The extragalactic neutrino background radiations from blazars and cosmic rays

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Abstract
Blazar emission of gamma rays and cosmic ray production of gamma rays in gas-rich clusters have been proposed recently as alternative sources of the high energy extragalactic diffuse gamma ray background radiation. We show that these sources also produce very different high energy extragalactic diffuse neutrino background radiations. An extragalactic neutrino background radiation may be detected by the new generation of large neutrino telescopes under construction and may be used to trace the origin of the extragalactic gamma radiation.

1. Introduction
In addition to the galactic diffuse gamma radiation, which varies strongly with direction and can be explained by cosmic ray interactions in the galactic interstellar medium [1], there appears to be a diffuse extragalactic gamma radiation which is isotropic at least on a coarse scale [2]. Its existence has been confirmed recently by analyses of observations with the Energetic Gamma Ray Experiment Telescope (EGRET) on board the Compton Gamma Ray Observatory (CGRO) [3–5]. Its intensity is represented well in the energy range 0.1–10 GeV by a power law,

$$\frac{dI_\gamma}{dE} = (1.5 \pm 0.5) \times 10^{-6} E^{-2.1\pm0.1} \text{ cm}^{-2} \text{ s}^{-1} \text{ ster}^{-1} \text{ GeV}^{-1}.$$  (1)

Various unresolved extragalactic discrete and diffuse sources of gamma rays had been suggested in the past to explain its origin, but all of them have later been questioned by observations [6]. Recently, however, attention has focused on two alternative sources of the extragalactic diffuse gamma ray background radiation (GBR): The detection of many active galactic nuclei (AGN) by EGRET in high energy gamma rays, all belonging to the blazar type [7], has led to the suggestion that the extragalactic diffuse GBR was produced by the summed emissions from unresolved blazars [8]. On the other hand, the discovery of very large mass of gas in intergalactic space within groups and clusters of galaxies with the ROSAT and EINOPS X-ray telescopes [9] has led to the alternative suggestion that cosmic ray interactions in groups and clusters produced the extragalactic diffuse GBR [10]. In this paper we show that these two alternative sources produce different extragalactic high energy neutrino background radiations (NBR). An extragalactic NBR may be detected by the new generation of large neutrino telescopes under construction and may help to trace the origin of the extragalactic diffuse GBR.
2. Production of gamma rays and neutrinos by hadrons

The main mechanism by which hadrons produce high energy gamma rays is by $\pi^0$ production in inelastic collisions with gas nuclei or background photons followed by their prompt decay, $\pi^0 \rightarrow 2\gamma$. For simplicity we will assume that the hadrons are protons and the target particles are gas nuclei (the results are very similar if the production takes place on background photons). Such collisions also produce charged pions, kaons and small quantities of other mesons. If their mean free path for interaction is much larger than their decay path, $\lambda_d = \gamma \sigma t$, with $\gamma \equiv E/m_0 c^2$, then they decay into charged leptons and neutrinos [11] (e.g., $\pi \rightarrow \mu \nu_\mu$, $K \rightarrow \mu \nu_\mu$, $\mu \rightarrow e\nu_e\nu_\mu$). Because of the small mean baryonic density (typically $n_b \ll 10^3$ cm$^{-3}$) of galactic and intergalactic gas, $\lambda_d n_b \sigma m \ll 1$, all the secondary unstable particles produced in cosmic ray collisions in the interstellar and intergalactic space decay before interacting with other gas nuclei. For a power law spectrum of cosmic ray nuclei, $dI_{CR}/dE \approx AE^{-p}$, and inclusive cross sections for meson production that obey Feynman scaling, the produced fluxes of $\gamma$-rays, $\nu_\mu$'s, $\nu_\tau$'s and $\nu_e$'s are all proportional at high energies to the flux of cosmic ray nuclei,

$$\frac{dI_\nu_e}{dE} \propto \frac{dI_\gamma}{dE} \propto \frac{dI_{CR}}{dE}. \quad (2)$$

In particular, if $\nu_\mu + \bar{\nu}_\mu$ production proceeds mainly via $\pi$, $K$ and $\mu$ decays then one can use the analytical methods developed, e.g., by Dar [12] and by Lipari [13] to show that the neutrino and gamma ray fluxes produced by cosmic rays are related through

$$\frac{dI_{\nu_\mu}}{dE} \approx 0.7\frac{dI_\gamma}{dE}. \quad (3)$$

Relation (3) can be verified also by detailed Monte Carlo calculations. It is valid as long as the $\gamma$'s are not absorbed in the intergalactic space, e.g., through the process $\gamma\gamma \rightarrow e^+e^-$. 

3. Blazar production of extragalactic GBR and NBR

When it was first suggested that the diffuse extragalactic GBR is the sum of gamma ray emission by unresolved AGN [14] only the relatively nearby quasar 3C 273 had been seen in high energy ($E > 100$ MeV) gamma rays [15]. Since the launch of CGRO, 33 AGN were detected with EGRET in high energy gamma rays [7], all of which seem to belong to the blazar class. Many more AGN including blazars, which are both bright and relatively close and which were within the EGRET field of view, have not been detected in high energy gamma rays, indicating that not all of these objects are so luminous in gamma rays, or their emission is highly beamed or has a low duty cycle. The beaming hypothesis is further supported by other features of the sources such as superluminal velocity, beamed radio emission, and a power-law gamma ray spectrum (with a power index between 1.4 and 3.0, with values between 1.8 and 2 being most common). Although it is difficult to see how the observed isotropic GBR can be produced by the highly beamed and time variable emission from blazars, many of which have a much harder spectrum than that of the GBR, some authors have actually shown that unresolved blazars with plausible evolution functions (which describe the time evolution of their density, luminosities, spectral features) could have produced the observed extragalactic GBR [8]. If blazars produce their high energy beamed gamma rays by pure electromagnetic processes, e.g., through inverse Compton scattering of soft photons from highly relativistic beams of electrons and positrons, or via electron-positron annihilation in flight, then blazars are not significant cosmic sources of high energy neutrinos. However, if blazars accelerate high energy cosmic ray nuclei that collide with matter or radiation and produce neutral pions that decay into their observed high energy gamma rays, then they also produce charged pions and kaons which decay into high energy neutrinos. Since the luminosities of blazars in high energy gamma rays are much larger than their luminosities in lower energy photons, the gamma ray emitting blazars cannot be "hidden sources" of high energy neutrinos [16]. The summed emission of such blazars produces both a diffuse extragalactic GBR and a diffuse extragalactic NBR which are related through Eq. (3).

Although the diffuse extragalactic gamma radiation has been measured only at energies below 10 GeV [2-5] it can be used to estimate the extragalactic diffuse NBR at much higher energies: The observed extragalactic diffuse GBR in the 0.1–10 GeV energy
range is well represented by a power law spectrum with power index \([3-5]\), \(p = 2.1 \pm 0.1\) (see Eq. (1)). The 33 blazars which were detected by EGRET in high energy gamma rays (30 MeV-30 GeV) have also power law gamma ray spectra with a similar average power index \([7]\). Their power law gamma ray spectra, if extrapolated to TeV energies, suggest that many of them should have been easily detected with currently available TeV gamma ray telescopes \([17]\). To date only Markarian 421, the nearest (at redshift \(z = 0.03\)) of the AGN seen by EGRET, was observed in TeV gamma rays with the Whipple Observatory gamma ray telescope \([18]\). This has been interpreted as being due to the absorption of TeV gamma rays from distant blazars by the extragalactic IR background radiation \([19]\). The spectral index of Markarian 421, which is implied by the combined EGRET and Whipple observations is \(p = 2.06 \pm 0.05\). If this is the typical power index of the high energy gamma ray emission by blazars then the extragalactic diffuse GBR must have this power index below 500 GeV where gamma ray absorption in intergalactic space is negligible. This power index is consistent with the best fitted \([3-5]\) power index of the extragalactic diffuse GBR which has been observed so far at energies smaller than 10 GeV. If the TeV gamma rays from blazars are produced by pion decay then Eq. (3) and the observed intensity of the extragalactic diffuse GBR (Eq. (1)) imply the existence of an extragalactic diffuse NBR with an intensity

\[
\frac{dI}{dE} \sim 1.0 \times 10^{-6} E^{-2.06 \pm 0.05} \text{[cm}^2 \text{s}^{-1} \text{ster}^{-1} \text{GeV}^{-1}],
\]

which extends at least up to energies of a few TeV. Without the knowledge of the gamma ray emission of blazars beyond 10 TeV it is not possible to predict reliably the extragalactic GBR and NBR beyond 10 TeV which are produced by blazars.

4. Cosmic ray produced extragalactic GBR and NBR

The second explanation of the extragalactic diffuse GBR was motivated by the recent discoveries with the X-ray telescopes aboard EINOSB and ROSAT that the intergalactic space within groups and clusters of galaxies contains a very large mass of gas, much larger than the total stellar mass in their galaxies \([9]\). Most of the high energy gamma ray emission of our Milky Way (MW) galaxy can be explained by cosmic ray interactions with its interstellar gas \([1.6]\). But simple considerations show that the summed contributions of gamma ray emission from external galaxies falls short by more than an order of magnitude \([14,6]\) in explaining the observed flux \([2-5]\) of the GBR \([21]\). However, whereas the ratio of the total mass of gas to light in the MW is only \([22]\) \(M_{\text{gas}}/L_{\text{MW}} \approx 4.8 \times 10^9 M_\odot/(2.3 \pm 0.6) \times 10^{10} L_\odot \approx 0.21 M_\odot/L_\odot\), recent X-ray observations of groups and clusters of galaxies have shown that they contain much larger mass of intergalactic gas than their total stellar mass \([9]\). For instance, analyses of recent observations with the ROSAT X-ray telescope of the compact group HCG62 and the Coma cluster yielded, \(M_{\text{gas}}/L_B \approx 4.4 \times 10^{14} M_\odot h^{-5/2}/2.4 \times 10^{10} h^{-2} L_\odot \approx 19 h^{-1/2} M_\odot/L_\odot\), within a distance of 0.24\(h^{-1}\) Mpc from the center of HCG62 \([23]\), and \(M_{\text{gas}}/L_B \approx (5.45 \pm 0.98) \times 10^{13} M_\odot h^{-5/2}/1.8 \times 10^{12} h^{-2} L_\odot \approx (30 \pm 6) h^{-1/2} M_\odot/L_\odot\), within a distance of 1.5\(h^{-1}\) Mpc from the center of the Coma cluster \([24]\), where \(H = 100 h \text{ km s}^{-1} \text{Mpc}^{-1}\) is the Hubble constant. It was also found that these ratios are rather typical of the groups and clusters of galaxies that have been detected in X-rays, and for large enough radii they are independent of radius. It was further argued on theoretical grounds that these ratios are universal in groups and clusters \([9]\) and they imply that most of the baryonic matter in the Universe, as estimated from Big Bang Nucleosynthesis, is in intergalactic gas within groups and clusters of galaxies \([25]\). This has been used by Dar and Shaviv \([10]\) to show that if cosmic rays are present in the intergalactic space within clusters and groups with average intensity comparable to the intensity of cosmic rays in the MW \([26]\), they could produce the extragalactic GBR by interactions with the intergalactic gas in groups and clusters \([27]\). Such a "universal" cosmic ray flux in groups and clusters could also produce high-energy diffuse galactic and extragalactic neutrino background radiations which are closely related to the diffuse galactic and extragalactic GBR through Eq. (3). If the extragalactic diffuse GBR was produced by a universal cosmic ray flux in groups and clusters, with an average...
flux similar to that observed in the Milky Way, then the predicted power index of the GBR and NBR above 10 GeV must change to 2.7, which is the observed power index of high energy cosmic rays near Earth below $10^3$ TeV. The GBR spectrum must steepen beyond 500 GeV because of the absorption of high energy gamma rays by pair production on background IR photons. However, since the intergalactic space is transparent to neutrinos the cosmic ray produced NBR extends all the way to the highest cosmic ray energies ($E > 10^3$ EeV = $10^{20}$ eV). If the primary cosmic ray flux consists mainly of protons then the flux of the extragalactic NBR can be normalized by imposing Eq. (3) at energies smaller than 10 GeV. From Eq. (2) it then follows that the intensity of the high energy NBR is given approximately by

$$\frac{dI_{\nu}}{dE} \approx 1.4 \times 10^{-6} \frac{dI_{CR}}{dE},$$

where the normalization was chosen to satisfy Eq. (3) at 10 GeV. For energies below $10^3$ TeV, where the cosmic ray flux consists mainly of protons, the last equation reads

$$\frac{dI_{\nu}}{dE} \approx 2.4 \times 10^{-6} E^{-2.7} \text{ cm}^{-2} \text{s}^{-1} \text{ ster}^{-1} \text{ GeV}^{-1}.$$

If the cosmic ray flux beyond $10^4$ TeV consists mainly of atomic nuclei with atomic weight $A$ then Eq. (5) must be replaced by

$$\frac{dI_{\nu}}{dE} \approx 1.4 \times 10^{-6} A^{-(p-1)} \frac{dI_{CR}}{dE},$$

where $p$ is the power index of the cosmic ray energy spectrum.

Eqs. (2), (3) and the observed diffuse galactic GBR can be used also to evaluate the diffuse galactic NBR. Whereas the diffuse galactic gamma radiation depends on galactic coordinates, reflecting variations in the local intensity of cosmic rays and in the density of interstellar gas in the MW, the extragalactic diffuse gamma radiation seems to be isotropic.

5. The atmospheric neutrino background

The main difficulty in detecting the galactic and extragalactic NBR is the atmospheric neutrino background. At low energies both the galactic NBR and the extragalactic NBR are masked completely by the atmospheric neutrino background which is produced by the decay of pions, kaons and muons in cosmic ray initiated cascades in the Earth’s atmosphere. However, muons at zenith angle $\theta$ with energies $E_\mu \gg m_\mu c^2/(15 \text{ sec } \theta \text{ km}/c\tau_\mu) \sim 2 \text{ sec } \theta \text{ GeV}$ reach the surface and stop before they decay. Most of the $\pi^\pm$’s and $K^\pm$’s in the Earth’s atmosphere decay before they suffer nuclear collisions if their energies are well below $\sim 115 \text{ sec } \theta \text{ GeV}$ and $\sim 850 \text{ sec } \theta \text{ GeV}$, respectively.

At higher energies the probability of unstable particles to decay before collision with atmospheric nuclei is proportional to $\cos \theta$ and inversely proportional to their energy, due to the relativistic dilation of their lifetimes. Because of Feynman scaling of meson production in high energy hadron collisions, a cosmic ray flux with a power law spectrum generates an atmospheric neutrino flux with the same power law spectrum (power index $p \approx 2.7$) and a weak zenith angle dependence at energies much smaller than $115 \text{ sec } \theta \text{ GeV}$. Around $115 \text{ sec } \theta \text{ GeV}$ the atmospheric neutrino spectrum steepens toward $p \approx 3.7$ at higher energies. At energies much greater than $850 \text{ sec } \theta \text{ GeV}$, and for zenith angles not too close to the horizon, the atmospheric neutrino flux is given approximately by [12,13]

$$\frac{dI_{\nu}}{dE} \approx 5.3 \text{ sec } \theta E^{-3.7} \text{ cm}^{-2} \text{s}^{-1} \text{ ster}^{-1} \text{ GeV}^{-1}.$$

Eq. (8) is valid as long as the cosmic ray flux consists mainly of protons and as long as the atmospheric neutrino flux is dominated by $\pi^\pm$, $K^\pm$, $K_L$ and $K_S$ decays. If the cosmic ray flux consists of nuclei of atomic weight $A$ and has a power index $p$, Eq. (8) must be replaced by

$$\frac{dI_{\nu}}{dE} \approx \frac{3.3A^{-p}}{E} \frac{dI_{CR}}{dE}.$$

Because of their short lifetime, $\tau \sim 10^{-12}$ s, most of the $D^{\pm}$’s which are produced in cosmic ray initiated atmospheric cascades with energies smaller than $4 \times 10^4 \text{ sec } \theta \text{ TeV}$ decay in the atmosphere. They have quite large branching ratios ($\sim 10$–20%) for semi leptonic decays and their contribution to the atmospheric neutrino background becomes important at energies
Because of their prompt decay the atmospheric neutrino background from the decay of charmed mesons is isotropic and has the same power index as that of the primary cosmic rays, whereas the atmospheric neutrino background from pions and kaons is proportional to $\sin \theta$ and is suppressed by an additional one power of $E$. Because of the decrease with energy of the decay probability of atmospheric pions and kaons, the prompt decay of charmed mesons and the fast increase with energy of the cross section for charm production in the energy range 100 GeV–1 TeV ($\sigma(p+p \rightarrow D^+D^− \bar{X}) \approx 2 \mu b$, 6 $\mu b$ and 30 $\mu b$ at 200 GeV [29], 400 GeV [30] and 800 GeV [31], respectively), the production and prompt decay of charmed mesons become an important source of atmospheric neutrinos (and muons) at energies greater than $\sim 100$ TeV. Unfortunately, it is difficult to predict accurately either the flux of prompt neutrinos at energies greater than 1 TeV [32], or the energy where the contribution from prompt decay of charmed mesons to the atmospheric neutrino background becomes more important than that of pion and kaon decays. This is because no experimental data is available on inclusive cross sections for charmed mesons production for energies greater than 1 TeV which are required for reliable predictions. Theory cannot come to the rescue because charm is believed to be produced by fusion of gluons at high energies. The energy dependence of the structure functions of gluons at high energies is poorly known and cannot be calculated by perturbative QCD [32]. Moreover, the chemical composition of the cosmic ray flux is totally unknown at energies greater than $10^3$ TeV. If the high energy cosmic ray flux consists of atomic nuclei then the energy where charm decay begins to dominate the production of atmospheric neutrinos is approximately $A$ times larger than the corresponding energy for a cosmic ray flux which consists mainly of protons.

6. Conclusions

In Fig. 1 we have plotted our predictions for the atmospheric NBR at zenith angles $\theta = 0^\circ$, 90$^\circ$, produced by pion and kaon decays (Eq. (8)), for the galactic NBR produced by cosmic rays (Eq. (3)), and for the extragalactic NBR produced by blazars (Eq. (4)) and by cosmic rays (Eq. (5)), respectively. As can be seen from Fig. 1, an extragalactic NBR produced by blazars may dominate the atmospheric NBR already at 10 TeV while an extragalactic NBR produced by a universal cosmic ray flux in groups and clusters may dominate the atmospheric NBR only at energies above $\sim 4 \times 10^3$ TeV provided that prompt decay of charmed mesons can be neglected.

In principle the extragalactic NBR can be distinguished from the galactic and atmospheric NBR, because it is isotropic while the atmospheric neutrino flux at high energies depends on zenith angle (as long as charm decay is negligible), and the galactic neutrino flux depends on galactic coordinates: The galactic NBR is nonisotropic even at very high energies because it is proportional to the column density of gas in the MW as seen in different directions from the solar system (located $\sim 8.5$ kpc away from the center of the MW galaxy). The atmospheric neutrino background from pion and kaon decays depends on zenith angle because the probabilities of very energetic pions and kaons to decay and produce neutrinos before being absorbed in the atmosphere depend on zenith angle (see Eq. (8) and Refs. [12,13]). However, if charm production dominates the atmospheric neutrino background at energies smaller than $10^3$ TeV there is no reliable way to distinguish between the atmospheric and the extragalactic NBRs produced by cosmic rays. If the gamma ray emission of blazars proceeds via $\pi^0$ decay then the extragalactic NBR which is produced by blazars (Eq. (4)), is detectable by the large neutrino telescopes under construction [32]. An extragalactic NBR which is produced by cosmic ray interactions in groups and clusters (Eq. (6)) is detectable only by future generations of large (> 1 km$^2$) neutrino telescopes [33], and provided that charm production does not dominate the atmospheric neutrino background already at $10^5$ TeV.

At very high energies ($E > 10^8$ GeV), where charm decay in the atmosphere begins to be suppressed, the contribution from prompt decay of heavy flavor mesons produced in proton-nucleus collisions may dominate the atmospheric neutrino background. Unfortunately, the present experimental information on heavy flavor production and decay cannot be extrapolated reliably to very high energies where their contribution may dominate the atmospheric NBR.

Many other exotic sources that may have generated an extragalactic high energy diffuse NBR have been
proposed by various authors [11,16,32]. In principle, the extragalactic NBR produced by them may be distinguished from the NBR produced by the above conventional sources, by their flux levels, their spectra, and their angular and temporal dependence.

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