CONSTRAINTS ON THE EXTRAGALACTIC INFRARED BACKGROUND FROM GAMMA-RAY OBSERVATIONS OF MARKARIAN 501

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ABSTRACT

We use the new results of the HEGRA detector on the TeV γ-ray emission from Mrk 501 to set upper limits on the energy density of the cosmic infrared background (CIRB). Contrary to previous interpretations of the γ-ray spectrum of Mrk 421 as showing an intergalactic absorption cutoff at 5 TeV, the observed spectrum of Mrk 501 extends beyond 10 TeV and appears to be unattenuated by γ-γ collisions with the low-energy CIRB photons. The upper limits on the CIRB intensity—derived both assuming an a priori shape for the CIRB spectrum and without model-dependent assumptions—are thus quite strong and almost come into conflict with the observational evaluations based on deep surveys of extragalactic sources in the near- and mid-infrared. If spectra at TeV energies for extragalactic γ-ray sources like this for Mrk 501 are confirmed with improved statistics, we may be forced to conclude that the process of γ-γ interaction in the intergalactic space is more complex than expected and that the average intergalactic magnetic field is extremely weak ($B < 10^{-11}$ G).

Subject headings: gamma rays: observations — infrared: general — scattering

1. INTRODUCTION

Cosmic history from the decoupling ($z = 1500$) to the epoch of the lighting of the first luminous sources (at redshifts $z \sim 3–5$) is one of the biggest unknowns of present-day observational cosmology. Both high redshifts and dust extinction during early active phases degrade the energetic optical UV photons emitted by massive stars, decaying particles, or more exotic energy sources, to the infrared wavelengths. Fundamental information on the total energy budget associated with astrophysical processes occurring at high redshifts is then provided by observations of the cosmic infrared background (CIRB).

Unfortunately, the infrared domain presents several difficulties of various levels for the observational astronomer because of the huge backgrounds from the Earth’s atmosphere, the interplanetary dust (IPD) and diffuse dust in the Milky Way, as well as the background produced by the telescope itself. Also, the sensitivity and stability of infrared detectors are far worse than those used in the optical. Because of all these things, the detection and characterization of the diffuse background flux of low-energy photons coming from primordial structures has so far been exceedingly difficult. Even dedicated experiments exploiting cooled platforms outside the atmosphere, among which the most important is DIRBE on COBE (Hauser 1996), have so far failed to detect significant signals from the CIRB above the intense foregrounds. The upper limits allowed by the foreground emission deconvolution of DIRBE maps are significantly higher than expectations over a substantial, and crucial, λ-range from a few to $\sim 100$ μm. The situation, at these wavelengths in particular, is not likely to improve in the future until a mission flying to the outer solar system gets rid of the fundamental limitation set by the IPD (both the scattered light and the dust reradiation).

Under these circumstances, a very interesting alternative to the direct detection of CIRB photons was suggested by Stecker & de Jager (1993) soon after the discovery of high-energy photon fluxes coming from distant blazars (by the Gamma Ray Observatory, Hartman et al. 1992, and by the Whipple Observatory, Punch et al. 1992). The idea is to infer the CIRB spectral intensity from combined GeV and TeV observations of a set of active galactic nuclei (AGNs), by exploiting the γ-γ interactions and pair production between the AGN high-energy photons and low-energy background photons in the line of sight to the source. The interaction is expected to produce an absorption feature, testable in principle, in the source TeV spectrum. Interesting limits have been discussed by Stecker & de Jager (1993), de Jager, Stecker, & Salamon (1994), and Dwek & Slavin (1994), and they are all based on TeV observations of the blazar Mrk 421.

To summarize, the best current upper limits on the CIRB in the spectral range 10–40 μm are those reported by de Jager et al. (1994), with a 2 σ upper limit of $\lambda I_\lambda < 2 \times 10^{-8}$ W m$^{-2}$ sr$^{-1}$. In the same large wave band interval, marginal detections, at levels of $2 \times 10^{-9} < \lambda I_\lambda < 2 \times 10^{-8}$ W m$^{-2}$ sr$^{-1}$, were reported by de Jager et al. (1994) and Dwek & Slavin (1994). At shorter wavelengths, 1–10 μm, upper limits have been obtained by Stecker & de Jager (1993), Stecker (1996), Dwek & Slavin (1994), and Biller et al. (1995). The most conservative bounds, accounting for the precise spectral shape of the CIRB, given by Dwek & Slavin (1994; $\lambda I_\lambda < 10^{-7}$ W m$^{-2}$ sr$^{-1}$), still keep a substantial factor (>10) higher than the expected contribution of known sources.

While all previous analyses relied uniquely on TeV observations of the blazar Mrk 421, we exploit here a new high-quality data set of TeV γ-ray observations by HEGRA of Mrk 501 during a state of high activity (Aharonian et al. 1997a) to further constrain the intensity of the diffuse IR background.

Two sets of constraints on the CIRB spectral intensity are derived in § 2. One is based on the assumption that the background spectrum is dominated by the contribution of distant galaxies and thus reflects the average galactic IR spectrum. The other constraint is free of model-dependent assumptions and treats the CIRB as a combination of 12 bins wherein the background spectrum is flat (in $\lambda I_\lambda$) with independent arbitrary limits.

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normalizations. Extremely tight constraints on the CIRB ensue from this analysis, reflecting the missing evidence of any absorption in the TeV spectrum of Mrk 501. A discussion is given in § 3 in terms of a low average past emissivity both of galaxies and of primeval energy sources. Indeed, the limits are so severe that they begin to conflict with the integrated IR flux of distant galaxies, recently detected in large numbers by ground-based and space observatories. Finally, we emphasize the alternative possibility that the interaction of high-energy γ-rays with low-energy photons is more complex than previously supposed. Photon energy, from 0.8 to 12.6 TeV, divided into 12 logarithmically spaced energy bins. The photon number spectrum at TeV energy photons is more complex than previously supposed.

The main difficulty with the derivation of the CIRB spectral intensity from TeV γ-ray absorption is the lack of knowledge of the production spectrum, which may deviate from a pure power law and/or show absorption at the source. Spectra measured within short time intervals, during which the source’s activity state is not likely to vary, are very valuable in this respect, although there is no evidence for strong spectral variability of the Mrk 501 emission (Aharonian et al. 1997b). For this reason we have confined our analysis to a spectrum based on data collected between March 15 and 20, rather than one using the whole March–April database in the updated version of Aharonian et al. (1997a).

As a first step in understanding the observed spectrum, we attempted to derive the allowed range of differential spectral indices α at the source and the CIRB absorption by fitting the observed γ-ray spectrum with a variety of assumptions for α and for the intensity I0 of the extragalactic IR background. We first assumed that the source spectrum in the observed range is a pure power law and that the low-energy background is dominated by the integrated contribution of distant galaxies. In such a case, the shape of the CIRB is well constrained and should reflect the average galactic spectrum, which has a minimum at λ ∼ 10 μm corresponding to the intersection of the stellar with the dust-emission component. We refer here to the detailed spectral shape estimated by Franceschini et al. (1991).

Then the fit was performed in a two-parameter space consisting of the source γ-ray spectral index α and the CIRB intensity I0 normalized to the model spectrum I0(λ) by Franceschini et al. (1991). For a given spectral index α the absorption due to the CIRB was first calculated and the resulting spectrum was then normalized to the detected γ-ray flux above 1 TeV. This procedure enabled us to avoid introducing a third parameter, the source spectrum normalization. Table 1 shows the optical depth assuming (I0/I0) = 1, for all 12 experimental energy bins.

Figure 2 summarizes the results of fitting the observed Mrk 501 spectrum. It plots contours of the χ2 two-dimensional distribution in the parameter plane, including the unphysical region corresponding to negative (I0/I0) values, where γ-rays are “created” in collisions with CIRB photons. The darker an area is the better the fit is (except for fits with χ2 < 1.45, corresponding to the blank inner region). The formal best fit (χ2 = 0.79–1.00 ···· 0.25 1.7 0.53–3.8 0.23 2.1 0.53–3.8
1.00–1.26 ···· 0.29 2.0 0.60–4.8 0.28 2.7 0.67–4.8
1.26–1.59 ···· 0.32 2.1 0.67–6.0 0.36 3.4 0.84–6.0
1.58–1.99 ···· 0.33 2.2 0.75–7.5 0.45 4.2 1.1–7.5
2.00–2.51 ···· 0.34 2.4 0.84–9.5 0.57 5.3 1.3–9.5
2.51–3.16 ···· 0.35 2.5 0.95–12. 0.71 6.7 1.7–12.
3.16–3.98 ···· 0.37 3.0 1.1–15. 0.86 8.4 2.1–15.
3.98–5.01 ···· 0.41 13.4 1.2–19. 1.13 10.9 2.7–19.
5.01–6.31 ···· 0.48 15.0 1.5–24. 1.43 13.4 3.4–24.
6.31–7.94 ···· 0.59 16.8 1.9–30. 1.80 16.8 4.2–30.
7.94–10.00 ···· 0.76 21.2 2.4–38. 2.27 21.2 5.3–38.
10.00–12.6 ···· 1.00 30.0 3.4–48. 2.85 26.7 6.7–48.

Note.—Optical depths and CIRB wavelength ranges responsible for the absorption of TeV γ-rays by Mrk 501 for a distance of 136 Mpc (H0 = 75 km s–1 Mpc–1). The first column shows the γ-ray energy range, the second, third, and fourth columns give the optical depth, CIRB wavelength of maximum absorption, and the wavelength range responsible for 90% of the optical depth for the model of Franceschini et al. (1991). The fifth, sixth, and seventh columns give the same quantities for constant I0 = 7.64 × 10–9 W m–2 sr–1.

2. DATA ANALYSIS AND RESULTS

We use the data set taken in 1997 March and April with the HEGRA stereoscopic system of four imaging Cherenkov telescopes (Hermann 1995). At that time Mrk 501 was in an extremely high state, the far brightest γ-ray source in the sky. The flare was observed by all TeV γ-ray observatories in the northern hemisphere (Breslin et al. 1997). The high γ-ray flux allowed the HEGRA observatory to measure the γ-ray energy spectrum in short time intervals. The spectrum measured between March 15 and 20 covers 1.2 orders of magnitude in photon energy, from 0.8 to 12.6 TeV, divided into 12 logarithmically spaced energy bins. The photon number spectrum at TeV γ-ray energies is consistent with a power law of differential spectral index α = 2.49 ± 0.11. This spectrum is shown in Figure 1 (data points) together with the allowed range of best-fitting power laws derived by the observational team (shaded region). Similar power-law spectra for Mrk 501 have been observed by various other groups (see, e.g., Protheroe et al. 1997).

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Finally, we attempted to obtain model-independent limits on the CIRB, with no a priori guess at the background spectrum. To compute them, we assumed conservatively that the high-energy source spectrum is the flattest allowed by the fits of Figure 1, i.e., $\alpha = 2.16$. We normalize the spectrum at the source to be $F_\gamma + 1.64\delta F_\gamma$ in the first experimental bin. This normalization factor is a source of uncertainty. It is partially justified by the fact that Mrk 501 is close enough (136 Mpc) compared with the optical depth (600 Mpc for $\lambda_{\text{max}} = 7.64 \times 10^{-9}$ W m$^{-2}$ sr$^{-1}$) that the content of this bin would be absorbed only by 20%.

The absorption of $\gamma$-rays of energy $E$ TeV is due to IR photons within a certain wavelength interval around the maximum absorption at $\epsilon_{\text{max}} = 2(m_c^2c^2)/E_\gamma$ [theoretical shape shown by the thin line and (b) assuming flat $\lambda_{\text{max}}$. The thick line shows the estimate of Franceschini et al. (1991), and the three data points are from Franceschini et al. (1997). These are three direct evaluations of the CIRB spectral intensity due to faint galaxies at $\lambda = 2.2, 6.7$, and 15 $\mu$m, based on the galaxy models fitting deep counts performed at these wavelengths.

Note that the obtained upper limits already fall very close to recent direct evaluations of the IR background based on deep IR surveys (Franceschini et al. 1997). As shown in Figure 3, the upper limits rely heavily on the error in the TeV flux measurement and are less stringent for $\lambda > 10$ $\mu$m, where the TeV $\gamma$-ray statistics are not as good.

### 3. DISCUSSION

In either case, both assuming the CIRB shape and relaxing it, the constraints on the CIRB intensity appear dramatic. Essentially, the Mrk 501 $\gamma$-ray spectrum does not display the expected effect of absorption, rather it shows a simple $E^{-2.5}$ power-law spectrum.

How reliable are these limits in view of the possible systematic errors of $\sim 25\%$ in the energy estimates of the HEGRA telescopes (Aharonian 1997)? This is very easy to estimate in
the case of a flat-binned $\lambda I_{\lambda}$ CIBR spectrum. The limits in Figure 3 would move upward and toward shorter wavelengths with the fractional amount of the energy overestimated. Similar relaxation would occur also in the case of a more specialized model CIBR spectrum. One could use the optical depths from Table 1 to estimate the amount of relaxation. Similarly, a higher normalization of the source spectrum would relax the model-independent limits by the ratio of the two normalizations.

Is this featureless spectrum of Mrk 501 inconsistent with that observed for Mrk 421, which is almost at the same distance? The latter has been interpreted by some authors (e.g., Stecker 1996) as showing a turnover at $\epsilon \approx 3-5$ TeV, which was attributed to $\gamma-\gamma$ absorption with the CIBR. In fact, new observations of this source during a high-activity state do not appear to confirm the presence of absorption (Krennrich et al. 1997) and show a significant counting rate above 5 TeV. So, at least during this high state, Mrk 421 seems to show a power-law spectrum similar to the spectrum discussed here for Mrk 501.

The constraints on the CIBR intensity from TeV observations of Mrk 501 start to approach the “measured” lower limits at 2.2, 6.7, and 15 $\mu$m given by the integrated emission of galaxies already resolved in deep integrations at those wavelengths. Deep surveys have been performed from the ground in the $K$ band and from space by the mid-IR camera (ISO/CAM; see Cesarsky et al. 1996) on the Infrared Space Observatory satellite in the two latter bands. A summary of these “direct” determinations of the galaxy contribution to the CIBR and a discussion of the related uncertainties are given by Franceschini et al. (1997) and Oliver et al. (1997). In any case, the CIBR cannot be lower than reported at these three wavelengths.

Few possibilities are left. The first one is that the CIBR is very close to the limits allowed by the $\gamma$-ray spectrum of Mrk 501 observed by Aharonian et al. (1997a). This would imply a very strong constraint on any signals unrelated to the emission of distant galaxies (see, e.g., Rowan-Robinson & Carr 1988 for a review).

But, in view of the fact that (1) the same power-law spectral shape as the one shown in Figure 1 for Mrk 501 has been confirmed by later integrations on this source (Aharonian et al. 1997b; Protheroe et al. 1997), that (2) apparently a similar shape is also suggested for Mrk 421, and that (3) an appreciable CIBR flux has already been detected and resolved into discrete sources, we find it more likely that we have to revise our concepts about the propagation of TeV $\gamma$-rays in intergalactic space, and that something complicates the process.

The question is as follows: why does the propagation of TeV $\gamma$-rays in intergalactic space not produce the expected absorption in high-energy spectra of distant sources? A possible solution could be that part of the source spectrum is regenerated in $\gamma$-ray cascading (pair production $\rightarrow$ inverse Compton). In such a cascading process, the $\gamma$-ray spectrum of the source is depleted around the region of maximum absorption. If the $\gamma$-ray emission of Mrk 501 at the source extends above $10^{-4}$ eV, the spectrum would be depleted in collisions with microwave background photons. The $e^+e^-$ pairs generated on the microwave background would inverse Compton scatter on the microwave background to generate photons of lower (TeV) energy, thus generating “bumps” on a power-law production spectrum (Protheroe & Stanev 1993). The resulting $\gamma$-ray spectrum may then appear unattenuated at observation. This would, however, require not only a $\gamma$-ray spectrum extending to very high energy but also a very low ($\sim 10^{-11}$ G) value for the extragalactic magnetic field in the direction of Mrk 501. Otherwise the $e^+e^-$ pairs would deflect in the magnetic field and form a halo around the source, well outside of the angular resolution of the HEGRA detector.

Many constraints, which are useful to disentangle these two possibilities, are expected soon with improved observations of the Mrk 501 outburst (which has been observed by the Whipple and CAT Cherenkov telescopes; Breslin et al. 1997) with different energy thresholds and wavelength bands and by refined forthcoming data on Mrk 421.

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REFERENCES

Aharonian, F. A. (HEGRA Collaboration) 1997, in AIP Conf. Proc. 410, 4th Compton Symp. (New York: AIP), 1631
Aharonian, F. A., et al. 1997a, A&A Letters, in press — 1997b, in AIP Conf. Proc. 410, 4th Compton Symp. (New York: AIP), 1397
Biller, S. D., et al. 1995, ApJ, 445, 227
Breslin, A. C., et al. 1997, IAU Circ. 6592
Cesarsky, C., et al. 1996, A&A, 315, 132
de Jager, O. C., Stecker, F. W., & Salamon, M. H. 1994, Nature, 369, 294
Dwek, E., & Slavin, J. 1994, ApJ, 436, 66
Franceschini, A., Toffolatti, L., Mazzei, P., Danese, L., & De Zotti, G. 1991, A&A, 89, 285
Franceschini, A., et al. 1997, in Proc. ESA Symp., The Far Infrared and Submillimeter Universe, ed. A. Wilson (ESA SP-401), 159
Hartman, R. C., et al. 1992, ApJ, 385, L1
Hauser, M. 1996, in AIP Conf. Proc. 348, Unveiling the Cosmic Infrared Background, ed. E. Dwek (Woodbury: AIP), 11
Hermann, G. 1995, in Proc. Int. Workshop, Towards a Major Atmospheric Cherenkov Detector IV, ed. M. Cresti (Padova), 396
Krennrich, F., et al. 1997, ApJ, 481, 758
Oliver, S. J., et al. 1997, MNRAS, 289, 471
Protheroe, R. J., Bhat, C. L., Fleury, P., Lorenz, E., Teshima, M., & Weekes, T. C. 1997, 25th Int. Cosmic Ray Conf. (Durban), in press (astro-ph/9710118)
Protheroe, R. J., & Stanev, T. S. 1993, MNRAS, 264, 191
Punch, M., et al. 1992, Nature, 358, 477
Rowan-Robinson, M., & Carr, B. 1988, in Proc. NATO/Adv. Study Inst. (Dordrecht: Kluwer), 125
Stecker, F. W. 1996, in AIP Conf. Proc. 348, Unveiling the Cosmic Infrared Background, ed. E. Dwek (Woodbury: AIP), 181
Stecker, F. W., & de Jager, O. C. 1993, ApJ, 415, L71