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Neutrino afterglows from dense environment of GRB jets

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The progenitors of 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.

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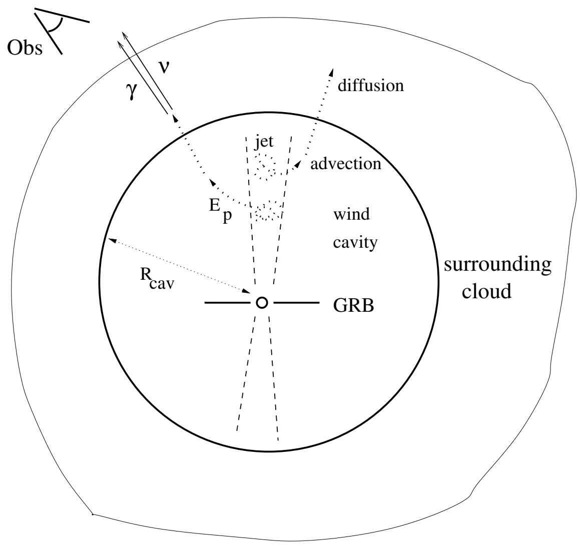

Figure 1: Schematic presentation of the long GRB which is produced in explosion of a massive WR type star within huge and dense cloud. The progenitor star produce stellar wind cavity with the radius, $R_{\rm cav}$, within which the relativistic jet propagates. Protons, accelerated in the outer parts of the jet, escape from it into the stellar wind region. In the wind cavity, protons either lose energy on the adiabatic process or move balistically through the cavity. They are injected into the dense giant cloud where during diffusion process, relativistic protons collide with the matter producing high energy neutrinos.

1. GRB within dense open cluster

Long duration GRBs are expected to be the final products of asymmetric explosions of short lived very massive stars. These progenitors of GRBs are not able to move in such a short period (of the order of Myrs) outside the parent dense cluster. Therefore, they are expected to be immersed in dense gas. In fact, a large population of such young and compact clusters in the nearby galaxies, with ages below 100 Myrs and masses above 10^6 M$_\odot$ and radii < 15 pc, has been found by using the Hubble Space Telescope (HST) (see e.g. [4], [6], [14], [17]). At farther distances, the proto-globular clusters are also observed, with the masses in the range $(1 - 20) \times 10^6$ M$_\odot$ and sizes of a few tens of pc [15]. Massive stars produce fast and dense stellar winds which are confined by the surrounding cloud. GRB jets have to propagate through the wind bubbles formed as a result of the interaction of the progenitors winds with the surrounding medium. We investigate the scenario in which the GRB jets propagate in dense medium of a huge cloud. Hadrons are expected to be accelerated within the relativistic jets of GRB (see Fig.1). The energies of protons, escaping to the medium from the jet, are relativistically busted with the Lorentz factor of the jet. After leaving the wind cavity, protons interact with the dense medium of the huge cloud producing high energy neutrinos through decay of pions. Depending on their energy, protons can be confined within the cloud losing efficiently energy. Since their interaction time scale takes thousands of years, those neutrinos cannot be identified with any specific GRB. Those neutrinos form a long time neutrino afterglow. Our aim is to estimate the contribution of neutrinos produced within such scenario to the extragalactic neutrino background in the universe.

2. Acceleration of hadrons in the jet

Relativistic jets of GRBs emit clearly non-thermal radiation. Therefore, they are expected to provide good conditions for the acceleration of particles. 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. This Lorentz factor of the jet is expected to be of the order of a few hundred for the total jet energy of the order of $\sim 10^{55}$ erg and the density of surrounding medium in the range $n = 0.1 - 10^4$ cm^{-3} (Sari et al. [11], see Eq. 14). In the case of decelerating jets, the relation between the distance from the jet base and the time, in the observer's reference frame, can be obtained by integrating the relation $dR = 2c[\Gamma(t)]^2 dt$. Then, $R = 8c\Gamma_0^2 t_0 (t/t_0)^{1/4} = R_0(t/t_0)^{1/4}$. and $R_0 = 8c\Gamma_0^2 t_0 \approx 6\times 10^{16} t_0 \Gamma_{2.7}^2$ cm. The jet Lorentz factor evolves with the distance from the jet base according to, $\Gamma(R) = \Gamma_0(R/R_0)^{-3/2}$. The maximum energies of protons, in the jet reference frame at the distance, R, from its base, are defined by their energy gains from the acceleration mechanism. Since the acceleration process in relativistic jets is not at present well known phenomena, the acceleration time scale is often parametrized by a simple formula related to the Larmor radius of the particle, $\dot{E}_{\rm acc} = cE/(\eta R_{\rm L}) \approx 10^{12} B/\eta_1$ eV/s, where $\eta = 10\eta_1$ is the so called acceleration parameter, and $R_{\rm L} = E/eB \approx 3\times 10^{-3} E/B$ cm is the Larmor radius and E is the proton energy in eV and B is the magnetic field strength in the jet (in Gauss) at the distance, R, from its base. The magnetic field can be estimated assuming that it is generated locally in the jet. Following Razzaque et al.[10], we relate the magnetic field to the local parameters of the jet by,

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

where $\beta = (\varepsilon_{\rm B}/\varepsilon_{\rm e})^{1/2} \approx 0.14$, $\varepsilon_{\rm B} \sim 0.001$ is a fraction of the shock energy that is carried by the magnetic field, $\varepsilon_{\rm e} \sim 0.1$ is a fraction of the shock energy that is carried by the relativistic electrons (see [9], [8], [16]), $L_{\gamma,iso} \approx L_0(t_{\rm L}/t)^\delta$ is the isotropic-equivalent γ-ray luminosity, $L_0 = 10^{52} L_{52}$ erg/s is the peak luminosity at the time $t_{\rm L} = 10$ s and the index $\delta = 1.17$ is applied as observed in the GRB 130427A [2]. For the applied scaling parameters and the Lorentz factor of the jet at one second after initial flash equal to 500, the magnetic field strength in the jet of GRB 130427A is estimated, at the distance at which protons escape from the jet, to be of the order of $\sim$ Gs.

On the other hand, we assume that protons lose mainly energy on the pion production in collisions with radiation and on the adiabatic expansion of the emission region within the jet. The adiabatic energy loss rate is defined as $\dot{E}_{\rm ad} = cE\Gamma/R$. By comparing the energy gains with the energy losses on the adiabatic process, we obtain the maximum energies of accelerated protons, $E_{\rm ad}(R) \approx 4\times 10^3 (\Gamma_{2.7} t_0 B/\eta_1)(R/R_0)^{5/2}$ TeV.

However, close to the base of the jet where the density of radiation produced in the jet is high, accelerated protons can also efficiently lose energy on pion production in collisions with photons. We estimate the distance, from the base of the jet, at which this energy loss process becomes negligible. The optical depth for protons on pion production in collisions with non-thermal radiation from the jet is, $\tau_{{\rm p}\varepsilon} = \sigma_{{\rm p}\varepsilon} n_\varepsilon R/\Gamma$, where $\sigma_{{\rm p}\varepsilon} = 5\times 10^{-28}$ cm^2, and n_ε is the number density of photons in the co-moving frame of a GRB jet estimated from (see e.g. [10]), $n_\varepsilon = d_{\rm L}^2 F_\varepsilon(t)/[R^2 c\Gamma\varepsilon_{\rm min}(1+z)]$, where $F_\varepsilon(t)$ is the observed hard X-ray photon flux at the time "t" after the initial flash. This flux is applied to vary as observed in the GRB 130427A according to $F_\varepsilon(t) = F_0(t/t_0)^{-\delta}$ [2]. The characteristic photon energy in the observer's reference frame, $\varepsilon_{\rm min}$, for which pion production process can occur is estimated from $\varepsilon_{\rm min} = \varepsilon_{\rm th}\Gamma/\gamma_{\rm p}(1+z)$, where $\varepsilon_{\rm th} \approx 200$ MeV, and the Lorentz factor of relativistic proton is $\gamma_{\rm p} = E_{\rm ad}/m_{\rm p}c^2$. We estimate the distance, $R_{\rm loss}$, from the base of the jet at which the energy losses limit acceleration of protons below $E_{\rm ad}$. This distance scale corresponds to the optical depth for pion production, $\tau_{\rm p\varepsilon}$, equal to unity.

The spectrum of accelerated protons is assumed to be well described by a power law function, $dN_{\rm p}/dE = A_{\rm p}E^{-2}$, where $A_{\rm p}$ is the normalization coefficient. If the interaction of relativistic protons in the jet is effective, then the injection spectrum is modified by the process of proton energy losses already in the jet. Therefore, the injected spectrum of protons takes the form, $dN_{\rm p}/dE = A_{\rm p}E^{-2}exp(-\tau_{\rm p\varepsilon}(E))$. The coefficient $A_{\rm p}$ is obtained from normalization of the proton spectrum to a part, $\varepsilon_{\rm p}$, of jet power which is assumed to be equal to $L_{\gamma,\rm jet} = L_{\gamma,\rm iso}\alpha^2/2\varepsilon_{\rm e}$. $\varepsilon_{\rm p}$ is assumed to be equal to 10% of the fraction of the power emitted from the jet in γ-rays, and $\varepsilon_{\rm e} = 0.1$ is the power in relativistic electrons.

Protons accelerated at a specific distance, R, from the base of the jet start to escape effectively from the jet when their diffusion distance (during adiabatic time scale) becomes comparable to the perpendicular extend of the jet, i.e. $Z_{\rm dif} = 0.1\alpha_{-1}R$, where $\tau_{\rm ad} = E/\dot{E}_{\rm ad}$ and $\alpha = 0.1\alpha_{-1}$ rad is the jet opening angle. In the case of the Bohm diffusion, this distance is given by $Z_{\rm dif} = \sqrt{2D_{\rm dif}\tau_{\rm ad}}$, and the Bohm diffusion coefficient is $D_{\rm dif} = cR_{\rm L}/3$. Then, protons escape with energies, $E_{\rm esc}(R) \approx 1.5\times10^8\alpha_{-1}^2\Gamma_{2.7}^3t_0B(R/R_0)^{-1/2}$ TeV. By comparing the maximum allowed energies of protons, $E_{\rm ad}$, at a specific distance from the jet base, R, with their escape energy, $E_{\rm esc}$, we obtain the distance above which locally accelerated protons start to effectively leakage from the jet into the surrounding medium, $R_{\rm esc} = 33.5R_0(\Gamma_{2.7}^2\eta_1\alpha_{-1}^2)^{1/3}$. We assume that the process of proton acceleration becomes inefficient when the jet becomes sub-relativistic, i.e. $\Gamma(R) = 1.1$. This happens at the distance $R_{\rm max} = R_0(\Gamma_0/1.1)^{2/3}$. Relativistic protons accelerated at a specific distance, R, are advected with the jet plasma flow. They might be able to loose energy on the adiabatic process up to the moment of their escape from the jet. Note that, the energies of protons , $E_{\rm jet}$, escaping from the jet to the progenitor star wind region, are additionally boosted by the Lorentz factor of the jet.

3. Propagation of hadrons around GRB

Protons, with the spectra calculated above, escape from the jet at first to the massive star wind cavity and after that to the giant cloud in which the massive star exploded. Below we discuss the conditions for the propagation of protons in these two regions. We argue that a significant amount of protons, injected from the jet, lose only a part of their energy due to the adiabatic process in the expanding GRB progenitor wind. The interaction of protons with the matter of the wind is inefficient since the density of the wind at the parsec distance scale is rather very low, $n_{\rm w} \approx 3.7\times10^{-3}\dot{M}_{-6}/(R_{\rm pc}^2v_3)$ cm^{-3}, where the wind velocity $v_{\rm w} = 1000v_3$ km s^{-1}, and the mass loss rate $\dot{M}_{\rm WR} = 10^{-6}M_{-6}$ M$_\odot$ yr^{-1}, and $R = 1R_{\rm pc}$ pc is the distance from the star in parsecs. On the other site, protons can lose significant amount of their energy in collisions with the background matter in the giant molecular cloud surrounding the progenitor star. Therefore, we concentrate on

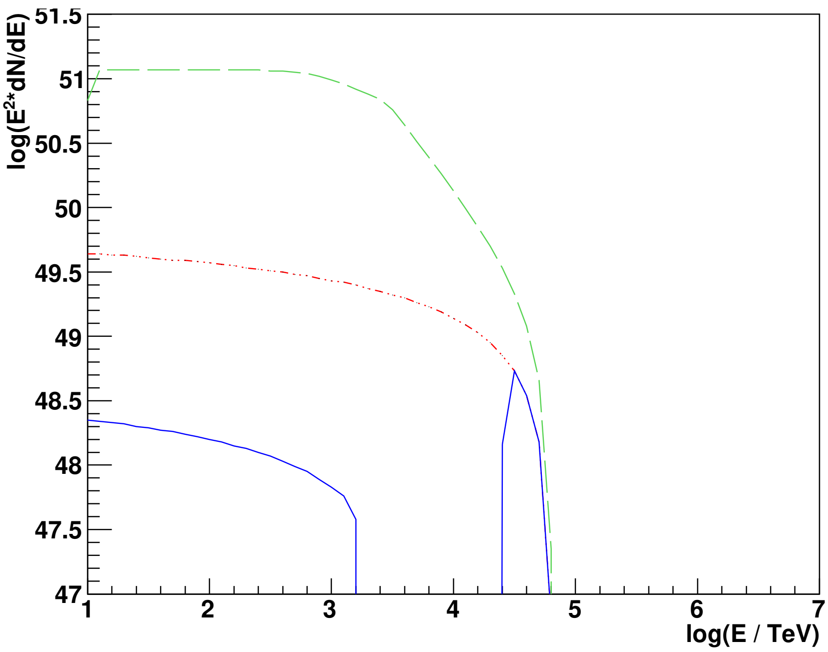

Figure 2: Spectral energy distribution (SED) of relativistic protons, which escaped from the progenitor star wind region into the giant cloud is shown for three considered models; (A) with adiabatic losses (solid curve), (B) without adiabatic losses (long dashed curve), and (C) with adiabatic losses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

the calculation of the neutrino spectra produced by these relativistic protons with the matter of the huge and dense cloud.

3.1 Propagation of hadrons in the wind cavity

The conditions within the stellar wind cavity change significantly with the distance from massive star the progenitor of the GRB. Let us consider the typical parameters of the WR type star mentioned above and its surface magnetic field strength of the order of $B_{\rm WR} = 10^3 B_3$ Gs. At large distance from the star, the magnetic field is estimated as, $B(R) = 3 \times 10^{-5} B_3/R_{\rm pc}$ Gs. Depending on the energy of protons, injected from the jet, they can be either captured by the magnetic field or escape almost ballistically through the wind. In the first case, protons are expected to suffer adiabatic energy losses in the expending wind. In the second case, they move freely to the giant cloud region without significant adiabatic energy losses. We estimate the energies of relativistic protons below which they are frozen in the stellar wind by comparing their Larmor radius with the distance from the star. It is found that protons with energies, $E_{\rm bal} < 3 \times 10^4$ TeV, are frozen into the GRB progenitor wind. But, the largest energy protons escape from the wind region balistically, without significant energy losses on the adiabatic expansion of the stellar wind. The energies of protons, after losing energy on the adiabatic process in the wind cavity, can be determined from $E_{\rm cav} = E_{\rm fin} R_{\rm fin}/R_{\rm cav}$, where $R_{\rm cav}$ is the radius of the cavity filled with the stellar wind. $R_{\rm cav}$ depends on the age of the star, its wind parameters and the parameters of the surrounding giant cloud (see [13]), according to $R_{\rm cav} = 18(M_{-6}V_3/n_2)^{1/5} t_3^{3/5}$ pc, where $t = 3t_3$ Myr is the age of the star up to the explosion, and $n_{\rm cl} = 100 n_2$ cm^{-3} is the density of the giant cloud.

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 defining considered scenario: $\Gamma_0 = 500$, $L_0 = 10^{52}$ erg s^{-1}, $\varepsilon_{\rm B} = 10^{-3}$, $\alpha = 0.1$, $\eta_1 = 10$. It is evident that adiabatic losses of protons, if important can significantly extract energy from relativistic hadrons. Therefore, we expect that interesting fluxes of neutrinos should be produced only in the case of free escape of protons to the surrounding dense cloud.

3.2 Propagation of hadrons in the cloud

Let us consider, as an example (see Introduction), a giant molecular cloud with the radius, $R = 30R_{30}$ pc and the mass $10^6 M_6$ $\mathrm{M}_\odot$ in which the GRB has been exploded. Then, protons, escaping from the jet, have to propagate through this cloud. The average density of such cloud can be estimated on $n_{\rm cl} \approx 270 M_6/R_{30}^3\ cm^{-3}$. We assume the magnetic field in the cloud is of the order of $B_{\rm cl} = 10^{-4} B_{-4}$ G. The Bohm diffusion coefficient of relativistic protons is then $D_{\rm dif} = R_{\rm L}c/3 \approx 3\times10^{23} E_{\rm TeV}/B_{-4}$ cm^2 s^{-1}. The diffusion time scale of protons through the cloud is, $T_{\rm dif} = R_{\rm cl}^2/2D_{\rm dif} \approx 1.35\times10^{17} R_{30}^2 B_{-4}/E_{\rm TeV}$ s. Then, the interaction rate of protons in the cloud is given by $T_{\rm int} = (cn_{\rm cl}\sigma_{\rm pp})^{-1} \approx 4\times10^{12} R_{30}^3/M_6$ s. We follow the cooling process of the example protons in collisions with the matter of the cloud on the pion production process to calculate the spectra of VHE neutrinos.

4. Delayed VHE neutrinos

We have simulated spectra of mesons produced by relativistic protons at given energy using CORSIKA Monte Carlo package [3]. 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. Protons are assumed to the injected locally in the jet with the power law spectrum and normalization described above. The multiple interactions of the lower energy protons with the matter of the cloud are also taken into account. In such a way, we are able to calculate the neutrino spectra from the GRBs with arbitrary parameters. Thus, we can estimate the contribution to the neutrino extragalactic background from the whole population of GRBs in the Universe.

4.1 Extragalactic Neutrino Background from GRBs

We calculate diffuse neutrino background from the whole population of GRBs taking into account the redshift rate of the GRBs, i.e. $R_{GRB}(z)$ (see e.g.[7]). 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 (on basis of the redshift dependences presented in [5]).

The differential flux of extragalactic neutrinos from GRBs calculated from,

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

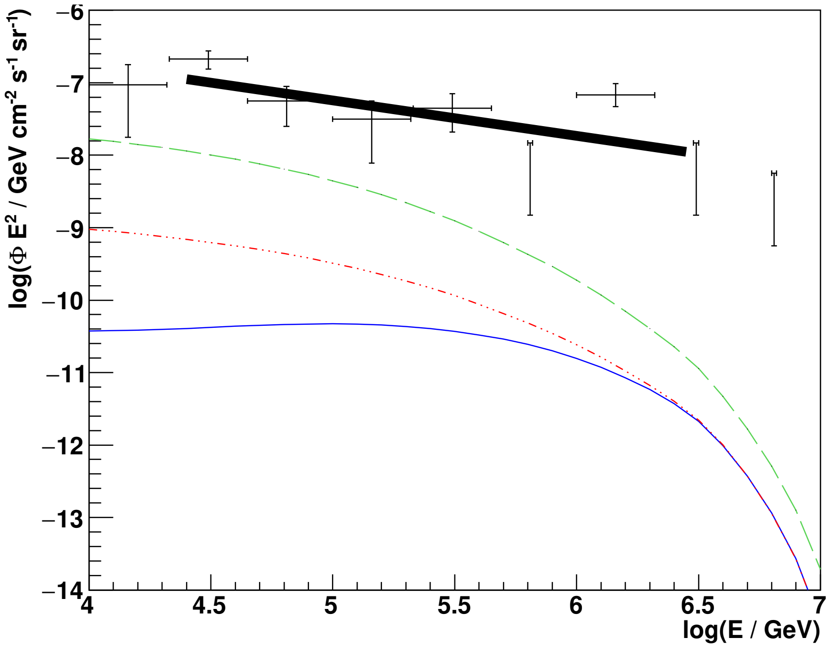

Figure 3: Extragalactic diffuse neutrino background (ENB) calculated for the three models with different assumptions on the importance of adiabatic energy losses of hadrons: (A) adiabatic energy losses within the jet and stellar wind taken into account (solid curve); (B) adiabatic losses important only in the jet (dot-dot-dot-dashed curve); (C) adiabatic losses not important (long, dashed curve). The spectrum of the extragalactic neutrino background, measured by the IceCube Collaboration[1], is shown as error bars and its power low model by the thick solid line.

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 $F(z, \Omega_m, \Omega_\Lambda) = \sqrt{\Omega_\Lambda (1+z)^{-3} + \Omega_m}$, with adopted $\Omega_\Lambda = 0.7$ and $\Omega_m = 0.3$.

On 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. It is shown, that significant contribution to measured by IceCube extragalactic neutrino background is obtained in the case of negligible adiabatic energy losses of relativistic hadrons. In such a case, considered model 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.

However, note that presented results base on the assumption that efficiency of acceleration of hadrons is equal to the efficiency of acceleration of leptons which power is equal to some fraction of the observed gamma-ray power of the GRB. The neutrino fluxes should be enhanced in case of more efficient acceleration of hadrons in comparison to leptons. Such difference might be related to the injection problem of particles (hadrons/leptons) into the acceleration mechanism.

5. Conclusion

We considered the model for the neutrino production in the surroundings of GRBs. In this scenario, protons, accelerated in the GRB jet, escape from the acceleration site in the GRB jet to the dense medium, producing neutrinos in collisions with the background matter. It takes quite a long time for relativistic hadrons to reach dense cloud. Therefore, our model does not predict neutrino emission accompanying the specific GRBs. On the other hand, neutrinos from the surrounding cloud, are produced with large delay, forming an extended afterglow emission impossible to directly observe from specific GRBs. Neutrino emission, produced in terms of this scenario, is expected to last for thousands of years after the initial GRB. Therefore, we conclude that the observed extragalactic neutrino background can originate in GRBs which exploded long time ago. They cannot be related to the presently observed population of GRBs at other energies.

Acknowledgments

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