplified internal shock (IS) model. They concluded that for a nominal $f_p = f_e^{-1} = L_p/L_e = 10$ ratio the model over-predicted the data by a factor 5, and a model-independent analysis comparing the observed diffuse neutrino flux to that expected if GRBs were the sources of the observed UHECR flux was also similarly off. This was a very important first result using a major Cherenkov neutrino facility to constrain astrophysical source models.

Subsequent analyses pointed out that using the same fixed shock radius IS model but correcting for various approximations and including besides the $\Delta$-resonance also multi-pion and Kaon channels as well as interactions with the entire target photon spectrum, lower predicted fluxes are obtained which not disagree with the 40+56 string data, and which indicate that 5 years of observations might be needed with the full 86 string array to rule out the simple IS model.

An issue with the fixed-radius IS models is that, even if one uses a distribution of radii $r_{\text{sh}}$ in eq. (1) based on observational distributions of variability times $t_v$ and bulk Lorentz factors $\Gamma$, this still denotes the shock initiation radius, and the baryon, photon and magnetic field densities decrease as the shocked mass shells expand beyond this radius, necessitating a time dependent calculation in addition to a statistical averaging. Such time-dependent IS proton acceleration and full physics $p\gamma$ neutrino diffuse flux calculations result, as expected, in a diminished predicted neutrino flux, as the opacity drops with distance away from the initial radii, giving a result which is well within the bounds of the 40+56 string upper limits. It remains to redo such comparisons against the full array data.

Fig. 3. Results from a time-dependent internal shock neutrino production calculation, including a sub-photospheric contribution, compared to IceCube 40+59. From [34]
Of course, an open question with GRBs is whether the basic internal shock model is correct for the prompt gamma-ray emission (and its related proton acceleration and $p\gamma$ production). The $\gamma$-ray spectral issues may no longer be a concern for IS models\cite{19,20} but the mechanical radiative efficiency still remains a question. On the other hand, dissipative photospheric models of the prompt $\gamma$-ray emission appear to address both the efficiency and spectra adequately, e.g.\cite{23,24,35} Early diffuse neutrino flux predictions from baryonic GRB photospheres were presented in\cite{36,37}. The results are different for magnetically dominated outflows, where the initial acceleration can be parameterized through $\Gamma(r) \propto r^\alpha$ where $1/3 < \alpha < 1$, as opposed to $\Gamma(r) \propto r$ in the baryon-dominated case. Diffuse neutrino flux predictions from both baryon-dominated and magnetically dominated photospheres were calculated by\cite{38,39,40} indicating no violation of the 40+56 string IceCube constraints, but approaching it. The main reason is that the photosphere radii are smaller than those of internal shocks, see eq. (1), hence photon and particle densities and $p\gamma$ optical depths are larger. Model independent calculations confirm this\cite{41}.

A more recent analysis of the IceCube four years data, including two years of the full array\cite{42} used the full physics of the $p\gamma$ interactions and the entire target photon spectrum to compare against the predictions of the standard IS Model, baryonic photosphere model and ICMART model, all three for fixed radius (steady state) emission zones. They concluded that at 99% confidence level less than 1% of the observed diffuse neutrino background can be contributed by the observed sample of 592 electromagnetically detected GRBs. This is a much larger burst sample with a more complete array, and while it would be important to redo this analysis with time-dependent expanding radius emission zones, this is likely to be a much stronger constraint. If the basic acceleration paradigm in these emission zones is correct, and the result continues to stand, it may be indicating that the ratio $L_p/L_e = f_p \lesssim 1$. Other photospheric models with substantially different
neutrino production physics\cite{43,44} have been investigated, but so far have been only qualitatively compared against the data.

4. Other types of GRBs as possible neutrino sources

The classical GRBs discussed above are what may be called “overt” (electromagnetically detected) GRBs, the majority (70-90%) of which are long GRBs ascribed to core-collapse events located at redshifts $z \gtrsim 1$. The rest, about 30-10% of the classical GRBs are short GRBs, which appear to be compact mergers and which have a luminosity lower by about one order of magnitude, being detected typically at lower redshifts $z \lesssim 1 - 1.5$. Their neutrino luminosity probably scales with their gamma-ray luminosity, and as such they are not expected to contribute much to the long GRB predicted diffuse neutrino fluxes.

There are, however, at least three other classes of GRBs in addition to the classical ones, which could contribute to the diffuse neutrino flux. These are the low-luminosity GRBs (LLGRBs), the choked GRBs, and the shock break-out GRBs (which may be an intermediate or transition class between the LLGRBs and the choked GRBs).

The low luminosity GRBs, not surprisingly, have been discovered only at low redshifts, some as low as $z = 0.0085$ (GRB080425/SN1998bw); at the same time, because of the low redshift, in most of these an associated supernova of type Ic has been spectroscopically detected. While the total number of detected LLGRBs is only a handful, the inferred local rate appears to be about an order of magnitude higher (per unit volume and time) than that of classical GRBs, e.g.\textsuperscript{45–47} A simple scaling of the classical long GRB IS shock paradigm has led to the expectation that LLGRBs could contribute a significant, or perhaps even dominant fraction of the total GRB UHECR and VHE neutrino diffuse fluxes.\textsuperscript{48–51}

Choked GRBs are core collapse objects similar in their dynamics to the observed classical long GRBs, where a relativistic jet has been launched from a central engine, the difference being that the jet did not make it out from the star, having stalled either because the accretion onto the central object did not last long enough, or because the stellar envelope is larger than in “successful” GRBs, where the jet has emerged.\textsuperscript{52} Internal shocks can be expected in such jets while they are still below the stellar surface, which can also accelerate protons and undergo $p\gamma$ interactions leading to neutrinos that emerge.\textsuperscript{52} In successful or overt GRBs (where the jet emerges and makes $\gamma$-rays) this neutrino burst from the sub-stellar phase of the jet acts as a precursor, while in truly choked jets, where the jet stalls and which are $\gamma$-dark, the neutrino burst reveals a failed GRB, which is a forerunner of a jet-boosted supernova. The spectrum should have a low energy (multi-GeV) $pp$ component as well as a higher energy $p\gamma$ TeV component, and these could be used to diagnose the stellar envelope extent and structure.\textsuperscript{53,55} More detailed calculations\textsuperscript{56–58} have explored possible signatures and their potential detectability by IceCube and Deep
Core, preliminary results and limits having been presented. The shock which propagates through the envelope of core collapse supernovae (ccSNe) eventually breaks out of the envelope, and this may happen whether a jet was launched from the core or not, and whether such a jet eventually emerges or not from the envelope and/or the optically thick precursor stellar wind. When it does emerge, an X-ray flash is observed; in some cases this was observed in what appeared to be a LLGRB, e.g. in another case it was seen in a core-collapse supernova unassociated with a GRB. It is tempting to identify the former with ccSNe where a jet was launched and emerged, and the latter with ccSNE where the jet did not emerge (or perhaps was not even launched, due to lack of enough angular momentum to feed a central accreting black hole or magnetar). The shock break-out occurs when the photons which previously were diffusively trapped become able to escape freely, which is thought to occur above the ejecting envelope, in the optically thick wind which precedes the SN explosion, e.g. If a jet was launched, an anisotropy of the envelope and the wind is expected, as indicated by the interpretation of GRB 060218. This would be expected whether the jet emerged or not. The ejecta of several of the SNe associated to LLGRB appear to have a semi-relativistic component, which is interesting for the production of UHECR, e.g. citeWang+07crhn, Wang+07crhn. The details of the shock break-out process, and whether the envelope becomes semi-relativistic (as appears to be the case in most of the SNe accompanying LLGRB) is of continued interest especially for its impact on their possible UHECR and VHE neutrino production, e.g.

5. The TeV-PeV diffuse neutrino background

The observed diffuse flux of sub-PeV to PeV neutrinos detected by IceCube and its extension down to the TeV range is believed to be of astrophysical origin. So far, however, no significant spatial or temporal correlations have been found with classical (high luminosity) GRBs detected electromagnetically by Swift or Fermi nor for that matter with any other type of known sources. Various possible types of candidate sources have been considered (a partial list is in). In particular starburst galaxies are a possibility (see and other references cited in), within which the actual production sites are likely to be hypernovae and supernovae, e.g. Another possibility are low-luminosity GRBs (LLGRBs, see). Their rate being higher than that of classical GRB, they could provide a significant neutrino background, and in γ-rays they are detectable only at low redshifts (a handful so far) but not at z > 0.5 − 1. However, one would expect sooner or later a ν − γ coincidence at low redshifts. Another interesting possibility are the choked GRBs. The shocks accelerating protons occur in the jet inside the star, hence they would be γ-dark, although the ejected envelope could lead to longer optical/IR longer

b In fact, many SN remnants show at late stages optical polarization attributed to scattering by an anisotropic ejecta
transients or supernovae. Note that buried jets of arbitrary luminosity, e.g., are subject to the caveat that high (classical) luminosities lead to radiation dominated buried shocks, which prevents Fermi acceleration; collisionless shocks able to Fermi-accelerate protons are expected only for low luminosity choked jets. Both LLGRBs and choked jets, being associated to ccSNe, are also likely to be predominantly located in starburst or starforming galaxies.

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