Very high energy neutrinos from Gamma Ray Bursts in dense clusters

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Abstract

The progenitors of long gamma-ray bursts (GRBs) are massive stars still immersed in dense stellar clusters. We consider a scenario in which protons accelerated within the jet of GRB can escape to dense regions. Protons interact efficiently with the matter of the cluster and produce high energy neutrinos. We calculate the spectra of relativistic protons within the cluster and spectra of neutrinos from their interactions with the matter. Neutrinos produced by the whole population of the GRBs should contribute to the extragalactic neutrino background. We calculate extragalactic neutrino background from GRBs and compare it with the observations of the IceCube

1. Model

Long GRB which is produced in explosion of a massive WR type star within huge and dense cloud (Fig.1). The progenitor star produce stellar wind cavity with the radius, R_{cav}, within which the relativistic jet propagates. Protons, accelerated in the outer parts of the jet, escape from it into the stellar wind region. In the wind cavity, protons either lose energy on the adiabatic process, due to the expansion of the stellar wind, or move balistically through the cavity. They are injected into the dense giant cloud. During diffusion process in the cloud, relativistic protons collide with the matter producing high energy neutrinos.

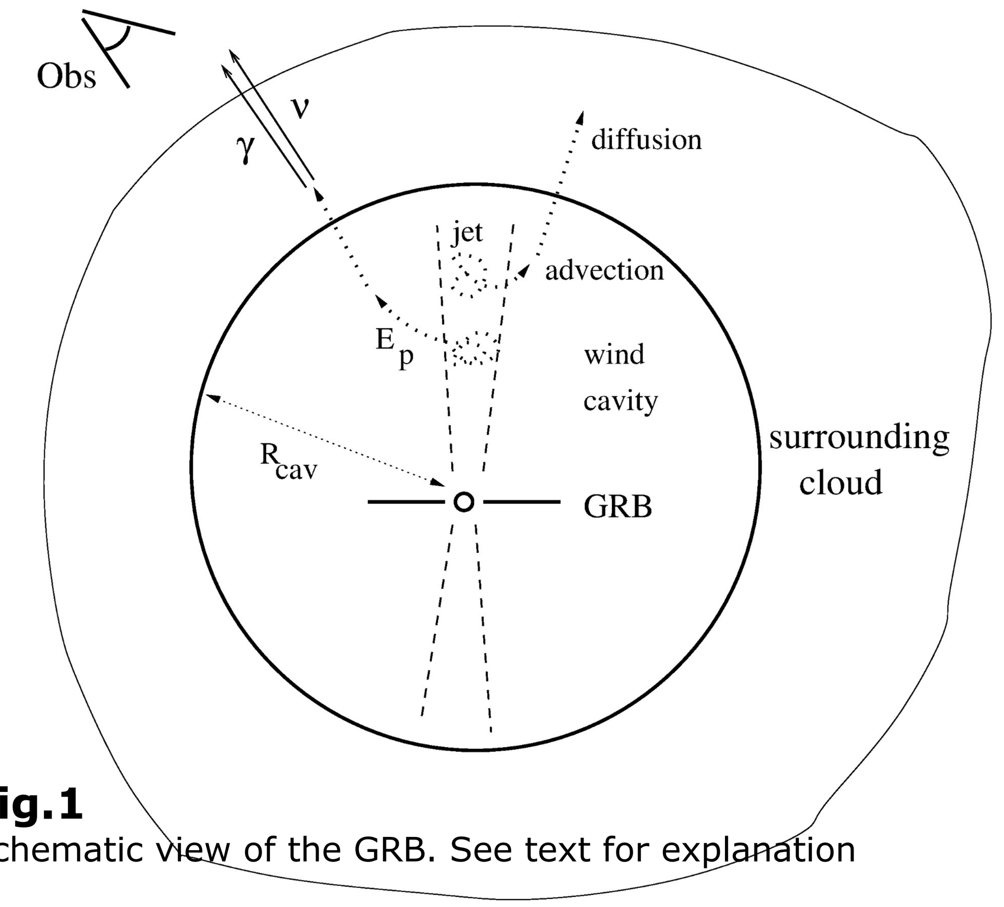

Fig.1
Schematic view of the GRB. See text for explanation

2. Hadron acceleration in the jet

We consider the decelerating jet of GRB which Lorentz factor (in the observer's reference frame) evolves in time as, $\Gamma(t) = \Gamma_0(t/t_0)^{-3/8}$, where $\Gamma_0 = 500\Gamma_{2.7}$ is the initial jet Lorentz factor at the time t_0 in seconds. Then jet Lorentz factor evolves with the distance from the jet base according to, $\Gamma(R) = \Gamma_0(R/R_0)^{-3/2}$, where $R_0 \approx 6\times10^{16}t_0\Gamma_{2.7}^2\ cm$.
Since the acceleration process in relativistic jets is not at present a well known phenomena, the acceleration time scale is often parametrized by a simple formula related to the Larmor radius of the particle. The magnetic field can be estimated assuming that it is generated locally in the jet. Following Razzaque et al.[1], we relate the magnetic field to the local parameters of the jet by:

$$B = \left(\frac{2\varepsilon_{\rm B}L_{\gamma,iso}}{R^2c\Gamma^2\varepsilon_{\rm e}}\right)^{1/2} \approx \frac{27\beta L_{52}^{1/2}t_{\rm L}^{\delta/2}}{\Gamma_{2.7}^3 t_0^{(\delta/2+1)}(R/R_0)^{(2\delta-0.5)}}\quad {\rm Gs}, \qquad \text{Eq.1}$$

where $\beta = (\varepsilon_B/\varepsilon_e)^{1/2} \approx 0.14$, $\varepsilon_B \sim 0.001$ is a fraction of the shock energy that is carried by the magnetic field, $\varepsilon_e \sim 0.1$ is a fraction of the shock energy that is carried by the relativistic electrons (see [2], [3]), $L_{\gamma,iso} \approx L_0(t_L/t)^{\delta}$ is the isotropic-equivalent γ-ray luminosity, $L_0 = 10^{52}L_{52}$ erg/s is the peak luminosity at the time $t_L = 10$ s and the index $\delta = 1.17$.
By comparing the energy gains with the energy losses on the adiabatic process, we obtain the maximum energies of accelerated protons,

$$E_{\rm ad}(R) \approx 4\times10^3(\Gamma_{2.7}t_0B/\eta_1)(R/R_0)^{5/2}\quad {\rm TeV}, \qquad \text{Eq.2}$$

We assume the spectrum of the form: $dN_p/dE = A_pE^{-2}exp(-\tau_{p\varepsilon}(E))$. The coefficient A_p is obtained from normalization of the proton spectrum to a part, ε_p, of jet power which is assumed to be equal to $L_{\gamma,jet} = L_{\gamma,iso}\alpha^2/2\varepsilon_e$. ε_p is assumed to be equal to 10% of the fraction of the power emitted from the jet in γ-rays, $\varepsilon_e = 0.1$ is the power in relativistic electrons and $\alpha = 0.1\alpha_{-1}$ rad is the jet opening angle.
Protons accelerated at a specific distance, R, from the base of the jet start to escape effectively from the jet when their diffusion distance becomes comparable to the perpendicular extend of the jet. By comparing the maximum allowed energies of protons, E_{ad}, at a specific distance from the jet base, R, with their escape energy, E_{esc}, we obtain the distance above which locally accelerated protons start to effectively leak from the jet into the surrounding medium, $R_{esc} = 33.5R_0(\Gamma^2_{2.7}\eta_1\alpha_{-1}^2)^{1/3}$. The process of proton acceleration becomes inefficient when the jet is sub-relativistic, i.e. $\Gamma(R) = 1.1$.

3. Propagation of hadrons around GRB

Protons, with the spectra calculated above, escape from the jet to the massive star wind cavity and after that to the giant cloud in which the star exploded. Protons with energies, $E_{bal} < 3\times10^4$ TeV, are frozen into the GRB progenitor wind. The largest energy protons escape from the wind region balistically, without significant energy losses on the adiabatic expansion of the stellar wind.
In Fig. 2, we show the proton spectra, escaping from the stellar wind region into the giant cloud, for the three different models for the energy losses of protons: (A) adiabatic energy losses within the jet and stellar wind taken into account; (B) adiabatic losses important only in the jet; (C) adiabatic losses not important. Those three models are considered since it is not to the end clear whether adiabatic losses of protons play any role during their propagation. As an example, we use the following parameters of considered scenario: $\Gamma_0 = 500$, $L_0 = 10^{52}$ $erg\ s^{-1}$, $\varepsilon_B = 10^{-3}$, $\alpha = 0.1$, $\eta_1 = 10$.

4. Extragalactic Neutrino Background

Protons, escaping from the jet, have to propagate through the giant cloud and collide with the matter. We have simulated spectra of mesons produced by relativistic protons at given energy using CORSIKA Monte Carlo package [4]. Then, the spectra of neutrinos, produced by relativistic protons in collisions with the matter, are obtained. The effects of energy losses of protons during their propagation within the jet and the wind region of progenitor star are taken into account as considered above. The multiple interactions of the lower energy protons with the matter of the cloud are also taken into account.
We calculate diffuse neutrino background from the whole population of GRBs taking into account model of the redshift rate of the GRBs, i.e. $R_{GRB}(z)$ [5] . We compute the neutrino fluxes produced at arbitrary redshifts, z, taking into account redshift dependence of the jet opening angle and isotropic equivalent gamma-ray luminosity [6].

$$\frac{dN}{dEdtdSd\Omega} = \phi = \frac{c}{4\pi H_0}\int_0^{z_{max}} dz\frac{R_{GRB}(z)}{F(z,\Omega_m,\Omega_\Lambda)}\cdot\frac{dN_\nu(E'_\nu)}{dE'_\nu}(1+z)^{-3/2}, \qquad \text{Eq.3}$$

where $E'_\nu = (1+z)E_\nu$ is the energy of neutrinos at redshift z, $H_0 = 71$km s^{-1} Mpc^{-1}, $z_{max} = 10$ and $F(z,\Omega_m,\Omega_\Lambda) = (\Omega_\Lambda(1+z)^{-3} + \Omega_m)^{1/2}$ with adopted $\Omega_\Lambda = 0.7$ and $\Omega_m = 0.3$.
In Fig 3, we show the extragalactic diffuse neutrino background produced in GRBs for the case of three considered models, which differ in the adiabatic energy losses of hadrons propagating around the GRB progenitor. Significant contribution to measured by IceCube extragalactic neutrino background is obtained in the case of negligible adiabatic energy losses ofrelativistic hadrons.

5. Conclusions

Neutrino emission, produced in terms of this scenario, is expected to last for thousands of years after the initial GRB. Therefore the observed extragalactic neutrino background can originate in GRBs which exploded long time ago.

Our model in the case of negligible adiabatic energy losses of relativistic hadrons is able to contribute significantly to the ENB at energies below ~100 TeV. The higher energy ENB should be produced in another process, e.g. in the inner parts of the relativistic jets of GRBs.

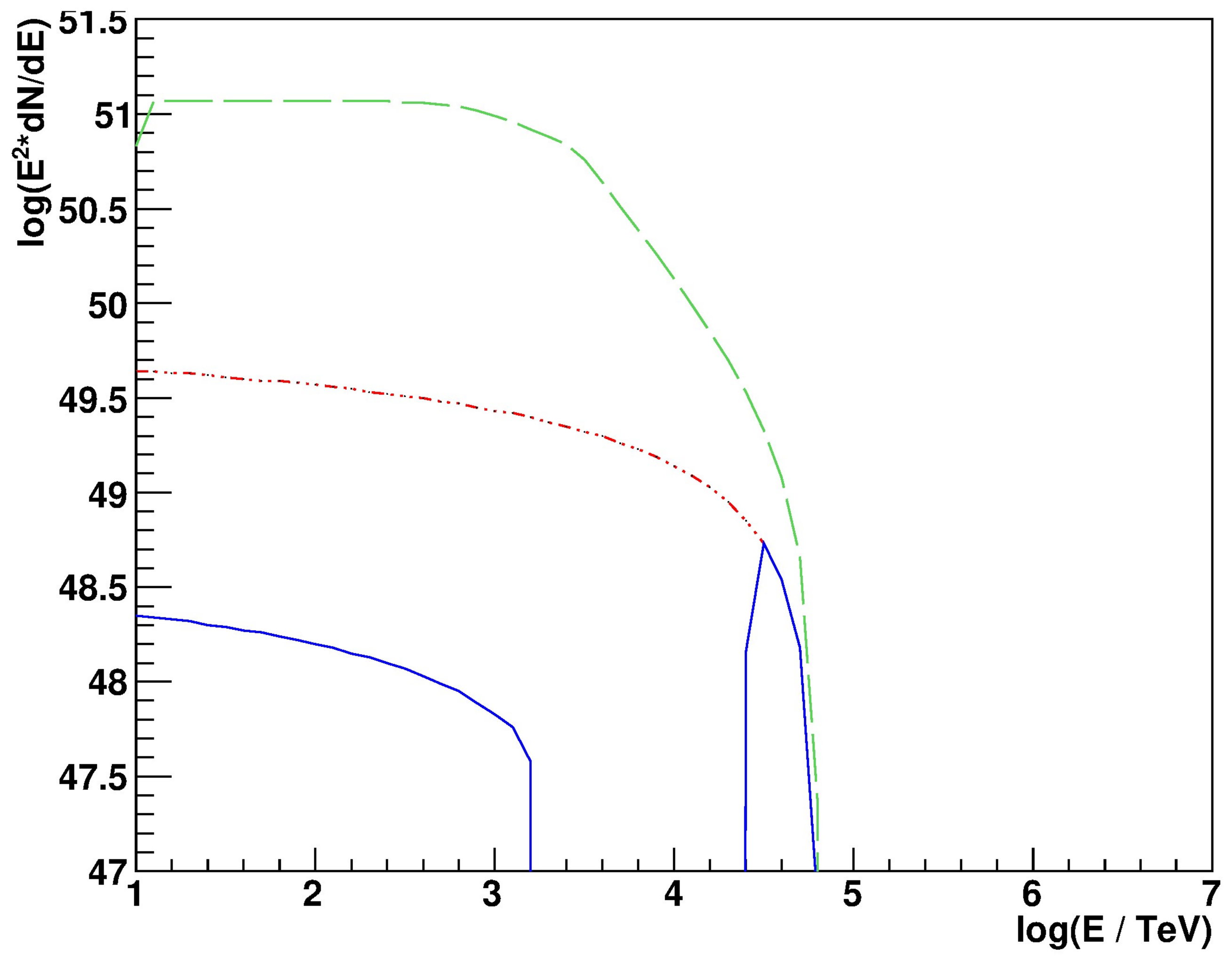

Fig.2
Spectral energy distribution (SED) of relativistic protons, which escaped from the progenitor star wind region into the giant cloud is shown for three considered models;
(A) with adiabatic losses (solid curve), (B) without adiabatic losses (long dashed curve), and (C) with adiabatic losses taken into account only inside the jet region (dot-dot-dot-dashed curve)

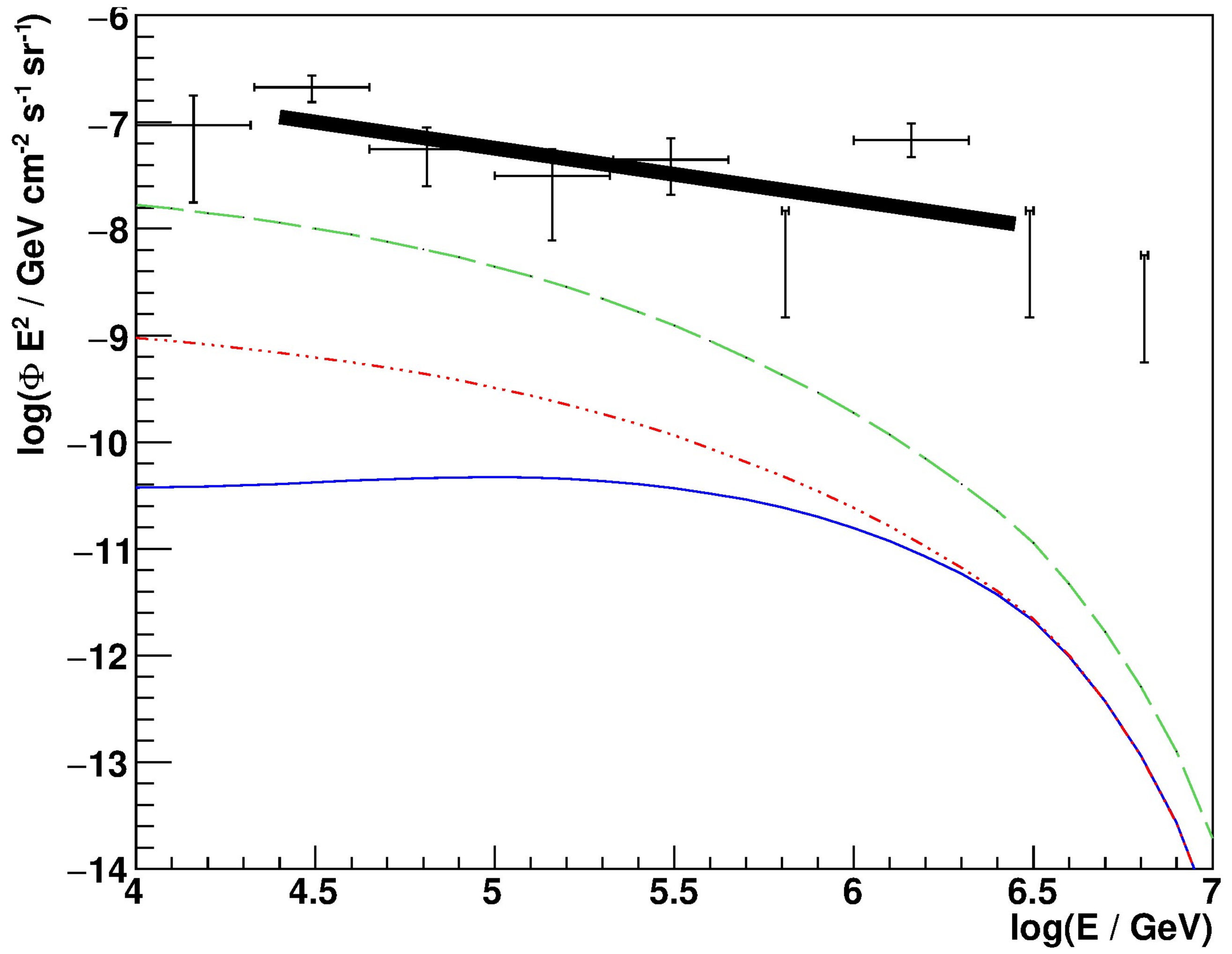

Fig.3
Extragalactic diffuse neutrino background (ENB) calculated for the three models with different assumptions on the importance of adiabatic energy losses of hadrons (as presented in Fig. 2). The spectrum of the extragalactic neutrino background, measured by the IceCube Collaboration [7], is shown as error bars and its power low model by the thick solid line.

References

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