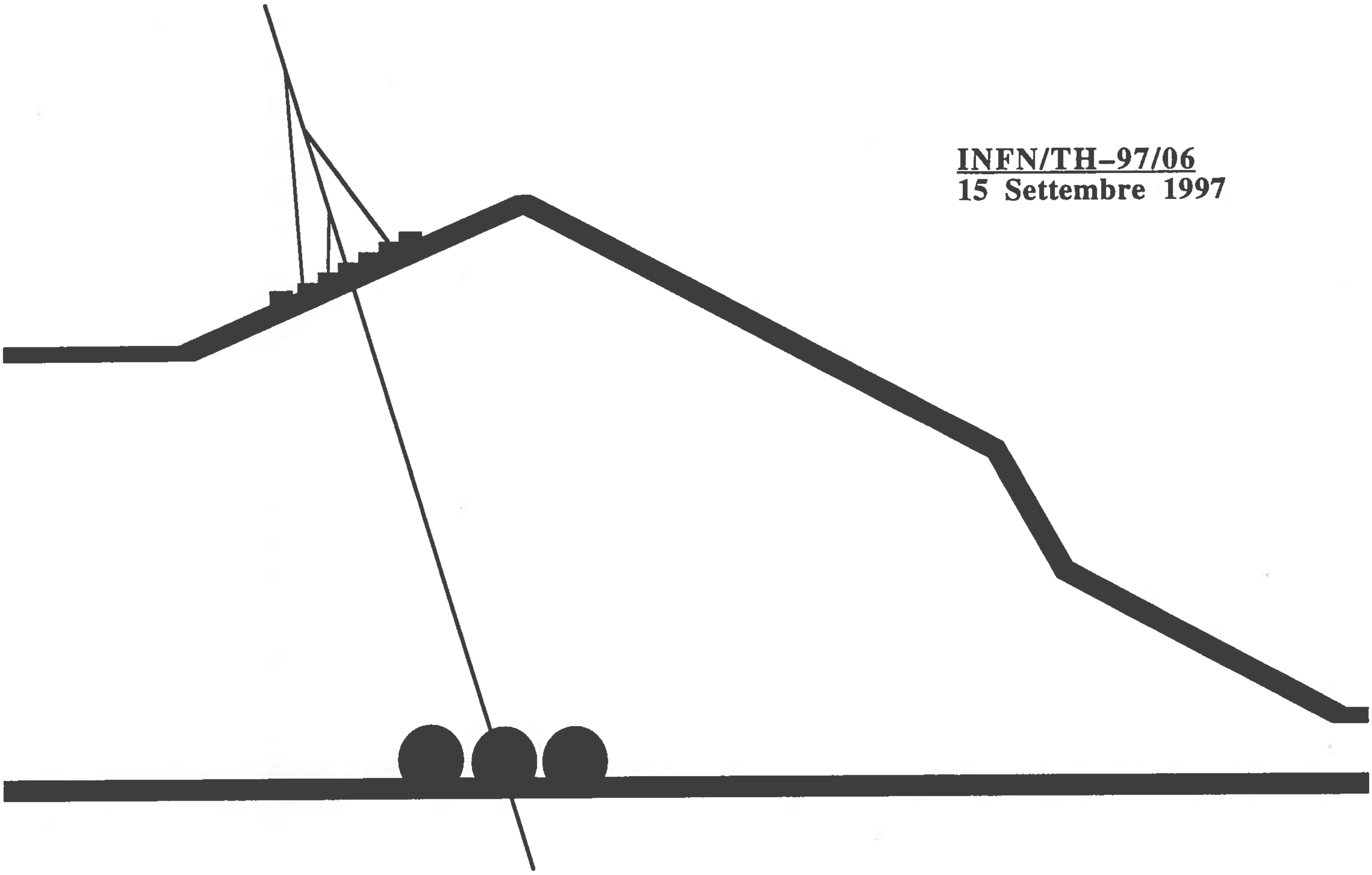

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50 TeV HEGRA Sources and Infrared Radiation

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Abstract

The recent observations of 50 TeV gamma radiation by HEGRA have the potential of determining the extragalactic flux of infrared radiation. The fact that radiation is observed in the range between 30 and 100 TeV sets an upper limit on the infrared flux, while a cutoff at $E_\gamma \approx 50$ TeV fixes this flux with a good accuracy. If the intrinsic radiation is produced due to interaction of high energy protons with gas or low-energy target photons, then an accompaning high-energy neutrino flux is unavoidable. We calculate this flux and underground muon flux produced by it. The muon flux is dominated by muons with energies about 1 TeV and can be marginally detected by a 1 km^2 detector like an expanded AMANDA.

The detection by HEGRA [1] of sources of gamma radiation with energy about 50 TeV, if confirmed, is a remarkable observation which hopefully is the first step in ultra high energy gamma astronomy. Besides its own importance, this radiation is an excellent tracer of infrared fluxes in intergalactic space.

The existence of an upper limit of the observed energies of photons is interpreted in [1] as absorption on diffuse infrared radiation (IR). This assumption looks reasonable due to the following argument. Observation by CASA [2] has not resulted in detection of these sources [3]. This detector has much higher flux sensitivity than HEGRA, but also higher energy threshold ($E_{th} = 100$ TeV), which is sharp and makes ineffective the observations of gamma ray sources below about 50 TeV [4]. Therefore the cutoff of the spectrum at 50 TeV must be very sharp. The known acceleration mechanisms and in particular shock acceleration cannot provide such a sharp cutoff, while absorption naturally results in an exponential cutoff.

On the other hand, the observation of 50 TeV gamma-radiation from the HEGRA sources, which are typically at a distance greater than 200 Mpc, implies that the flux of diffuse IR radiation is lower than was theoretically estimated (see [5, 6] and references therein[1]).

It is interesting to note that recently the EASTOP collaboration analyzed their data on Mk 421, which was detected by HEGRA with 3.8σ excess over background. At energy higher than 40 TeV EASTOP collaboration established [8] the 90% c.l. upper limit $1.2 \cdot 10^{-13}$ cm^{-2}s^{-1} close to the flux observed by HEGRA. Within the statistical errors there is no serious contradiction between these two measurements. In our analysis we concentrate on the source 0116+319 detected by HEGRA at 5.7σ level with flux $1.4 \cdot 10^{-13}$ cm^{-2}s^{-1} at $E > 50$ TeV.

We shall discuss some consequences of the HEGRA observations. One of them is the deriviation of the flux of IR radiation consistent with these observations. If the intrinsic flux has its origin in the interaction of high energy protons with gas or target photons then an accompanying high energy neutrino flux is unavoidable. We shall also discuss the detectability of this flux.

Let us parametrize the density of IR photons in intergalactic space, $n(\varepsilon)$, as

$$n(\varepsilon) = \frac{n_0}{\varepsilon_0}\left(\frac{\varepsilon}{\varepsilon_0}\right)^{-\nu}, \qquad (1)$$

where ε is the energy of the IR photons and the normalization value is fixed at $\varepsilon_0 = 1 \cdot 10^{-2}$ eV. One can formally use Eq.(1) for an unlimited range of energies because at $\varepsilon \leq 3 \cdot 10^{-3}$ eV the microwave radiation dominates while at $\varepsilon \geq 0.3$ eV optical radiation does.

The probability of absorption (the inverse absorption length) of high energy photons with energy E_γ is given by [9]:

$$\frac{dW}{dl} = \frac{4}{E_\gamma^2}\int_{m_e}^{\infty} d\varepsilon_c \sigma(\varepsilon_c)\varepsilon_c^3 \int_{\varepsilon_c^2/E_\gamma}^{\infty} d\varepsilon \frac{n(\varepsilon)}{\varepsilon^2}, \qquad (2)$$

where m_e is the electron mass, ε_c is the photon energy in the centre of momentum system of two colliding photons and $\sigma(\varepsilon_c)$ is the cross-section for pair production

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[1] The high flux of IR radiation predicted theoretically has recently been questioned by Whipple observations [7] of Mkn421 at energies of a few TeV.

$(\gamma + \gamma \to e^+ + e^-)$, which is given in terms of velocity $v = (1 - m_e^2/\varepsilon_c^2)^{1/2}$ as [10]:

$$\sigma(v) = \frac{3}{16}\sigma_T(1-v^2)\left[(3-v^4)\ln\left(\frac{1+v}{1-v}\right) + 2v(v^2-2)\right], \tag{3}$$

where σ_T is the Thompson cross-section.

After simple calculations one obtains:

$$l_{abs}^{-1} = \frac{dW}{dl} = \frac{3\Phi_\nu}{4(1+\nu)} n_0 \sigma_T \left(\frac{E_\gamma \varepsilon_0}{m_e^2}\right)^{\nu-1}, \tag{4}$$

where

$$\Phi_\nu = \int_0^1 v dv (1-v^2)^{\nu-1}\left[(3-v^4)\ln\left(\frac{1+v}{1-v}\right) + 2v(v^2-2)\right], \tag{5}$$

For integer values of ν this integral can be solved, e.g.,

$$\Phi_1 = 14/9, \quad \Phi_2 = 22/45, \quad \Phi_3 = 56/225. \tag{6}$$

Over the whole range $1 < \nu < 3$, a parametrization accurate to better than one percent is given by

$$\Phi_\nu \approx 0.0791 + 1.857 e^{-0.802\nu} + 11.43 e^{-2.876\nu}. \tag{7}$$

For convenience, we tabulate Φ_ν for some selected values of ν in Table 1.

ν	1.5	1.7	1.9	2.0	2.1	2.3	2.5	2.7	2.9
Φ_ν	0.789	0.640	0.532	0.489	0.451	0.387	0.337	0.297	0.263

Table 1: The value of the function Φ_ν of Eq. (5) for some values of ν.

Now one can put an upper limit on the density of IR photons for the energy range 10 – 50 TeV (the range of HEGRA detectability for the set of detectors used in the analysis in [1]) imposing the condition $l_{abs} \geq r_s$, where $r_s = (c/H_0)z$ is a distance to a HEGRA source[2] (we use the Hubble constant $H_0 = 75$ km s^{-1}Mpc^{-1}).

To explain the HEGRA results we have to assume $l_{abs} \approx r_s$ at $E_\gamma \approx 50$ TeV. This condition fixes the flux of IR radiation for a given ν. The calculated fluxes are exposed in Fig. 1 for different values of ν. One can see that these fluxes are much lower than ones estimated before.

The probability of photon absorption (inverse absorption length) is displayed in Fig. 2 together with inverse distance to the source 0116+39 (redshift z=0.059) shown by the horizontal line. One can observe the dramatic increase of absorption at $E_\gamma = 100$ TeV. The differential flux is suppressed by a factor of 60 – 70 in comparison with that at 50 TeV, and integral spectrum is suppressed even more due to the sharp cutoff of spectrum at 100 TeV. This may explain why the source is not observed by the CASA detector.

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[2] Since all three HEGRA sources have redshifts $z < 0.06$, the effects of cosmological evolution are very small.

Photons of the intrinsic radiation with energy between 50 and 100 TeV are absorbed on IR radiation and photons with higher energies on microwave radiation. The produced electrons and positrons emit photons by scattering off the microwave radiation. However, on a scattering length, they are strongly deflected in intergalactic magnetic field and thus the cascade radiation is spread over a large solid angle. This makes the contribution of the cascade radiation to the flux within the angle of observation negligible [11]. For the energy range of interest, $E_\gamma \geq 1 \cdot 10^3$ GeV, the energy of radiating electrons is $E_e \geq 2 \cdot 10^4$ GeV, and on scattering length, $l = 1/\sigma_T n_{bb}$, the electron is deflected in magnetic field to the angle larger than 0.01 *rad*, unless the magnetic field in intergalactic space is smaller than $2 \cdot 10^{-13}\ G$, which may appear unrealistic.

Let us consider now neutrino radiation. If the observed gamma radiation is produced by protons then the ratio of intrinsic neutrino to gamma ray flux is 1.1 for $\gamma = 2.1$ and 1.0 for $\gamma = 2.3$.

Deep underground, the high-energy neutrino flux is accompanied by an equilibrium muon flux, i.e the ratio of these fluxes is depth independent. This ratio is determined by the neutrino-nucleon interaction and the muon energy losses. For the calculations of muon fluxes displayed in Fig. 3, we used the ratios from Ref.[9],[13]. For values of γ around 2.1–2.3 the muon spectrum becomes steeper for muon energies higher than ~ 1 TeV. This is due to the fact that for energies below 1 TeV both the neutrino-nucleon cross section and muon pathlength grow approximately linearly with energy, while above this value they grow very slowly.

As a consequence, most of the muons crossing the detector have energies about 1 TeV. The calculated flux corresponds to ~ 10 muons with energies higher than 1 TeV crossing the area 1 km^2 per year. They can be marginally detected by the future detectors like AMANDA. It should be realised that the number of visible neutrino sources could be much larger than the number of TeV gamma sources because of the absence of absorption of neutrinos.

In conclusion, the observations of HEGRA taken at face value imply that the flux of extragalactic IR radiation is much lower than was predicted before. The combined results of HEGRA and CASA favour the explanation of a 50 TeV cutoff due to absorption on IR radiation. In this case the flux of IR radiation is almost precisely fixed. The flux at $E \sim 1 - 2$ TeV is within detectability power of, say, the Whipple telescope. The accompaning neutrino radiation can be marginally detected by a future 1 km^2 detector like an expanded AMANDA.

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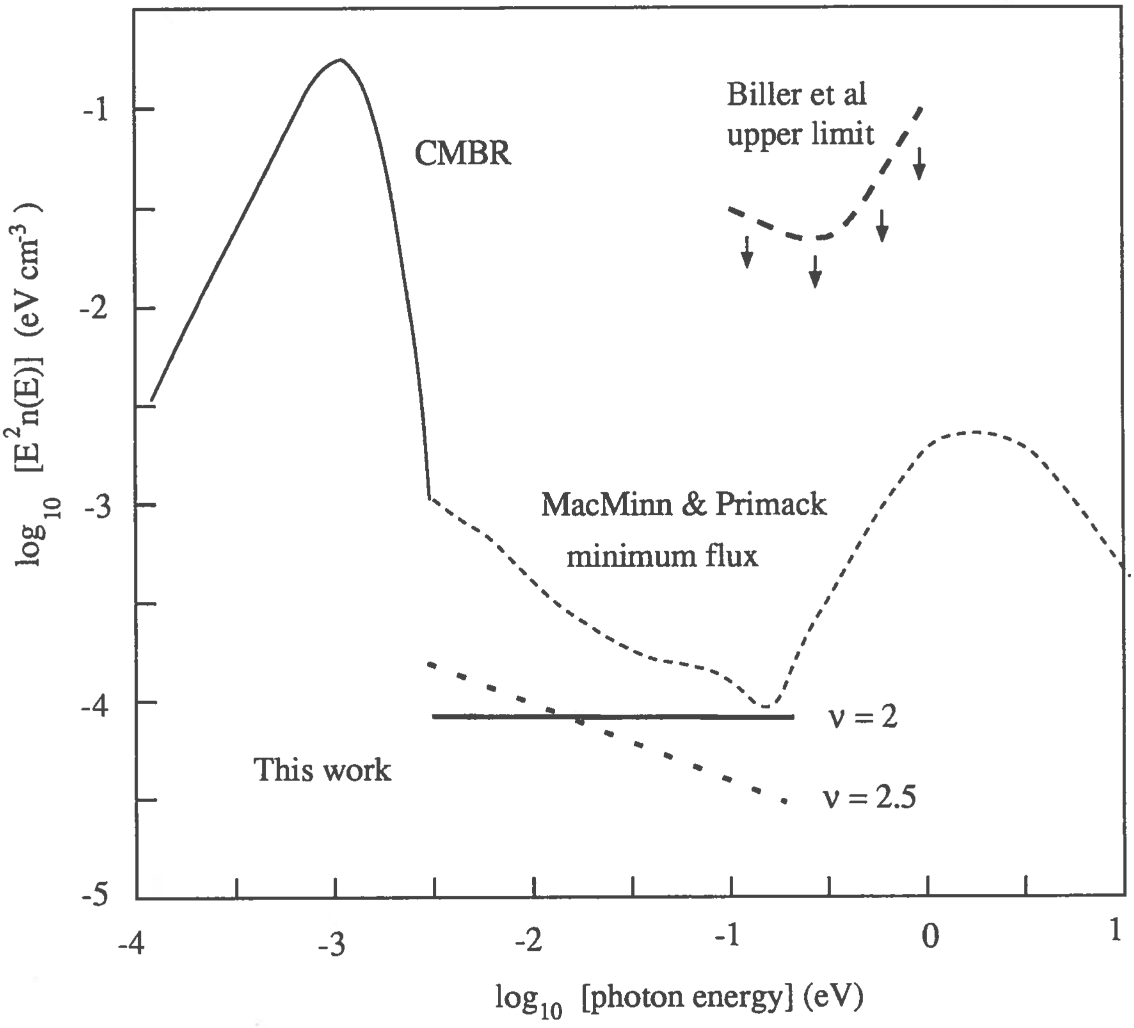

Figure 1: Energy density of the extragalactic radiation field as a function of photon energy (logarithmic scales). The curves shown are the cosmic microwave background (CMBR), the lowest curve of the analysis of MacMinn and Primack [4], the upper limit from the analysis of Biller et al. [10], and the flux needed for interpretation of HEGRA data according to our analysis for two values of the slope parameter ν of the IR flux, $\nu = 2$ and $\nu = 2.5$.

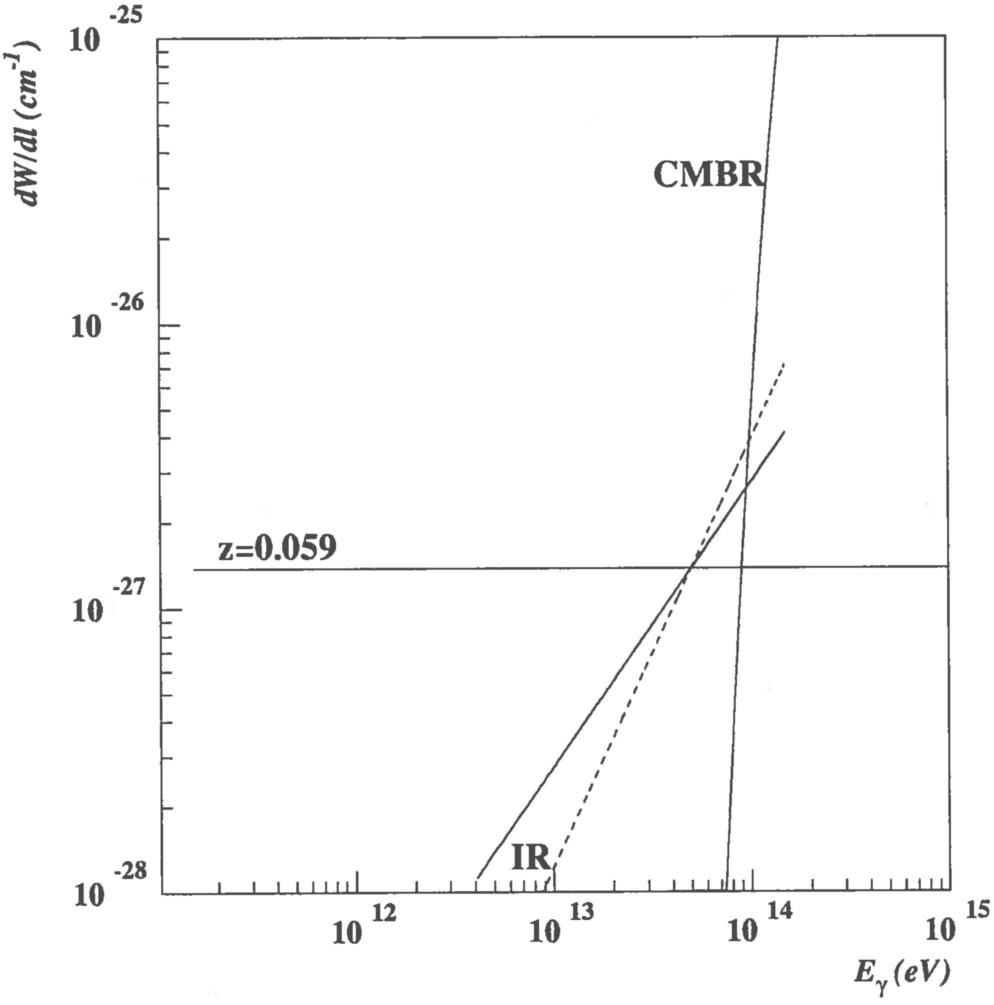

Figure 2: Probability of photon absorption (inverse absorption length) on microwave radiation (CMBR) and IR radiation in case of $\nu = 2$ (solid curve) and $\nu = 2.5$ (dashed curve). The curve labelled $z = 0.059$ shows the inverse distance to the source 0116+319.

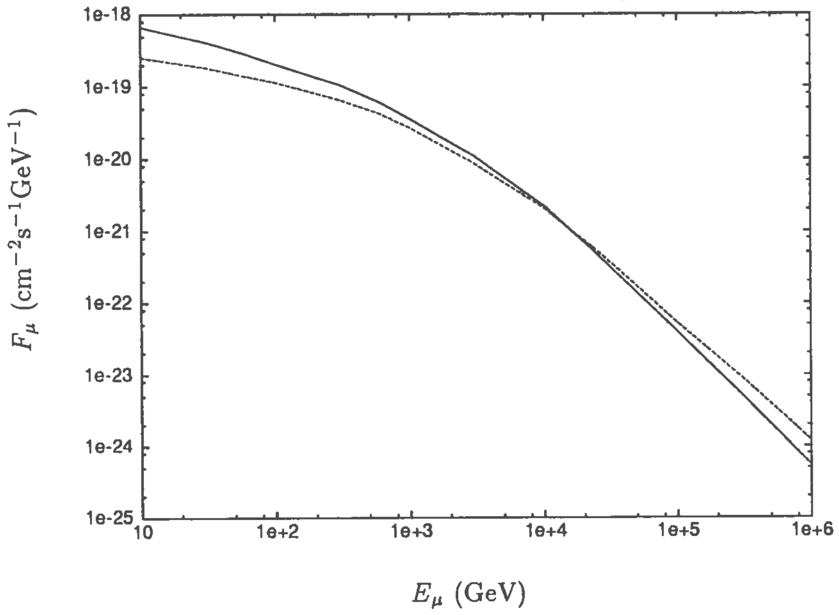

Figure 3: Deep underground equibrium muon flux produced by high energy neutrinos from 0116+319 source. The energy losses of muons are taken for water. The solid curve corresponds the neutrino spectrum index $\gamma = 2.3$, and dashed curve - to $\gamma = 2.1$ Flux of muons for the neutrino spectrum index $\gamma = 2.3$ is higher at low energies than that for $\gamma = 2.1$ because both fluxes are normalized by the HEGRA gamma ray flux at $E = 50\ TeV$.