High energy neutrinos from GRBs

F.De Paolis, G.Ingrosso, D.Orlando and L.Perrone [a]

[a] University & INFN of Lecce

It is by now recognized that GRBs can accelerate protons to relativistic energies and that high density media may be present nearby the source. We compute the high-energy γ-ray and neutrino fluxes from the decay of pions produced through the interaction of accelerated protons with nucleons in the surrounding medium. Then, we estimate the flux of high-energy muons induced on a detector by upward-going neutrinos interacting through charge current processes with the surrounding matter.

1. An hadronic model for γ-ray emission

The γ-ray emission from GRBs observed by BATSE at keV-MeV energy, is usually believed to have been originated by leptonic mechanisms such as synchrotron or inverse Compton processes.

It is also well known that GRBs are sources of high-energy γ-rays, as it has been shown by the EGRET spark chamber, which detected γ-rays in the energy band ~ 30 MeV - 20 GeV, from a high percentage of bright BATSE bursts. Clearly, the natural question which raises is the production mechanism of γ-rays with energy $E_\gamma > 1$ GeV since, if the electron emission spectra which fit BATSE observations are extrapolated in the high-energy domain, the obtained photon fluxes at Earth are well below the values detected by EGRET.

Within the framework of the fireball model for GRBs, it has been recently argued that GRB events could release roughly the same amount of energy $\mathcal{E} \sim 10^{54}\Delta\Omega$ erg and that a substantial fraction of $\mathcal{E}$ remains in form of accelerated protons [1]. These protons could in turn interact with nucleons in the medium surrounding the GRB source, giving rise to π^0 and ultimately, from π^0 decay into two γs, producing a high-energy γ-ray flux [2]

A key requirement of the above model, is the existence of a dense enough cloud (as a target for pN interactions), surrounding the GRB source and/or situated along the line of sight to the observer, close enough to the source. In order to have an observable high-energy γ-ray flux on Earth, the cloud number density n has to be in the range $10^8 - 10^{11}$ cm^{-3}. Clearly, the target cloud could in principle re-absorb the produced γ-rays via γH interactions. However, this is not the case, since clouds nearby GRB sources are expected to have a high ionization degree, so that the relevant γ-ray absorption processes are γe and γp interactions, which have small enough cross-sections. As implied by Fermi type shock acceleration models in the relativistic regime, the accelerated proton flux $j_p(E_p, r)$ follows a power-law energy spectrum with index $a_p = 2.2$ [3], E_p being the accelerated proton energy. Moreover, the flux radial dependence will take into account: a) the geometrical dilution factor r^{-2}; b) the deflection of the proton trajectories, due to the presence of the magnetic field B (of assumed intensity $\simeq 1\mu$G) in the region surrounding the GRB source; c) the probability that the pN interaction occurs after a path of length $l(E_p, r) = R_L(E_p)\ \arcsin[(r - r_0)/R_L(E_p)]$. Here $R_L = E_p/(eB)$ is the proton Larmor radius.

A feature of the proposed model is a temporal spread of the high-energy γ-ray signal on Earth with respect to the low energy γ-rays observed by BATSE, as a consequence of the proton deflection due to the magnetic fields (for more details see [2]).

2. High-energy neutrino emission

For a proton power law spectrum, $j_p(E_p) \propto E_p^{a_p}$, and inclusive cross sections for meson production obeying Feynman scaling, the spectrum of γ-rays, ν_e's and ν_μ's are all proportional at high energies. In particular, if $\nu_\mu + \bar{\nu}_\mu$ production proceeds mainly via π, K and μ decays, this proportionality relation can be derived from the analytical methods developed, for example, by [4] and [5], and also verified by detailed Monte Carlo simulations. Clearly, this is valid as long as photons are not re-absorbed in the cloud itself.

In Fig 1 we show the neutrino fluences $\Phi_\nu(E_\nu)$ at Earth in the first 200 s of the signal life produced by a GRB event situated at distance $z = 1$.

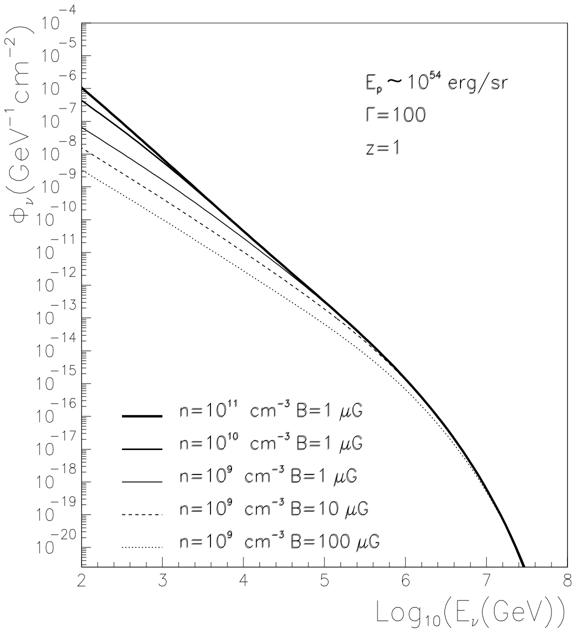

Figure 1. Expected neutrino fluences $\Phi_\nu(E_\nu)$ for different values of model parameters n and B, the total assumed GRB energetics is 10^{54}erg/sr The redshift z is taken equal 1 and the Lorentz factor Γ of the expanding fireball is equal 100.

3. Neutrino signal detectability

High-energy neutrinos from astrophysical sources can be detected by collecting the upward-going neutrino-induced muons produced through charge-current interactions with the matter surrounding the detector [6]:

$$\nu_\mu(\bar{\nu}_\mu) + N \rightarrow \mu^-(\mu^+) + X \, . \qquad (1)$$

Current underground and underwater/ice experiments are investigating the sky in order to discover signs of neutrino sources, but unfortunately no "excess" has been found till now [7].
Here, in the frame of the model described above, a numerical calculation has been performed in order to estimate the expected neutrino induced muon flux from GRBs. The results are then compared with the available experimental upper limits.
Following [8], neutrino propagation is accomplished by solving the transport equation in dense media. The effect of "regeneration" due to neutrino neutral current interactions is also taken into account.
Key quantities for this calculation are the deep inelastic neutrino-nucleon cross sections, since at high energy the details of nucleon structure become important. Cross sections have been calculated using the approach of ref [9], selecting the set of parton density functions provided by the CTEQ group [10],(third version), as they are particularly suitable for high energy calculations.
After being produced, muons interact with matter mainly by ionization up to energy lower than few hundreds of GeV. At higher energies electromagnetic discrete processes, such as e^+e^- pair production, bremsstrahlung and photonuclear interaction, begin to dominate. The analytical formulas for computing muon energy losses due to these processes have been taken from [11] and [12]. The expected flux of upward-going induced muons has been achieved, in a similar way as done for neutrinos, by solving the transport equation for muons propagation.
In Fig. 2, assuming the same parameter values adopted in Fig. 1, we give the number of muons events per cm^2, as expected from a single GRB source, as a function of the cosine of zenith angle

θ. The dependency on θ is a consequence of

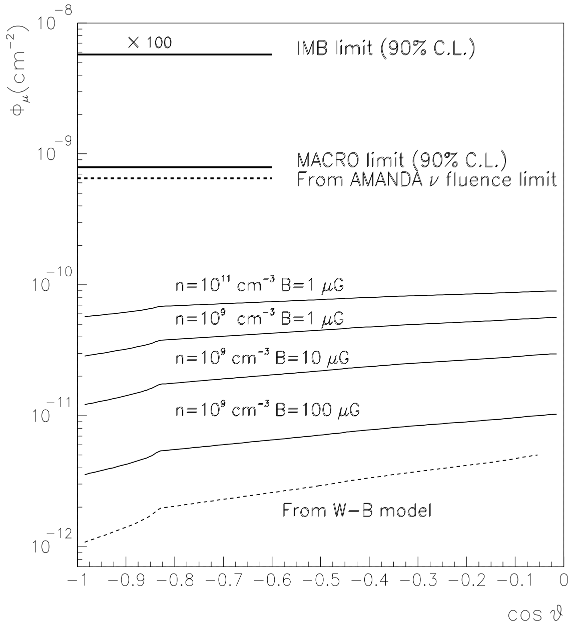

Figure 2. For the same parameters values as in Fig. 1, the total number of events per cm^2 is given as a function of the cosine of zenith angle θ. The thin dashed line is calculated for the Waxmann and Bahcall model [13]

neutrino absorption in Earth, which cannot be neglected at high energy. Moreover, the suppression at $\cos\theta \leq -0.8$ reflects the hard discontinuity of Earth density in correspondence of the nucleus. In Fig. 2 the calculated fluxes are compared with upper limits by current experiments (MACRO [7], IMB [14], and AMANDA [15]). (Note that the IMB limit has been lowered to fit the figure. Moreover, the AMANDA limit, shown as a dashed line, has been estimated starting from the declared upper limit on neutrino flux). Finally, for comparison purposes we show in Fig. 2 the number of events calculated by assuming as theoretical input the well-known Waxmann and Bahcall [13] model of neutrino production from GRBs.

As it results from Fig. 2, current experiments have not the required sensitivity to exclude or confirm our predictions, due to the weakness of the expected neutrino flux from a single GRB source.

Neutrinos telescopes of the next generation like ANTARES, NEMO, NESTOR [16] , with effective area ranging from 0.1 to 1 Km^2, will be likely capable to success to this task.

REFERENCES

1. T.Totani MNRAS 307 (1999) L41
2. F.De Paolis, G.Ingrosso and D.Orlando, A&A 359 (2000) 514
3. J.Bednarz M.Ostrowski, Phys. Rev. Lett. 80 (1998) 3911
4. A.Dar , Phys. Rev. Lett 51 (1995) 227
5. P.Lipari, Astrop. Phys. 1 (1993) 195
6. T.Gaisser, F.Halzen and T.Stanev, Phys. Rep. 258 (1995) 173
7. MACRO Collaboration, hep-ph/0002492, to be published on ApJ
8. V.A.Naumov, L.Perrone Astrop. Phys. 10 (1999) 239
9. R.Gandhi, C.Quigg, M.Reno, I.Sarcevic, Astrop. Phys. 5 (1996) 81
10. H. L. Lai, et al. (CTEQ Collaboration), Phys. Rev. D 51 (1995) 4763
11. W.Lohmann, R.Kopp and R.Voss CERN yellow report 85-03 (1985)
12. S.Bottai, L.Perrone hep-ex/0001018, to be published on Nucl. Instr.& Meth. A
13. E.Waxmann, J.Bahcall, Phys. Rev. D 59 (1998) 023002
14. B.Szendy et al., ApJ 444 (1995) 415
15. R.Carlton Bay, Ph.D. Thesis, astro-ph/0008255
16. L.Moscoso, Taup99 Sept 6-10 (1999) Paris