A common solution of two cosmic puzzles

Shlomo Dado and Arnon Dar
Department of Physics, Technion, Haifa 32000, Israel
E-mail: dado@phep3.technion.ac.il arnon@physics.technion.ac.il

Abstract. We show that the properties of the background of astronomical neutrinos above 30 TeV, which was discovered with IceCube, are those expected from the all sky high-energy gamma-ray background radiation (GBR), which was measured below 2 TeV with Fermi-LAT, if both backgrounds were formed by the decay of mesons produced in hadronic collisions of the high energy cosmic rays (CRs) with diffuse matter in/near the CR sources.

1. Introduction
The high energy gamma ray background radiation (GBR) was first discovered 36 years ago with the SAS-2 satellite [1] and was later studied in detail with the Compton Gamma Ray Observatory [2] (CGRO) and more recently with the Fermi gamma ray satellite [3]. Recently, also a high energy neutrino background radiation (NBR) was discovered with the megaton IceCube detector [4] deep under the ice of the south pole. High energy particle physics offers three mechanisms of common production of GBR plus NBR. They include (1) production of mesons in hadronic collisions of cosmic rays (CRs) with diffuse matter in/near source, in the interstellar medium (ISM) of galaxies [5] and in the intergalactic medium (IGM) [6], whose decays produce photons, electrons and neutrinos, (2) photo production of mesons in CR collisions with radiation fields in/near gamma ray sources [7], and (3) decay/annihilation of massive dark matter particle relics from the Big Bang [8]. But, until recently no compelling evidence of a connection between the NBR and the all sky GBR has been found [9].

Here we reexamine hadronic production of mesons as the main origin of both the high energy NBR and GBR. The expectation that meson decay is the main origin of very high energy astronomical gamma rays rather than leptonic production is based on the facts that inverse Compton scattering of background photons by high energy electrons is suppressed by the Klein Nishina cross section, and that the population of high energy electrons is suppressed by synchrotron losses and by inverse Compton scattering from background photons. As for photo-meson production by CR collisions with the radiation fields in/near the main cosmic accelerators, it has an effective threshold too high to produce the high energy GBR and NBR observed below PeV. In contrast to [9], we find that the very high energy NBR discovered with IceCube [4] is that expected from the all sky GBR observed with Fermi-LAT at much lower energies [3], if the NBR and GBR were commonly produced in hadronic collisions of the high energy CRs with matter in/near the main CR sources.
2. Hadronic production of secondaries

Hadronic collisions of high energy nucleons of energy $E_p$ with diffuse matter produce $\gamma$-rays, $\nu$’s and $e^\pm$’s mainly through $\pi$ and $K$ decays. If the lab frame energy $E$ of these secondary particles is expressed as $x E_p$, the distribution of $x$ is independent of $E_p$, to a good approximation [10]. Consequently, in a steady state a flux $\Phi_p \propto E_p^{-\beta}$ of CRs in a diffuse matter produces through hadronic collisions secondary $\gamma$-rays, $\nu$’s, and $e^\pm$’s with a flux per unit volume

$$\Phi_i(E) \propto \sigma_{in}(E_p) n_u c \Phi_p(E_p)/\bar{x}_i$$

(1)

where $i = \gamma, \nu, \text{or } e^\pm$, the mean value $\bar{x}_i$ depends only on the distribution of $x$ in the inclusive production $pp \rightarrow i X$ but not on $E$, $E_p = E/\bar{x}_i$ is the mean energy of cosmic ray protons that produce particles $i$ with energy $E$, and $\sigma_{in} \approx 30 \times (E_p/\text{GeV})^{0.058}$ mb is the pp total inelastic cross section.

Eq. (1) implies that CR collisions with diffuse matter produce secondary fluxes of $\gamma$-rays, $\nu$’s and $e^\pm$’s with the same power-law spectrum $\propto E^{-\beta+0.058}$ and different normalization. These fluxes are later modified by propagation effects: attenuation of high energy $\gamma$-rays mainly by Compton scattering from free electrons and by pair production on background photons, oscillations of neutrinos in space that spread the neutrino flux over the three neutrino flavors, diffusion propagation of high energy $e^\pm$’s in magnetic fields, and energy loss of $e^\pm$’s by synchrotron emission and inverse Compton scattering of background photons.

3. The GBR-NBR connection

We shall assume that Fermi acceleration and galactic confinement yield a power-law spectrum $\Phi_p \sim E^{-\beta}$ of high energy cosmic CRs, and that hadronic collisions of high energy CRs with diffuse matter inside or near the CR sources, produce mesons (mostly pions and K mesons) that decay to the observed high energy $\gamma$-rays, $\nu$’s and $e^\pm$’s. The local flux of high energy cosmic ray nucleons (free protons and nucleons bound in light nuclei that hereafter will be denoted by $p$) between several GeV and the cosmic ray knee energy $E_{\text{knee}} \approx 1$ PeV/nucleon is well described by

$$\Phi_p(E) \approx C (E/\text{GeV})^{-\beta} \, \text{fu}$$

(2)

where [12] $C \approx 1.8$, $\beta \approx 2.70$ and $\text{fu} = 1/(\text{GeV cm}^2 \text{s sr})$ is the flux unit. Between the CR ‘knee’ and CR ankle at $E \sim 3$ EeV, $C \approx 114$, and $\beta \approx 3.0$ (Apel et al. 2013). We will ignore the small differences between CR protons and nucleons bound in CR nuclei (A,Z) at the same energy per nucleon, because such nucleons contribute only a few percents to the total CR p flux and most of them are bound in light nuclei whose inelastic cross section per nucleon is $\sim \sigma_{pA}/A \approx \sigma_{pp}$, i.e., roughly the same as that of free protons.

CR protons escape the Galaxy by diffusion through its turbulent magnetic fields. For a Kolmogorov spectrum [13] of random magnetic fields, their escape time satisfies $\tau_{\text{esc}}(E) \propto E^{-1/3}$. In a steady state, the supply rate of high energy CR protons by the Galactic CR sources (s) per unit volume is equal to their escape rate from the Galaxy. Hence, the source spectrum of CR protons satisfies $\Phi_s \propto \Phi_p/\tau_{\text{esc}} \propto E^{-\beta_s}$ where $\beta_s = \beta - 1/3$. Roughly, $\beta_s = \beta - 1/3 \approx 2.37$ for $E < E_{\text{knee}}(p)$, which is consistent with Fermi acceleration modified by escape by diffusion, and $\beta_s \approx 2.67$ for $E_{\text{knee}}(p) < E < E_{\text{ankle}}(p)$.

We shall assume that above TeV production of Galactic and extragalactic $\gamma$-rays and neutrinos is mainly through $\pi$ and $K$ decays. As long as the high energy neutrinos and gamma-rays are produced by CRs with energy well below the CR knee whose inside/near source spectral index is $\beta_j \approx 2.7 - 1/3 - 0.06 \approx 2.31$, and $\pi$ decays dominate the $\nu$ and $\gamma$ production, their fluxes satisfy [14]

$$\Phi_\nu(E) \approx 0.42 \Phi_\gamma(E)$$

(3)
per $\nu$ flavor. Well above the CR knee where $\beta_1 \approx 3 - 1/3 - 0.06 \approx 2.61$, inside/near source hadronic $\pi$ and K production by cosmic ray protons yields (per $\nu$ flavor)

$$\Phi_{\nu}(E) \approx 0.52 \Phi_{\gamma}(E) .$$

Eqs. (3),(4), cannot be tested directly with current data because they neglect the attenuation of high energy $\gamma$-rays, and because the NBR was measured at $E_{\nu} > 35$ TeV, while the published Fermi-LAT data on the GBR and on the extragalactic gamma background [3] are limited to $E < 2$ TeV (see Figures 1,2). (Other recently reported measurements of the high energy GBR with Cherenkov telescopes, such as those with H.E.S.S around 15 TeV [15] and in the ARGO-YBJ experiment around 1 TeV [16], were limited to the Galactic plane $|b| < 2^\circ$.) The attenuation of Galactic $\gamma$-rays of energy below TeV is negligible, while the observed extragalactic $\gamma$-rays background (EGB) is strongly absorbed above 100 GeV. The full sky GBR measured with Fermi-LAT in the energy range 100 GeV - 2 TeV can be corrected for the attenuation of the EGB and used in Eq.(3) to predict $\Phi_{\nu}$ in this energy range, which then can be extrapolated to the energy range of the NBR detected with IceCube using $\phi_{\nu}(E) \propto \sigma_{\mu\nu}((1 + z) 20 E) \Phi_{\gamma}((1 + z) 20 E)$, which follows from Eq. (1) for extragalactic CR sources. In this relation, $1+z \approx 2.5 \pm 0.5$ is the redshift at the peak of star formation rate (i.e., of supernova explosions and GRBs) and of the evolution function of the emission by BL Lac objects - presumably the main extragalactic sources of high energy CRs. Eq. (1) predicts that the non attenuated EGB behaves like $E^{-2.31}$ well below the CR knee. Indeed, the EGB measured with Fermi-LAT below 820 GeV was best fit with an exponential cutoff power-law [3]

$$\Phi_{\text{EGB}} \approx (6.42 \pm 0.40) \times 10^{-7} (E/\text{GeV})^{-2.30 \pm 0.02} e^{-E/E_c} \text{fu}$$

where $E_c \approx 366 \pm 100$ GeV ($\chi^2/\text{df} = 6.9/23$). This best fit is shown in Fig. 1. Presumably, the power-law represents the unattenuated EGB at energies well below the "knee", produced by high energy cosmic rays in external galaxies. Eqs. (3) and (5) then yield $\phi_\nu \approx 1.03 \times 10^{-11}$ fu per $\nu$ flavor at $E=100$ GeV whose extrapolation to $E>50$ TeV yields an isotropic extragalactic [EG] neutrino flux per $\nu$ flavor,

$$E^2 \Phi_{\nu}[\text{EG}] \approx 0.85 \times 10^{-8} [E/100 \text{ TeV}]^{-0.61 \pm 0.05} \text{GeV}^2 \text{fu}.$$ 

Similarly, the Galactic [MW] contribution $E^2 \Phi_{\nu}[\text{MW}] = E^2 (\Phi_{\text{GBR}} - \Phi_{\text{EGB}}) \approx 2.49 \times 10^{-7}$ GeV$^2$ fu to the GBR at $E=\text{TeV}$ and Eq. (3) can be used to estimate $\Phi_{\nu}[\text{MW}]$, which can be extrapolated to $E>50$ TeV, yielding

$$E^2 \Phi_{\nu}[\text{MW}] \approx (2.62 \pm .20) \times 10^{-8} [E/100 \text{ TeV}]^{-0.61 \pm 0.05} \text{GeV}^2 \text{fu}$$

per $\nu$ flavor. The predicted energy flux of the NBR (all flavors and per flavor) obtained from the 'unattenuated GBR'

$$E^2 \Phi_{\nu} \approx (1.04 \pm 1.50) \times 10^{-7} [E/100 \text{ TeV}]^{-0.61 \pm 0.05} \text{GeV}^2 \text{fu}$$

is compared in Figures 2 and 3, to the all flavors and per flavor NBR measured with IceCube [4]. The Milky Way contributes $\approx 76\%$ and extragalactic sources contribute $\approx 24\%$. The sky distribution of the NBR measured with IceCube is expected to coincide with that of the unattenuated high energy GBR, which is roughly that measured by Fermi-LAT at 100 GeV. This distribution that is peaked sharply around the Galactic center is shown in Figure 4. Its peak, however, subtends only a small solid angle: The GBR that was measured with Fermi-LAT near 100 GeV [3] suggests that only $\sim 4.2\%$ of the neutrino events point back towards the Galactic center within latitudes $-8^\circ \leq b \leq +8^\circ$ and longitudes $-80^\circ \leq l \leq +80^\circ$, which
Figure 1. The flux of the extragalactic gamma-ray background (EGB) as function of gamma-ray energy measured with Fermi-LAT [3] and the best fit exponentially cutoff power-law. The straight line represents an expected unabsorbed broken power-law EGB with a break near 25 Tev and a power-law index -2.31 below the break and -2.61 above it, produced by the decay of mesons produced in hadronic collisions with diffuse matter in external galaxies.

Figure 2. Comparison between the energy flux of the NBR (all flavors) above 20 TeV measured with IceCube and that expected from the unattenuated GBR below 2 TeV as inferred from the GBR and EGB measured with Fermi-LAT. Also shown is the best fit single power-law to the unattenuated GBR (spectral index -2.36) in the energy range 100 GeV - 2 TeV estimated from the Fermi-LAT measurements.

cover only $\approx 0.43\%$ of the full sky. Also plotted are the sky distribution of the GBR at $E>1$ GeV measured with EGRET aboard the Compton Gamma Ray Observatory and normalized to the flux measured by Fermi-Lat at 100 GeV. The diffuse gamma-ray emission (flux and sky distribution) from the Galactic plane ($0^\circ < b < 2^\circ$) and from point sources measured at higher energies (e.g., [15] and references therein) with buried muon detectors (e.g., CASA-MIA), water Cherenkov detectors (e.g., Milagro and HWAC) and atmospheric Cherenkov detectors (e.g., H.E.S.S., MAGIC, and VERITAS), are generally consistent within errors with that extrapolated from the Fermi-LAT GBR assuming $\Phi_\gamma(E) \propto E^{-2.30}$ modified by attenuation in the Galactic and extragalactic background light.

4. Conclusion
We have shown that the fluxes of very high energy backgrounds of astronomical neutrinos (NBR) and gamma rays (GBR), measured, respectively, with IceCube [4] and Fermi-LAT [3], satisfy the simple relation, which follows from meson production in high energy hadronic collisions of cosmic rays in/near their main Galactic and extragalactic sources. An additional stringent test of their common hadronic origin is whether the sky distribution of the NBR measured with IceCube is approximately that of the unattenuated GBR near 100 GeV. Such a test, however, requires much higher statistics than currently available from IceCube and knowledge of the effective area of IceCube for each event.
Figure 3. Comparison between the energy flux of the NBR (per $\nu$ flavor) above 50 TeV, which was inferred from the first 3 years measurements with IceCube [4], and the flux of the NBR (per $\nu$ flavor) expected from the GBR and EGB, which were measured with Fermi-LAT [3]. The separate contributions of extragalactic (EG) neutrinos and neutrinos from our Galaxy (MW) to the NBR are also shown.

Figure 4. The sky distribution of the high energy GBR as function of Galactic latitude, observed with Fermi-LAT [3] at 100 GeV. Also shown is the sky distribution observed with EGRET aboard the Compton Gamma Ray Observatory at $E > 1$ GeV [17] normalized to the Fermi-LAT distribution. The NBR is predicted to have nearly the same sky distribution as that of the unattenuated high energy GBR.

5. References
[1] Fichtel C E, Simpson G A and Thompson D J 1978 ApJ 222 833
[2] Sreekumar P et al 1998 ApJ 494 523
[3] Ackermann M et al (Fermi-LAT Collab.) 2012 ApJ 750 3, 2015 ApJ 799 86
[4] Aartsen M G et al (IceCube Collab.) 2015 ApJ 809 98, (2014) PRL 113 101101, 2013 Science 342 1242856
[5] Abbasi R et al (IceCube Collab.) 2011 ApJ 732 18
[6] Dar A and Shaviv N J 1995 Phys. Rev. Lett. 16 748; Zatsepin G T and Kuz’min V A 1966, JETP Let 4 78; Berezinskii V S and Smirnov A I 1975 ApJSS 32 461; Margolis S H, Schramm D N and Silberberg R 1978 ApJ 221 990; Eichler D 1978 ApJ 222 1109 Eichler D and Schramm D N 1978 Nature 275 704; Stecker F 1979 ApJ 228 919; Dar A 1983 Phys. Rev. Lett. 51 22, 1985 PhLB 159 205, 1991 AIP Conf. Proc. 227 497; Halzen F, Learned J and Stanev T 1990 AIP Conf. Proc. 198 39; Stecker F W et al 1991 PRL 66 2697; Berezinsky V S 1991 NuPhS 19 375; etc.
[7] Dar A and Shaviv N J 1995 Phys. Rev. Lett. 75 3052
[8] Mannheim K 1993 Phys. Rev. D48 2408
[9] Feldstein B et al 2013 Phys. Rev. D88, 015004 and references therein.
[10] See, e.g., Murase K, Ahlers M and Lacki B C 2013 Phys. Rev. D88 121301; Tamborra I, Ando S and Murase K 2014 JCAP 09, 043; Anchordoqui L et al 2014 J. High Ener. Phys. 1-2 1 and references therein.
[11] Feynman R P 1969 Phys. Rev. Lett. 23 1415
[12] Fermi E 1949 Phys. Rev. 75 1169
[13] Olive K et al (PDG Collab.) 2014 Chin. Phys. C38 090001
[14] Kolmogorov A Dokl. Akad. Nauk SSSR 1941 303 301 reprinted in 1941 Proc. R. Soc. London A 434 9.
[15] Dar A and Shaviv N J 1996 Astropar. Phys. 4 343
[16] Abramowski A et al (H.E.S.S. Collab.) 2014 Phys. Rev. D90 122007
[17] Pohl M et al 1997 ApJ 49 159