An Upper Limit on the Infrared Background Density from HEGRA data on Mkn 501

B. Funk, N. Magnussen, H. Meyer, W. Rhode, S. Westerhoff, B. Wiebel-Sooth

Universität Wuppertal, Fachbereich Physik, Gaußstr. 20, 42097 Wuppertal, Germany

Abstract

The energy spectrum of Mkn 501 in the TeV energy regime, as measured by the HEGRA (High Energy Gamma Ray Astronomy) Čerenkov telescopes during its low state in 1995/96 and during a fraction of the 1997 outburst in the TeV energy regime, is shown to place stringent upper limits on the still unknown infrared photon density in the energy region between $3 \cdot 10^{-3}$ and $3 \cdot 10^{-1}$ eV. Assuming two different shapes for the unknown infrared photon spectrum in this energy range we calculate upper limits on the infrared photon density on the basis of the power-law fit obtained for the observed spectrum up to the maximum energy.

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1 corresponding author: magnus@wpos7.physik.uni-wuppertal.de

2 Now at: University of California, Santa Cruz, CA 96064, USA
1 Introduction

The cosmologically important extragalactical diffuse infrared background (DIRB) in the astronomical window from the optical to the infrared (IR) has not yet been directly determined experimentally due to large systematic errors driven by local effects. As realized already a long time ago, the detection of extragalactic TeV-\(\gamma\) sources would enable one to indirectly measure this photon density due to unavoidable pair production losses of TeV photons in infrared photon fields (Gould & Schröder 1966, Stecker et al. 1992). Interpreting the Whipple data of Mkn 421 (redshift \(z = 0.031\)), Stecker et al. (1994) claimed to have seen an exponential cut-off resulting from cosmic absorption of an otherwise smooth power law \(\gamma\)-ray spectrum. The authors suggested that the IR-density is given by
\[
n(\varepsilon) \approx (0.8^{+0.6}_{-0.4} \cdot 10^{-3} \varepsilon^{-2.6}(h/0.75)) \text{ cm}^{-3}\text{eV}^{-1}
\]
where \(h\) refers to the normalization factor of the Hubble constant \((H_0 = h100\text{km s}^{-1}\text{Mpc}^{-1})\). A similar analysis has been carried out by Dwek & Slavin (Dwek & Slavin 1994). The inferred large values of the diffuse near-infrared background density extrapolated to the infrared would imply that it is virtually impossible to discover any extragalactic source above a few TeV. However, Biller et al. (Biller et al. 1995) correctly pointed out that unless the source spectrum is known, one measured TeV source can only yield an upper limit, because the cut-off may be due to internal absorption at the source. They obtain a conservative upper limit of \(\varepsilon^2n(\varepsilon) = 0.04\text{eV cm}^{-3}\) at \(\varepsilon = 0.1\text{eV}\).

In the meantime, besides Mkn 421 (Punch et al. 1992, Petry et al. 1996) Mkn 501 (redshift \(z = 0.034\)) is now the second extragalactic TeV source to be discovered and extensively monitored with the Whipple and HEGRA Čerenkov telescopes (Kerrick et al. 1995a, Bradbury et al. 1997). Both objects belong to the blazar subclass of galaxies showing powerful non-stellar activity characterized by rapidly variable, polarized continuum emission. As the outburst of Mkn 501 in early March 1997 (Aharonian et al. 1997) and the two outbursts of Mkn 421 in Spring of 1995 and 1996 (Kerrick et al. 1995b, Gaidos et al. 1996, Buckley et al. 1996) have shown, both objects also exhibit rapid variability with large amplitudes in the TeV energy range. The HEGRA collaboration showed that between March 16 and March 20 (about 27 hours observation time) the Mkn 501 energy spectrum in the TeV energy range extended beyond 10 TeV without a visible break in the power law spectrum with a differential power law index of 2.49 ± 0.11 (stat.) ± 0.25 (syst.) (Aharonian et al. 1997). During the quiescent state of Mkn 501 in 1996, this source was observed with the HEGRA CT1 telescope for 220 hours. The measured energy spectrum for this period can be described by a differential power law index of 2.5 ± 0.4 (total error) (Petry 1997).

In the following we first discuss the current situation regarding models and observations of the DIRB and then derive an upper limit on the DIRB from the measured energy spectrum of Mkn 501 in 1997 for IR photon energies between \(3\cdot10^{-3}\) eV and \(3\cdot10^{-1}\) eV.
2 Models and Observations of the DIRB

The current experimental and model situation regarding the DIRB is summarized in fig. 1. Since the published energy spectra for both of the extragalactic sources show no spectral break we do not incorporate the claimed detections of the DIRB density based on preliminary Mkn 421 spectra (Stecker et al. 1994). We include, however, the recent tentative detection of the far-infrared background radiation (Puget et al. 1996) by COBE which is an important step towards a direct measurement of the flux in the IR-regime and which is at the moment rather weakly constrained by the results given by Hauser in Calzetti et al. (1995).

![Graph showing energy density of the extragalactic diffuse background radiation.](image)

Fig. 1. Energy density of the extragalactic diffuse background radiation; stars: tentative FIRAS detection of the FIR background without CMBR (Puget et al. 1996), full downward triangles: upper limits from the DIRBE experiment ([Hauser, p. 135], all references in square brackets are taken from Calzetti et al. 1995), squares: lower limit from faint blue galaxies [Tyson, p. 103], circles: upper limit of possible detection [Paresce, p. 307], open triangle: IRAS upper limit (Boulanger & Perault 1988), full upward triangles: evolution model dependent lower limits from number counts of infrared-bright galaxies from Hacking & Soifer 1991, solid line: average model from MacMinn & Primack including the CMBR (MacMinn & Primack 1996), dashed line: average model from Fall, Charlot & Pei added to the CMBR (Fall et al. 1996), dotted line: upper limit derived in this paper.
Due to the cosmological implications of the DIRB photon density a great number of diffuse IR models ranging from simple power laws to multicomponent spectra have been developed by many authors. A large number of parameters such as the star/galaxy formation rate, the number distribution of star masses, the dust content and all cosmological parameters enter into these models. In fig. 1 we show the predictions of two complex models: The model which we later employ for the numerical calculation is by MacMinn & Primack (MacMinn & Primack 1996) who have calculated the DIRB for various realizations of cosmological parameters and dark matter models. The results clearly depend on the set of parameters, and the flux predictions vary at most by a factor of 3. Accounting for the uncertainties of the model an average DIRB spectrum is assumed in the following. The model by Fall, Charlot & Pei (Fall et al. 1996) is based on the assumption that the star formation rate is directly related to the consumption of neutral gas. The density of neutral gas can be determined from analyses of Ly\(\alpha\) absorption lines as seen in distant quasar spectra thus leading to a cosmological rate of star formation out to distances of \(z \approx 5\). Once the rate is known, the emissivity of the universe in the IR can be calculated as a function of \(z\). The dashed curve in fig. 1 shows the case where the neutral gas is fully consumed during the formation process referred to as the closed box scenario.

3 Gamma-ray absorption

For \(\gamma\)-rays of energy \(E\) propagating from a distant source at redshift \(z_o\) towards a terrestrial observer the threshold energy for pair creation in interactions with low energy photons of present-day energy \(\epsilon\) from an isotropic diffuse background radiation field is given by

\[
\epsilon_{th} = \frac{2(me^2)^2}{E(1-\mu)(1+z_o)^2}
\]

where \(\mu = \cos \theta\) denotes the cosine of the scattering angle. A soft photon density strongly varying with energy is thus reflected in the optical depth \(\tau_{\gamma\gamma}\) determining the number density of target photons at the resonant energy \(\propto E^{-1}\). The pair creation cross section is given by

\[
\sigma_{\gamma\gamma} = \frac{3\sigma_T}{16} (1-\beta^2) \left[ 2\beta(\beta^2 - 2) + (3 - \beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right) \right]
\]

with

\[
\beta = \sqrt{1-\frac{1}{\gamma^2}} \quad \text{and} \quad \gamma^2 = \frac{\epsilon}{\epsilon_{th}}.
\]
Here $\sigma_T = 6.65 \cdot 10^{-25}$ cm$^2$ denotes the Thomson cross section. For the computation of the optical depth we use the geodesic radial displacement function $dl/dz = \frac{2}{H_0^2}(1 + z)E(z)^{-1}$. With the proper physical distance, $l(t)$, between a pair of well-separated points as a function of time given by $l(t) = l_0 a(t)$, the cosmological expansion rate is $H(t) = \frac{\dot{a}}{a} = H_0 E(z)$ with the dimensionless function $E(z)$. Under the assumption that the mean mass density is dominated by non-relativistic matter the cosmological equation for the expansion rate is given by (see e.g. Peebles 1993, eq. (13.3))

$$\frac{\dot{a}}{a} = H_0 E(z) = H_0 [\Omega(1 + z)^3 + \Omega_R(1 + z)^2 + \Omega_\Lambda]^{1/2}$$  \hspace{1cm} (4)

where $\Omega, \Omega_R$, and $\Omega_\Lambda$ are the three contributions to the Hubble constant due to the present mean mass density, the radius of space curvature, and the cosmological constant $\Lambda$, respectively, with $\Omega + \Omega_R + \Omega_\Lambda = 1$. For a cosmological model with $\Omega = 1$, $\Lambda = 0$, and negligible space curvature the function $E(z)$ simplifies to $(1 + z)^{3/2}$ and the optical depth can be written as

$$\tau_{\gamma\gamma}(E, z) = \int_0^{z_0} dz \int_{-1}^{+1} d\mu \int_{\epsilon_{th}}^{\infty} d\epsilon n_b(\epsilon)(1 + z)^3 \sigma_{\gamma\gamma}(E, \epsilon, \mu, z)$$  \hspace{1cm} (5)

$$= \frac{c}{H_0} \int_0^{z_0} dz (1 + z)^{1/2} \int_0^2 d\mu \int_{\epsilon_{th}}^{\infty} d\epsilon n_b(\epsilon) \sigma_{\gamma\gamma}(E, \epsilon, \mu, z)$$  \hspace{1cm} (6)

for a non-evolving present-day background density $n_b$, i.e. $n_b'(z, \epsilon')d\epsilon' = (1 + z)^3 n_b(\epsilon)d\epsilon$ where the prime indicates comoving frame quantities. Numerical results for the optical depth using specific models for the background radiation will be obtained below.

Under the assumption of a particular model for the IR-density one can numerically integrate equation (5) and obtain the optical depth $\tau_{\gamma\gamma}(E, z)$. For a source spectrum $\Phi(E)$ the observed spectrum is then simply given by $\Phi(E) \times \exp(-\tau_{\gamma\gamma}(E, z))$. While for an optical depth smaller than unity the universe appears transparent, it becomes opaque for larger values of $\tau_{\gamma\gamma}(E, z)$. This defines the $\gamma$-ray horizon ($\tau_{\gamma\gamma}(E, z) = 1$) which is the size of the visible $\gamma$-ray universe at a given energy. The $\gamma$-ray horizon is shown for two values of the Hubble constant in fig. 2. It turns out that at energies between $10^{10}$ and $10^{15}$ eV the size of the visible universe is a decreasing function of energy. Note that the adopted model does not take into account the extragalactic diffuse radio background which only becomes important above the characteristic energies of air showers accessible by HEGRA-type experiments.
4 Results

Petry (Petry 1997) and Aharonian et al. (Aharonian et al. 1997) have shown that the TeV energy spectrum of Mkn501 can be described by an unattenuated power law with differential indices of $-2.5 \pm 0.4$ (total error) in 1996 and $-2.49 \pm 0.11$ (stat.) in May 1997, respectively. For the analysis of the 1996 data taken with the HEGRA CT1 telescope during about 220 hours of observation time in fig. 3 we show the integral flux spectrum with the fitted power law index of $-1.5 \pm 0.3$ (total error) indicating the reduced error in the fit of the integral spectrum due to the correlated bins. This flux is compared to the Crab nebula integral spectrum as measured in the 1995/96 observation period with the CT1 telescope (37 hours). From the analysis of the 1997 Mkn501 (27 hours) and Crab nebula data (10 hours) as measured with the HEGRA CT system we show the differential flux spectra in fig. 4. From the observed unattenuated energy spectrum extending up to 10 TeV we conclude that the optical depth for this source is less than unity, i.e., $\tau_{\gamma\gamma}(E = 10\text{ TeV}, z = 0.034) < 1$. To derive the upper limit on the DIRB photon density we take $\tau_{\gamma\gamma} = 1.0$ and $h = 1.0$, and assume a specific shape of the IR-density.

For the energy range $3 \cdot 10^{-3} \text{ eV} < \epsilon < 3 \cdot 10^{-1} \text{ eV}$ we make an ansatz for the infrared spectrum based on the results of two different models (outside this
Fig. 3. Average integral spectrum of $\gamma$-rays from Mkn 501 as measured in 1996 (220 hours) and from the Crab nebula as measured in the period 1995/96 (37 hours) with the HEGRA CT1 telescope. The lines represent power-law fits. The error bars correspond to the statistical errors (from Petry 1997).

Fig. 4. Average differential spectrum of $\gamma$-rays from Mkn 501 between March 15 and March 20, 1997 (27 hours) and from the Crab nebula (10 hours) as measured with the HEGRA CT system. The Crab data points are scaled by a factor of 0.2. The lines represent power-law fits. Only statistical errors are shown. The energy scale has a 20% systematic error (from Aharonian et al. 1997).
energy range only the MacMinn & Primack model shown in fig. 1 is used): (i) $\epsilon^2 n(\epsilon) = n_0 (\epsilon/E_p)^\nu$ with the pivot energy point $E_p = 3 \cdot 10^{-2}$ eV and (ii) the shape of the spectrum in this energy range is assumed to be identical with the models by MacMinn & Primack but its absolute level is varied in the calculation. The results for the first ansatz are presented in fig. 5 where values of $\nu$ and $n_0$ below the curve are still allowed by the detection of Mkn 501 at 10 TeV. To illustrate the impact of a still not excluded observation of the unabsorbed spectrum extending up to 15 TeV, a second curve was added in the figure. Using the second model ansatz the observation of Mkn 501 at 10 TeV restricts the normalization $N$ of the spectral segment between $3 \cdot 10^{-3}$ eV and $3 \cdot 10^{-1}$ eV to $N < 1.8$ (times the flux assumed in this work). At the pivot energy point of $3 \cdot 10^{-2}$ eV we thus determine upper limits of $\epsilon^2 n(\epsilon) = 1.1 \cdot 10^{-3}$ eV/cm$^3$ for the MacMinn & Primack model and $1.0 \cdot 10^{-3}$ eV/cm$^3$ for the powerlaw ansatz and assuming the slope of the spectrum to be flat ($\nu = 0$) around the pivot point. A comparison with fig. 1, where we have added the upper limit curve derived using the MacMinn & Primack ansatz, indicates that these limits are about two orders of magnitude below those accessible by direct measurements at this energy and that they are compatible with the tentative FIRAS measurement of the IR density (Puget et al. 1996).

As pointed out in the introduction, the measurement of single spectra, even if a break-off feature is observed, does not permit a determination of the actual level of the DIRB density. Up to the end of the 1997 observation period (October 1997) the blazar Mkn 501 continued to be in a high state with respect to TeV emission. The increasing statistics will enable Čerenkov telescope experiments to extend observations to higher energies and search for cut-off features. The relationship between the infrared photon density in the
energy range from $3 \cdot 10^{-3}$ eV to $3 \cdot 10^{-1}$ eV, assuming a powerlaw spectrum

$$\epsilon^2 n(\epsilon) = n_0(\epsilon/3 \cdot 10^{-2} \text{ eV})^{-0.4},$$

and the maximum observable energy, i.e., $E_{\text{max}}$ with optical depth $\tau = 1$, for different values of redshift $z$ is shown in fig. 6. If e.g. no cut-off is observed up to around 70 TeV we would thus derive, using the above described procedure, an upper limit on the DIRB density of about 0.1 times the average MacMinn & Primack model prediction.

Fig. 6. The normalization $n_0$ of the infrared photon density in the energy range between $3 \cdot 10^{-3}$ to $3 \cdot 10^{-1}$ eV assuming a spectrum $\epsilon^2 n(\epsilon) = n_0(\epsilon/3 \cdot 10^{-2} \text{ eV})^{-0.4}$ which would result from our calculations as a function of the maximum observable energy (with optical depth $\tau = 1$) for three values of redshift $z$.

5 Conclusions

Based on the observation of the unabsorbed Mkn 501 $\gamma$-spectrum extending beyond 10 TeV, we have derived a stringent upper limit on the extragalactic diffuse infrared photon energy density in the energy range from $3 \cdot 10^{-3}$ to $3 \cdot 10^{-1}$ eV of 1.8 times the prediction of an average model by MacMinn & Primack. This translates into an upper limit of the energy density at the used pivot energy point of $3 \cdot 10^{-2}$ eV of $1.1 \cdot 10^{-3}$ eV/cm$^3$. For the second ansatz, i.e., a power-law ansatz for the DIRB around this pivot energy point, we determined upper limits on the normalization as a function of the spectral index, e.g. for a flat spectrum $\epsilon^2 n(\epsilon) = n_0$, the resulting upper limit is $n_0 = 1.0 \cdot 10^{-3}$ eV/cm$^3$. These upper limits are about 2 orders of magnitude below upper limits derived from current direct measurements at this energy.
and are not in contradiction to a value of the DIRB density derived from preliminary evidence of TeV emission reported by Meyer & Westerhoff (Meyer & Westerhoff 1996).
The results presented in this paper are well compatible with other analyses of the infrared photon density based on the HEGRA CT data of Mkn501 (Mannheim 1997, Stanev & Franceschini 1997). They are also in good agreement with an empirical calculation of the DIRB based on galaxy luminosity functions in the IR (Malkan & Stecker 1997) which in turn is in good agreement with recent DIRB models derived from star formation data (Guiderdoni et al. 1997).

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