Neutrinos from Gamma Ray Bursts

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Abstract.

The observed fluxes of cosmic rays and gamma rays are used to infer the maximum allowed high-energy neutrino flux allowed for Gamma Ray Bursts (GRBs), following Reference [1]. It is shown that if GRBs produce the ultrahigh-energy cosmic rays, they should contribute (a) at least 10% of the extragalactic gamma ray background between 3 MeV and 30 GeV, contrary to their observed energy flux which is only a minute fraction of this flux, and (b) a cumulative neutrino flux a factor of 20 below the AMANDA-ν2000 limit on isotropic neutrinos. This could have two implications, either GRBs do not produce the ultrahigh energy cosmic rays [2,3] or that the GRBs are strongly beamed and emit most of their power at energies well above 100 GeV [4] implausibly increasing the energy requirements, but consistent with the marginal detections of a few low-redshift GRBs by MILAGRITO [5], HEGRA-AIROBICC [6], and the Tibet-Array [7]. All crucial measurements to test the models will be available in the next few years. These are measurements of (i) high-energy neutrinos with AMANDA-ICECUBE or an enlarged ANTARES/NESTOR ocean detector, (ii) GRB redshifts from HETE-2 follow-up studies, and (iii) GRB spectra above 10 GeV with low-threshold imaging air Cherenkov telescopes such as MAGIC and the space telescopes AGILE and GLAST.

INTRODUCTION

Gamma Ray Bursts (GRBs) have for decades persisted as a new and unexplained phenomenon in astrophysics, prompting numerous speculations about their nature and origin [8]. After the discovery of X-ray and optical counterparts, the cosmological origin of GRBs is now beyond doubt, and the physics scenario employs the cataclysmic release of \( E \sim 10^{54} \) ergs, one solar rest mass equivalent, under near vacuum conditions. Quasi-thermal neutrinos at 20 MeV energies are the expected prime carriers during the first stages of energy release [9], and the difficulties in converting this energy into a high-entropy fireball during a neutron star merger have been pointed out [10]. The difficulties could be overcome by assuming a disk phase with Poynting flux extraction during coalescence [11], or a hypernova scenario [12], and possibly by considering the interaction between the neutrino magnetic moment.
(which arises in any model explaining finite neutrino masses) and the magnetic field gradients in the collapsing object. Owing to the large distances of GRBs and the strong stellar background at the nuclear binding energy scale, there is little hope for detecting the initial neutrino emission component. There could be a very powerful neutrino emission component in the GeV range due to internal dissipation driven by proton-neutron diffusion \[13,14\], and the background at these energies is significantly lower.

At high energies, neutrino detection becomes easier, since the weak interaction cross section, the muon range, and the angular resolution all increase with energy. As the consequence of a low mass-load (high entropy) in GRBs, the exploding matter can attain ultra-relativistic velocities, typically corresponding to Lorentz factors \(\Gamma \sim 300\), and can form relativistic shocks which are efficient in accelerating particles to even higher energies \[15\]. This is known to occur in the relativistic jets expelled from Active Galactic Nuclei (AGN) \[16\], which transport some \(E \sim 10^{60}\) ergs over their lifetime and have typical Lorentz factors of \(\Gamma \sim 10\). As a matter of fact, GRB and AGN jets involve almost identical concepts in their theoretical modeling.

It is thus not surprising that after the hypothesis of the association of GRBs and ultrahigh-energy cosmic rays (UHECRs) by Milgrom and Usov \[17\] an effort was launched to parallel the advanced theory of accelerated protons in AGN \[18–27\] for GRBs \[28–33\]. If the proton acceleration mechanism operates at the gyro time scale or faster, both AGN and GRBs represent possible classes of sources for UHECRs. The difference is that the AGN produce roughly two orders of magnitude more cumulative flux in the observed gamma ray band, and thus are likely much stronger sources of cosmic rays and neutrinos, too. Moreover, spatial coincidences between GRBs and UHECRs and the equality of local GRB and UHECR emissivities appear as a poor heuristic basis for the claim of a common origin in view of the fact that GRBs are typically too distant to allow for cosmic rays to reach Earth unimpeded by energy losses in interactions with the microwave background.

While this can be regarded as an argument disfavoring the hypothesis \[1–3\], there is one more aspect which deserves a closer look. This aspect is related with the shape of the multi-wavelength spectra of relativistic jet sources. The canonical spectral shape consists of two components, one peaking at lower energies, and one peaking at higher energies. The first component has a flux density that is independent on the photon energy \(E\) (in the radio/mm range in AGN and in the X/\(\gamma\)-ray range in GRBs) which steepens by the factor \(E^{-1}\) at higher energies. This part of the spectrum is successfully modeled as the synchrotron radiation from accelerated electrons. If protons are accelerated in the sources, too, then there must be a second peak due to the hadronically-induced radiation at high energies in the canonical spectrum. Such a component has been found in the spectra of AGN jets in the MeV-to-TeV range, albeit it could also be interpreted as being due to inverse-Compton scattering of low-energy photons by the synchrotron-emitting electrons.

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Naturalness would then provoke the assumption that GRB spectra have a corresponding peak at ultrahigh energies which has escaped detection so far.

This is consistent with the fact that due to the typical high redshifts of GRBs, such an emission component would be attenuated by pair production in traversing the intergalactic radiation fields [35,36]. We could be fooled by beaming statistics, if the dominant isotropic gamma ray output of GRBs went into a diffuse channel, e.g. due to cascading in the intergalactic medium wiping out directional memory and temporal correlation [33].

The issue highlights the importance of neutrino observations. Neutrinos suffer practically no energy losses (except for adiabatic losses owing to the expansion of the Universe) and can therefore be used to measure the flux of cosmic rays escaping from GRBs. Prompt UHE protons escaping from relativistic outflows suffer from synchrotron and adiabatic losses [27], and therefore the neutron-escape fraction of cosmic rays from internal shocks should be the dominant one. Protons from external shocks would have a too steep spectrum to be important at UHE energies for reasonable energetics [34]. The neutron-fraction of the escaping cosmic ray flux can be inferred from measurements of neutrinos in the 100 TeV range. These neutrinos would be correlated with the electromagnetic bursts. Cosmic rays also give rise to an uncorrelated secondary neutrino flux during propagation through the microwave background due to photo-production of pions.

The paper first provides a general bound on the neutrino emission from GRB-like sources, constrained by the observed diffuse gamma-ray and cosmic ray proton fluxes. Secondly, more specific assumptions regarding the spectral shape of the emitted protons are employed to find out the expected flux of high-energy neutrinos following the Milgrom & Usov hypothesis. Finally, this would have consequences for the properties of high energy gamma-ray emission from GRB which are briefly discussed.

**UPPER LIMIT FOR GRB-LIKE PHOTO-HADRONIC SOURCES OF NEUTRINOS**

Recently, Mannheim, Protheroe, and Rachen [1] (MPR) have derived an upper limit for the neutrino flux from extragalactic sources, in the framework of photo-production models in which the neutrinos originate from pions produced in hadronically-induced interactions of accelerated protons with low-energy photons. With every neutrino, there is a minimum number of photons and neutrons associated, and the flux of those is not allowed to exceed observed omnidirectional fluxes of cosmic ray protons and gamma rays. In their Fig. 3, MPR show this limit for sources with conditions typical for AGN (steady sources with flux density spectral index $\alpha = 1$). Here, the focus is on the short-lived GRBs in which the synchrotron
target photons have a flat spectrum ($\alpha = 0$). The relation between cosmic ray and neutrino fluxes at ultrahigh-energies (above $\sim 10^7$ GeV proton energy in the comoving frame) is then given by

$$Q_{\nu}(E) = 416Q_{cr}(25E)$$  \hspace{1cm} (1)

i.e. the neutrino yield can be up to factor of 5 larger than in the case of AGN [37].

The experimental upper limit on a possible extragalactic proton contribution to the local flux of cosmic rays is consistent with an extrapolation of the observed, presumably protonic, spectrum at $10^{10}$ GeV down to $10^6$ GeV using a spectral index of 2.75. Owing to the steepness of this spectrum, saturating the upper limit implies an increasing emissivity of the putative GRB-like sources with decreasing energy. The electromagnetic and neutrino luminosities of GRB-like sources are the same. Below PeV energies, their electromagnetic output begins to reach the level of the observed extragalactic gamma ray background and the upper limit levels off. Generally, since gamma-rays from pion decays and from pair production are reprocessed by electromagnetic cascades, only the bolometric (integrated) fluxes can be compared.

Equation (1) still ignores the effect of cosmic ray attenuation, which is important for sources with strong redshift evolution. A strong redshift dependence $\propto (1+z)^{3.4}$ of the cumulative source emissivity is assumed for the GRBs. This corresponds to the observed dependence for star formation in galaxies and AGN [38]. Above $10^{10}$ GeV, the upper limit spectrum steepens rapidly due to the inescapable energy losses of pions and muons in compact, variable sources [27]. Below PeV energies, the increase is only by a factor of 2, since the constraint from the diffuse gamma-ray background imposed by $L_\gamma \simeq L_\nu$ (where $L_i$ denotes the bolometric luminosity emitted in species $i$) becomes the stronger one, and AGN-like conditions have $L_\gamma = 2L_\nu$ (due to the contribution of gamma-rays from Bethe-Heitler pairs). For realistic model assumptions, the turnover at $10^{10}$ GeV would occur at even lower energies (see next section). Figure 1 also shows previously predicted fluxes for GRBs based on a simplified treatment of the photo-production kinematics [31] and for AGN [25] for comparison.

**GENERIC GRB NEUTRINO FLUX**

For the calculation of an upper limit for GRB-like sources, explicit model assumptions required for a generic GRB model have not been made. A crucial assumption is that of the slope of the energy distribution of accelerated protons.

The external shock where the ejecta impact the external medium is highly relativistic and should thus produce particle spectra $\propto E^{-2.2}$ [34]. If protons accelerated
at the external shock were to explain the UHE cosmic rays, the power in the low-energy part of the population would have to be unrealistically high, and the GRBs radiatively extremely inefficient.

Internal GRB shocks are expected to be only mildly relativistic owing to the velocity differences of superseding shells being smaller than those with the external medium, and therefore a proton spectrum \( \propto E^{-2} \) seems possible. Such an energy distribution delivers a large fraction of the energy in the proton population at UHE energies. The shape of the neutrino spectrum follows \( \propto E^{-1} \) below \( E_b = 100(\Gamma/300)^2 \) TeV and \( \propto E^{-2} \) above, until the spectrum steepens above 10 PeV due to energy losses of the muons in the expanding ejecta. The actual spectrum will be slightly more curved (see the lower thick solid curve in Fig. 1), since the photo-hadronic interactions are dominated by the \( \Delta \)-resonance in the 100 TeV range, whereas by multiple pion production above PeV lab frame energies. A more accurate treatment using the SOPHIA code [37] must await future work.

Since the protons must suffer synchrotron and adiabatic losses upon escape [27], the neutrons produced in photon collisions dominate the escaping fraction of cosmic ray baryons at ultrahigh energies. The generic GRB neutrino flux following

\[
\begin{align*}
\text{FIGURE 1.} \quad \text{Sketch of the neutrino upper limit (}\nu_\mu + \bar{\nu}_\mu\text{) for GRB-like photo-hadronic sources (upper thick solid line) and generic GRB flux if Milgrom & Usov hypothesis were true (lower thick solid line). For comparison, the upper limit for AGN-like sources is shown in the optically thin (thin line labeled } \tau_{n\gamma} < 1 \text{) and optically thick (thin line labeled } \tau_{n\gamma} \gg 1 \text{) cases, respectively. Also shown is the atmospheric neutrino flux between horizontal and vertical directions (hatched narrow band), and the experimental limit from AMANDA (as reported at the } \nu\text{-2000 conference by S. Barwick). For further details, see text.}
\end{align*}
\]
from the assumption that GRBs produce the UHE cosmic rays above $10^9$ GeV (excluding the super-Greisen events), is shown in Fig. 1. The corresponding integral gamma-ray flux is given by $F_\gamma = \frac{2}{3}(2 \times 10^{-7} \times \ln[100]) \text{ GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ which corresponds to 10% of the extragalactic gamma ray background between 3 MeV and 30 GeV ($1.5 \times 10^{-5}$ in the same units). Comparing with the extragalactic gamma ray background between 1 GeV and 30 GeV ($4.2 \times 10^{-6}$), the number is 33%. The factor $\ln[100]$ takes into account the bandwidth of the neutrino spectrum (the limit for AGN-like sources shown in Fig. 1 takes into account a factor $\exp[1]$ as the bolometric correction for trial spectra of the form $\propto E^{-1} \exp[-E/E_{\text{max}}]$).

Note, however, that the secondaries produced during propagation of UHE cosmic rays in interactions with the microwave background add another (albeit uncorrelated, and therefore truly diffuse) neutrino component at EeV energies (similar to the dotted curve in Fig. 1) and also add an electromagnetic component emerging in the observed gamma-ray band. This component has an energy flux level comparable to the minimum of the upper limit for AGN-like sources at $10^9$ GeV, since photo-production occurs close to the threshold energy in interactions with photons from the microwave background. The spectrum is rather sharply peaked at UHE energies and has a bolometric correction of $\sim \exp[1]$. The corresponding gamma-ray flux is $2 \times 10^{-7} \text{ GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$, so that the combined GRB contribution to the extragalactic gamma ray background would be $1.6 \times 10^{-6}$ in the same units (11% of the 3 MeV-30 GeV background or 38% of the 1 GeV-30 GeV background).

Constraints on the total isotropic energy per burst, their radiative efficiency, and the burst rate have not been imposed here. It is clear, however, that if GRBs shall explain the UHE cosmic rays, the current physical interpretation of GRBs is severely challenged by the dramatically increased energy demands.

**IMPLICATIONS FOR HIGH-ENERGY GAMMA-RAY TAILS**

The powerful high-energy gamma-ray emission implied by the Milgrom & Usov hypothesis raises the possibility for falsification by gamma-ray observations. However, the current generation of ground-based telescopes are sensitive only above 300 GeV corresponding to a pair-attenuation length of $z = 0.3$. Only a small number of bursts is expected to occur at redshifts less than 0.3. From an analysis of the 2nd BATSE catalogue data, the expected rate of 100 per year [39] is too low for the small field of view of imaging air Cherenkov telescopes to make a chance detection. The large-field-of-view detectors MILAGRITO, Tibet, and HEGRA-AIROBICC have not found strong evidence for GRBs, but their thresholds are in the TeV domain where less than one GRB per year is expected to occur. It is interesting to note, however, that the groups have all reported marginal evidence for single GRBs which is statistically conceivable [5–7]. The implied flux is consistent with the Mil-
grom & Usov hypothesis [4]. This high-energy tail would have an extremely hard spectrum rising above 10 GeV, since EGRET has not discovered evidence for an upturn. Clearly, this is a challenging possibility to be tested by AGILE, GLAST, or MAGIC.

SUMMARY AND CONCLUSIONS

Non-thermal power law emission and afterglows over a broad range of wavelengths indicate the acceleration of charged particles to relativistic energies in GRBs. If GRBs are the sources of UHE cosmic rays, they must produce at least 10% of the extragalactic gamma ray background between 3 MeV and 30 GeV and a diffuse flux of neutrinos in the 100 TeV to 10 PeV regime which is a factor of 20 below the AMANDA-$\nu$2000 limit on isotropic neutrinos. The time stamp associated with GRBs increases the sensitivity further compared with the sensitivity for an isotropic, uncorrelated background. Low-redshift GRBs would also have powerful high-energy tails in their gamma ray spectra which are consistent with the marginal detections reported by the MILAGRO, HEGRA, and Tibet Collaborations. The next years will bring rapid progress to the understanding of GRBs and their high-energy emissions, with improved measurements of GRB neutrinos, redshifts, and high-energy gamma-ray tails using AMANDA-ICECUBE/ANTARES/NESTOR, HETE-2 follow-up programs, and MAGIC/AGILE/GLAST.

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