Origin of the High Energy Cosmic Neutrino Background

Shlomo Dado and Arnon Dar
Department of Physics and Space Research Institute, Technion, Haifa 32000, Israel
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The diffuse background of very high energy extraterrestrial neutrinos recently discovered with IceCube is compatible with that expected from cosmic ray interactions in the Galactic interstellar medium plus that expected from hadronic interactions near the source and in the intergalactic medium of the cosmic rays which have been accelerated by the jets that produce gamma ray bursts.

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Introduction.—Based on combined 3-year data, the IceCube collaboration has reported recently [1] the discovery of a diffuse background of high energy (HE) astrophysical neutrinos with energy above 60 TeV that extends at least up to 3 PeV, in excess (5.7σ significance level) of that produced by cosmic ray (CR) interactions in the atmosphere. The neutrino events did not point back to any identified sources and are consistent with an isotropic distribution of arrival directions. Their best fit power law to the energy flux per flavor above 60 TeV is

$$E^2\phi_\nu = 1.5 \times 10^{-8}\left(\frac{E}{100\ \mathrm{TeV}}\right)^{-0.3}\frac{\mathrm{GeV}}{\mathrm{cm^2\ s\ sr}}. \quad (1)$$

So far, the origin of this diffuse background of high energy neutrinos is not known. A natural source of high energy astrophysical neutrinos is the decay of mesons produced in collisions of CR nuclei with matter and radiation. Several models of cosmic ray production of neutrinos in or near cosmic ray sources [2] have been used to estimate the astrophysical diffuse background of high energy neutrinos. But, uncertain assumptions and free adjustable parameters prevented meaningful conclusions. Moreover, no evidence of neutrino emission from pointlike or extended CR sources was found in four years of IceCube data [3]. These include supernova remnants, the nearest most luminous gamma ray bursts (GRBs) such as [4] 130427A at redshift $z = 0.34$, the giant elliptical galaxy M87 at a distance of 16 Mpc that contains the nearest active galactic nucleus (AGN) in the northern sky, and Markarian 421, at a distance of 133 Mpc, the brightest γ-ray blazar in the northern sky. In particular, the null detection of high energy neutrinos with IceCube from 100 stacked GRBs has been used to set a strong limit on the contribution of GRBs to the diffuse background of high energy neutrinos [5]. But, this flux limit was based on the assumption that the neutrino emission in GRBs roughly coincides in time and beaming with the prompt gamma ray and early afterglow emissions, as expected [6] in the fireball models of GRBs.

GRB neutrinos, however, may be produced mainly through hadronic production of mesons by GRB cosmic rays in the giant molecular clouds (GMCs) where most core collapse supernovae take place rather than through photoproduction of mesons, which are assumed to take place in GRB "fireballs" during their prompt gamma ray and early afterglow emissions [6]. Such hadronic production of mesons, which is expected in the cannonball model of GRBs [7], is delayed and spread over much larger beaming angles than the prompt gamma ray and early afterglow emissions (the early time GeV emission from GRBs observed with Fermi-LAT, most probably, is not from π^0 decay but from inverse Compton scattering by the high energy electrons of their self emitted synchrotron radiation [8]). A large spread in the neutrino arrival times (due to CR diffusion through the GMC) reduces the detected flux from individual GRBs and stacked GRBs. Hence, limits on the flux of GRB neutrinos [5] based on no detection in selected time and sky windows centered on visible GRBs may not be applicable to the diffuse flux of neutrinos from all past GRBs, which may contribute significantly and even dominate the isotropic component of the diffuse background of high energy neutrinos.

Moreover, in this Letter, we show that the spectrum, sky distribution, and intensity of the diffuse background of high energy neutrinos recently discovered with the IceCube detector [1] are compatible with those of a nonisotropic Galactic background expected from hadronic collisions of very high energy cosmic rays in the Galactic interstellar medium (ISM) plus an isotropic extragalactic background expected from hadronic collisions near source and in the intergalactic medium (IGM) of high energy cosmic rays accelerated by the highly relativistic jets, which produce GRBs in star forming galaxies.

The Galactic Background.—Because of Feynman scaling [9], very high energy (VHE) cosmic rays with a power-law flux $\phi_p \propto E^{-k}$ per nucleon that collide with the baryons of an "optically thin" gas produce mesons whose leptonic and semileptonic decays produce neutrinos at a rate $\dot{n}_\nu \approx 4\pi K\bar{\sigma}_{\rm in}(pp)\phi_p n_b$ per unit volume. The constant K depends [10] only on the power-law index k, $\sigma_{\rm in}(pp)$ is the inelastic pp cross section, and n_b is the baryon density of the gas. Since the average energy of the produced neutrinos is $\sim 1/50$ that of the CR nucleons, production of neutrinos in the 60 TeV–3 PeV energy range requires CR nuclei with energy per nucleon well above the CR "knee" where $\sigma_{\rm in}(pp) \approx 62 E_{\rm PeV}^{0.085}$ mb. The CR flux per nucleon in the 100 PeV–10 EeV energy range is roughly [11] $\phi_p = 0.07 E_{\rm GeV}^{-2.67}\ {\rm GeV}^{-1}\,{\rm cm}^{-2}\,{\rm sr}^{-1}\,{\rm s}^{-1}$ with $E_{\rm GeV} = E/{\rm GeV}$. This flux represents quite well the CR flux per nucleon between the CR knee and CR ankle. Presumably, these very high energy (VHE) CRs are accelerated by the highly relativistic jets of supernovae of type Ic that produce GRBs, most of which point away from Earth [12,13].

Most of the gas and dust in the galaxy ($M_{\rm gas} \approx 5.5\times 10^9 M_\odot$) resides in a relatively thin Galactic disc whose mean surface density within $\sim$12.5 kpc from its center is [14] $\Sigma_{\rm gas} \approx 10 M_\odot {\rm pc}^{-2}$, and beyond it the mid-plane density drops exponentially in the radial direction like $n_0 \exp[-(R-R_\odot)/R_s]$ with $n_0 = 0.9\ {\rm cm}^{-3}$ with a scale height $R_s = 3.75$ kpc and where $R_\odot \sim 8.5$ kpc is the distance of the solar system from the center of the disc. This gas and dust are embedded in a large cosmic ray halo with roughly a constant density in the Galactic disc. Hence, the total neutrino luminosity of the Galaxy is given roughly by

$$dL_\nu \approx K \bar{\sigma}_{\rm in}(pp)(M_{\rm gas}/m_p) 4\pi \phi_p(E) E dE, \qquad (2)$$

where $K = 0.06$ for $k = 2.7$. A rough estimate of the neutrino event rate in IceCube due to Galactic $\nu' s$ with $E_\nu > 60$ TeV, is

$$\dot{N}_\nu \approx K \int d^3\mathbf{R} \frac{n_b(\mathbf{R})}{|\mathbf{R}-\mathbf{R}_\odot|^2} \int A \sigma_{in} 4\pi \phi_p dE, \qquad (3)$$

where $A(E)$ is the mean effective area of IceCube for neutrinos of the e, μ, τ flavors (assuming equal mixing due to oscillations). For an energy-weighted [2] $\langle A(E)/E \rangle = 24.5\ {\rm cm}^2/{\rm GeV}$ above 60 TeV, and $n_b(\mathbf{R})$ as parametrized in Ref. [14], Eq. (3) yields $\dot{N}_\nu \approx 3.6\ {\rm y}^{-1}$ neutrino events pointing back to the Galactic disc and peaked towards the Galactic center. The contribution of CRs accelerated in episodes of mass accretion onto the Galactic central massive black hole may contribute significantly to this concentration. All together, the energy spectrum of these Galactic neutrino background is expected to have an $\sim E^{-2.67+0.085} \approx E^{-2.58}$ spectrum, and its sky distribution is expected to follow roughly that of the diffuse Galactic gamma rays in the energy range 100 MeV–100 GeV, which are produced mostly by hadronic π^0 production and leptonic bremsstrahlung in the Galactic disc and are not absorbed significantly by the background light in the Galaxy.

GRB Neutrinos.—There is mounting observational evidence that long duration GRBs and their afterglows are produced by the interaction of highly relativistic jets of plasmoids (cannonballs) of ordinary matter ejected in stripped envelope supernova explosions, mainly of type Ic, with the radiation and matter along the jets' trajectories [13]. In particular, the prompt γ-ray pulses and early-time x-ray flares are produced by the jet electrons through inverse Compton scattering (ICS) of photons in a light halo (glory) surrounding the progenitor star. Such a light halo is formed by scattered stellar light from ejecta of presupernova eruptions [15]. Thus, the total kinetic energy of the baryons in the jet is $E_k \sim (m_p/m_e)$ times E_γ, the total emitted gamma ray energy. The jet decelerates by the swept in particles in front of it. Its random magnetic fields transform its kinetic energy by Fermi acceleration to CRs' energy with a spectrum E^{-2}. The CRs escape the jet by diffusion through its random magnetic fields. For a Kolmogorov spectrum [16] of the random magnetic fields, their diffusion coefficient is $\propto E^{1/3}$, which yields a residence time $\tau(E) \propto E^{-1/3}$ and a CR flux $A E_{\rm GeV}^{-2.33}$, where $A \approx E_k/3$ GeV.

The CR jets move through the GMCs with practically the speed of light and produce narrow beams of high energy neutrinos mainly through π and K production in hadronic collisions with the baryons along their path in the GMCs. Under the assumption of Feynman scaling [9], CR spectrum $\sim E^{-2.33}$, and a baryonic column density N_p of the GMC, roughly, a fraction [17] $f_\nu \approx 0.09 \sigma_{\rm in}(pp) N_p$ of the CR flux is converted to $\nu_\mu + \nu_e$ flux with the same $\sim E^{-2.33}$ power-law energy spectrum.

Star formation in GMCs in the local universe (redshift $z = 0$) seems to have a threshold around a surface density [18] $\Sigma_{\rm th} \approx (129 \pm 14) M_\odot pc^{-2}$, i.e., a baryon column density $N_p \approx 1.63\times 10^{22}\ {\rm cm}^{-2}$. Such a column density is consistent with the mean column density $N_p = (8\pm 2)\times 10^{21}(1+z)^{1.25}\,{\rm cm}^{-2}$ inferred [19] from x-ray absorption after correcting it for the observed metallicity [20] of GRB host galaxies $Z(z) = 0.54(1+z)^{-1.25} Z_\odot$, i.e., $N_p(z) \approx 1.47\times 10^{22}(1+z)^{2.5}\,{\rm cm}^{-2}$. Hence, for a ballistic motion of the jet with approximately the speed of light through the GMC, we adopt $f_\nu \approx 7.8\times 10^{-5}(1+z)^{2.5}(E/100\ {\rm TeV})^{+0.085}$.

Assuming isotropic emission, the gamma ray energy emitted by a GRB is $Eiso = 4\pi D_L^2(z) F_\gamma/(1+z)$, where $D_L(z)$ is the GRB luminosity distance in a flat ΛCDM universe with a Hubble constant $H_0 = 67.3$ km/s Mpc, matter density $\Omega_M = 0.315$, dark energy density $\Omega_\Lambda = 0.685$ and baryon density $\Omega_b = 0.049$, all in critical mass units [21], and F_γ is the observed γ-ray fluence from the GRB. If the γ-ray energy is beamed into a solid angle $\Delta\Omega$, then the true GRB gamma ray energy is $Eiso\Delta\Omega/4\pi$, and the true GRB rate is $\dot{N}_{\rm GRB} 4\pi/\Delta\Omega$. Consequently, the total power in γ-ray emission by GRBs at redshift z is

$$Eiso \frac{\Delta\Omega}{4\pi} d\dot{N}_{\rm GRB}(z) \frac{4\pi}{\Delta\Omega} = Eiso d\dot{N}_{\rm GRB}(z), \qquad (4)$$

independent of the beaming angle of GRBs.

Noting that the full sky rate of GRBs is [22] $\dot{N}_{\rm GRB} \approx 3$/day, the flux of GRB neutrinos of all flavors per sr at Earth can be written as

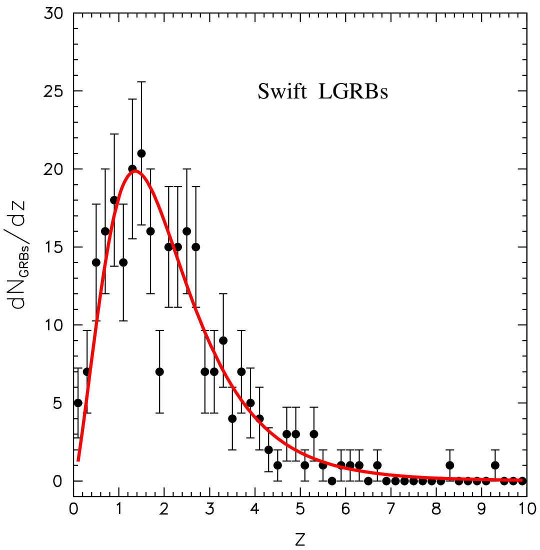

FIG. 1 (color online). The redshift distribution of the 262 Swift LGRBs with known redshift that were detected before November 15, 2013 and their expected distribution [25] assuming the rate of GRBs/SNe traces the star formation rate.

$$E^2\phi_\nu \approx \frac{\dot{N}_{\rm GRB}}{N_{\rm GRB}}\frac{m_p}{m_e}\Sigma_i \frac{f_\nu(z_i)(1+z_i)^{2/3}Eiso(z_i)}{12\pi[D_L(z_i)]^2}\left[\frac{E}{m_p}\right]^{-1/3}, \quad (5)$$

where the summation extends over all $N_{\rm GRB} = 136$ long duration GRBs with known redshift and $Eiso$, which were reported before May 15, 2014 in the Greiner Catalog of GRBs [23] and in the GCN Circulars Archive [24], respectively. The distribution of such long GRBs as function of z is shown in Fig. 1. For that distribution, Eq. (5) yields $E^2\phi_\nu \approx 0.58 \times 10^{-8}(E/100\ \text{TeV})^{-0.25}$ GeV/cm^2 s sr per neutrino flavor.

To a very good approximation, all the VHE cosmic ray nuclei from GRBs reach shortly (on a cosmic time scale) the IGM without any energy loss. In the IGM, they continue to produce neutrinos in collisions with the IGM baryons. Most of the baryons in the universe ($> 90\%$) reside in the IGM with a density $n_b(z) = 2.5 \times 10^{-7}(1+z)^3$ cm^{-3}. Hence, the effective column density encountered by a CR nucleon, which is ejected into the IGM at redshift z, is $Np(z) \approx n_b(0)(c/H_0)\int_0^z dz'(1+z')^3/(1+z')\sqrt{(1+z')^3\Omega_M + \Omega_\Lambda}$. Using a conversion coefficient $f_\nu(z_i)$ for such $N_p(z)$ in Eq. (5), the IGM contribution to the diffuse VHE energy isotropic neutrino background due to GRBs is $E^2\phi_\nu \approx 0.11 \times 10^{-8}(E/100\ \text{TeV})^{-0.25}$ GeV/cm^2 s sr per neutrino flavor.

Extragalactic ISM Neutrinos.—The bolometric luminosity per unit volume in the local universe ($z = 0$) is [26] $LD(0) \approx 1.4 \times 10^8 L_\odot/Mpc^3$. The bolometric luminosity of our Milky Way (MW) galaxy is $L_B(MW) \approx 2.3 \times 10^{10} L_\odot$. The ratio $LD(0)/L_B(MW) \approx 6.0 \times 10^{-3}$ Mpc^{-3} is approximately also the observed ratio of their core collapse supernova rates and consequently also of their GRB rates. Assuming that the VHE neutrino luminosity of external galaxies (EG) due to hadronic CR interactions in their ISM is proportional to their GRB rates, then a rough estimate of the cumulative neutrino flux from all external galaxies is

$$E^2\phi_\nu(\text{EG}) \approx \frac{4\pi LD(0)R^2_{\rm MW}c}{3L_B(\text{MW})H_0} 2.9E^2\phi_\nu(\text{MW}). \quad (6)$$

The factor 2.9 is the effective value of $N_p(z)/N_p(0) \approx (1+z)^{2.5}$ inferred from GRBs x-ray absorption in the GRB host galaxies, weighted by the star formation history [27] as in Eq. (5). Equation (6) yields an estimated $E^2\phi_\nu(\text{EG}) \approx 0.03 \times E^2\bar{\phi}_\nu(\text{MW})$ contribution to the diffuse extragalactic background of VHE neutrinos, where $E^2\bar{\phi}_\nu(\text{MW})$ is the average Galactic neutrino background per sr.

Conclusions.—Meson production in hadronic interactions of very high energy cosmic rays in the Galactic ISM is expected to produce a diffuse Galactic background of very high energy neutrinos with an energy flux $E^2\phi_\nu \propto E^{-2.58}$. The predicted number of Galactic neutrino events (all flavors) in IceCube with $E > 60$ TeV is roughly 3.6 events per year. Their neutrino arrival directions are expected to trace the ISM column density in their arrival directions, i.e., point back mainly to the Galactic disc with a concentration towards the Galactic center. Their sky distribution is expected to follow closely that of the diffuse Galactic gamma ray background in the energy range 100 MeV–100 GeV where the ISM is transparent to the γ rays that are produced mostly by π^0 decay and leptonic bremsstrahlung.

Meson production in hadronic interactions of very high energy cosmic rays accelerated by the highly relativisic jets, which produce GRBs within giant molecular clouds in star forming galaxies, where most GRBs take place, is expected to produce an isotropic background of very high energy neutrinos with a per flavor flux $E^2\phi_\nu \approx 0.64 \times 10^{-8}(E/100\ \text{TeV})^{-0.25}$ GeV/cm^2 s sr. Such an energy flux produces ~3 neutrino events per year with $E > 60$ TeV in the IceCube detector.

Cosmic ray interactions in the ISM of external galaxies are expected to contribute to the *isotropic* background of very high energy neutrinos a per flavor energy flux $E^2\phi_\nu \approx 0.03 \times 10^{-8}(E/100\ \text{TeV})^{-0.58}$GeV/cm^2 s sr. Such an energy flux produces ~0.1 neutrino event per year with $E > 60$ TeV in the IceCube detector.

Figure 2 compares the predicted per-flavor flux of VHE neutrinos with energy above 60 TeV due to the hadronic interaction of cosmic rays in the Galactic ISM (represented there by an equivalent isotropic MW flux), in giant molecular clouds of star forming galaxies where most core

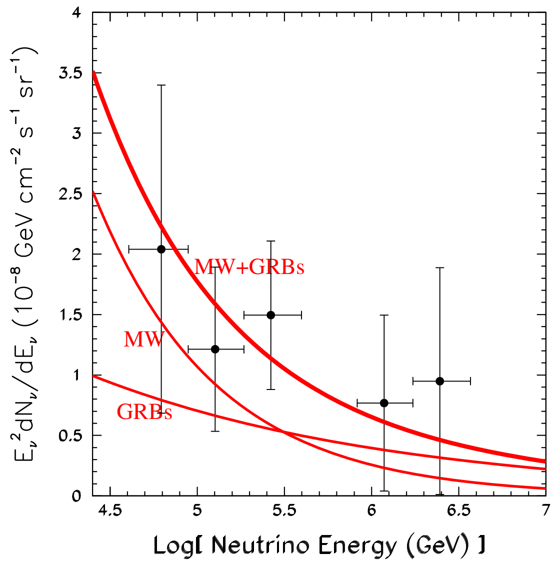

FIG. 2 (color online). Comparison between the flux of an isotropic neutrino background that was inferred from 3 years measurements with IceCube [1], and that expected from cosmic ray production in the Galactic ISM and in the molecular clouds of external galaxies hosting supernovae that produce GRBs.

collapse supernovae, and hence GRBs, take place and in the IGM, and the measured flux [1] with IceCube. It shows that the predicted flux is compatible with that observed by IceCube. Special effort was made to base our estimates only on general considerations and priors, and avoid completely free adjustable parameters. However, in view of the large uncertainties in the values of the priors, the good agreement between the expected and the observed neutrino flux by IceCube cannot be used to draw firm conclusions beyond the statement that they are compatible. Obviously, much larger statistics are needed to test conclusively whether the diffuse background of VHE neutrinos is a sum of a Galactic nonisotropic background with a spectrum $\sim E^{-2.58}$ and intensity proportional to the Galactic column density in their arrival direction, plus an isotropic extragalactic background with a harder spectrum $\sim E^{-2.25}$.

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