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AN UPPER LIMIT TO THE INFRARED BACKGROUND FROM OBSERVATIONS OF TeV GAMMA RAYS

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ABSTRACT

An upper bound to the energy density of infrared background radiation is derived from considering the effect of γ-γ interactions on the observed TeV gamma-ray spectrum of the active galaxy Markarian 421. This upper bound proves to be the most restrictive for the wavelength range of 10–12 μm. These constraints are presently limited by the uncertainty of extrapolating the source spectrum from 5 to 500 GeV. Observations in the regime less than 100 GeV would significantly improve these limits, allowing for a wide range of IR production models to be constrained.

Subject headings: cosmic rays — diffuse radiation — infrared: general

1. INTRODUCTION

Several mechanisms may be responsible for generating a background IR radiation field. The most obvious candidate is normal galaxy formation. Other contributions may include the pregalactic formation of very massive objects (VMOs) and/or of "Jupiters" (which are possible dark matter candidates), energetic explosions that may have led to galaxy clustering, radiation emitted by accreting black holes (such as believed to exist in active galaxies), or by-products from the decay of weakly interacting particle relics of the big bang (see for example Bond, Carr, & Hogan 1986). The spectra produced by these mechanisms may be shifted, either in part or in whole, to the far-infrared by reprocessing of the radiation off dust grains. This fact makes the entire IR range from 0.1–1000 μm (0.001–10 eV) of interest, and makes the studies of the high-energy tail of the cosmic microwave background radiation (CMBR) and of the near-infrared background very much complementary endeavours. A large portion of this range ($\sim$0.1–10 eV) may be uniquely accessible to high energy and very high energy gamma-ray astronomy via the process $\gamma\gamma \rightarrow e^+e^-$. This fact was first noted by Gould & Schréder (1967), and has been more recently restated by several authors (Aharonian, Coppi, & Volk 1994; Stecker & de Jager 1993). This has led to a number of claims of background IR measurements and upper limits based on GeV and TeV observations of the active galaxy Markarian 421 (hereafter Mrk 421) (Stecker & De Jager 1993; De Jager, Stecker, & Salamon 1994; Dwek & Slavin 1995). Here we reevaluate the Mrk 421 data on which these claims are based and find less stringent upper limits to the IR background than those previously quoted.

2. DIRECT EXPERIMENTAL LIMITS

Figure 1 shows the current experimental upper limits on the background IR flux. These include the compilation by Cowie (Cowie 1988; Hurwitz, Martin, & Bowyer 1986; Feldman et al. 1981; Maucherat-Joubert et al. 1980; Paresce & Jacobsen 1980; Dube et al. 1977; Spinrad & Stone 1979; Matsumoto, Akiba, & Murakami 1988). The recent results of Kawada et al. (1994) are given as well. Also shown are the current limits from the Diffuse IR Background Experiment (DIRBE) based on brightness measurements of the south ecliptic pole region (Hauser 1991). The ultimate DIRBE sensitivity to the IR background does not depend on the inherent sensitivity of the experiment itself, but rather on the ability to model local (i.e., Galactic) sources of IR which must be subtracted. It is hoped that such modeling will enable a sensitivity level $\sim$1% of the current limit to be reached. Limits in the UV regime are also given for the work of Lieu et al. (1993) and Martin, Hurwitz, & Bowyer (1991).

3. PREVIOUS LIMITS FROM TeV OBSERVATIONS

A limit to the background IR photon density may also be set based on observations of the high-energy gamma-ray spectrum of the extragalactic source Mrk 421 by the EGRET and Whipple experiments (Michelson et al. 1992; Punch et al. 1992), where the effect of attenuation due to γ-γ interactions with the IR field is considered. Stecker & de Jager (1993) have derived an upper limit from these observations in a model-dependent manner in which the general shape of the IR-attenuated spectrum is assumed a priori. These authors, together with Salamon, have written a further paper in which a measurement (as opposed to an upper limit) is claimed based on the data (De Jager, Stecker, & Salamon 1994). A similar analysis by Dwek & Slavin (1994) only derives a new upper limit. The latter two analyses concentrate on evidence for a

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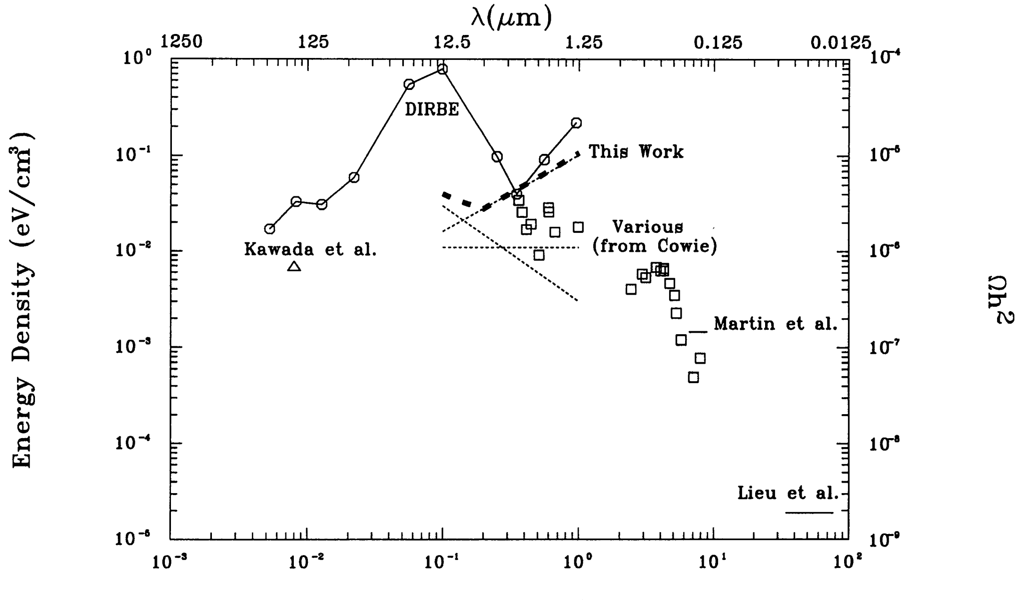

FIG. 1.—Experimental upper limits on the background IR energy (see text for references). The energy density is expressed both in units of eV cm^{-3} (*left axis*) and in terms of the critical density, Ω, times h^2, where the Hubble constant is given by 100 h km s^{-1} Mpc^{-1} (*right axis*). Dotted lines shows limits derived in this work for assumed IR spectral indices of 1.2 (positive slope), 2 (flat), and 3 (negative slope). The bold, dashed line shows the limit derived given that this slope is unknown.

possible turnover in the energy spectrum in the highest energy Whipple data points.

Several points are in order regarding analyses of the type mentioned above. The first is that a study of the Mrk spectrum alone can only yield an upper limit. Several mechanisms can be responsible for a reduction in observed flux at higher energies, including changes in the inherent source spectrum and/or attenuation due to IR photon fields local to the source. The latter could easily mimic the effect that would be due to IR background in the same energy regime. Due to this ambiguity, the presence of an IR background can never be firmly demonstrated based on studies of a single source. However, upper limits can be derived under the assumption that the primary source flux at least does not increase at higher energies in such a way as to offset the attenuation due to the IR background. The second point is that the shape of the IR spectrum is not known a priori and may potentially contain significant structure. Finally, the behavior of the highest energy Whipple data do not bear on the current upper limits to the IR background flux, nor do potential systematics of factors of ~ 2 in the Whipple data. The current limits are restricted almost entirely by uncertainties in the extrapolation of the spectrum between EGRET and the lowest energy Whipple point. This is illustrated in Figure 2 which shows the differential Mrk flux measurements of EGRET (Lin et al. 1994) and Whipple (Mohanty et al. 1993). The solid line indicates a single power-law fit which results in an acceptable χ^2 of 13 for 9 degrees of freedom. However, the dashed line also indicates an acceptable fit (within a 95% confidence level) to the EGRET points which passes several orders of magnitude above the Whipple data. In other words, it is conceivable that attenuation may already be taking place at even the lowest energy Whipple point. It is this possibility that determines the upper limit to the IR flux.

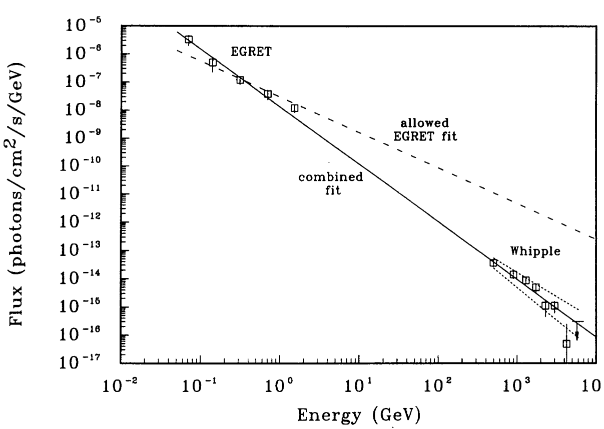

FIG. 2.—Differential Mrk 421 flux measurements by EGRET (Lin et al. 1994) and Whipple (Mohanty et al. 1993). The dotted line indicates the range of systematic errors for the Whipple data. The solid line indicates a single power-law fit which yields a χ^2 of 13 for 9 degrees of freedom. However, the dashed line also indicates an acceptable fit to the EGRET points within a 95% confidence level which passes several orders of magnitude above the Whipple data and thus allows for the possibility of IR absorption.

4. A LIMIT BASED ON OBSERVATIONS OF MARKARIAN 421

Here we calculate an upper limit to the IR background based on EGRET and Whipple measurements of Mrk 421 taking into account those considerations mentioned above. The Whipple data quoted in the 23d ICRC proceedings will be used (Mohanty et al. 1993), and EGRET data will be taken from the Second Compton Symposium (Hartman et al. 1994). Given the proximity of Mrk 421, IR evolutionary considerations can be ignored. It will also be assumed that the flux level of Mrk 421 during the 1992 Whipple observations was the same as during the EGRET measurements which were taken 8 months prior and 3 months after these observations. Note that this is not guaranteed owing to the recently observed variability of this source (Tadahashi et al. 1994; Kerrick et al. 1995), however, it is not unreasonable given the apparent duty cycle of the variability.

Since this is an upper limit, the Hubble constant will be assumed to be 100 km s^{-1} Mpc^{-1} in calculating the attenuation due to IR photons. Furthermore, systematic uncertainties will be taken into account so as to lower the flux values of the Whipple data, making it look more like absorption and thus leading to a higher IR estimate. Specifically, each Whipple data point will be lowered according to

$$\text{New Flux} = (\text{Old Flux}) \times \left(\frac{1}{1.5}\right)\left(\frac{E}{0.5\ \text{TeV}}\right)^{-0.3} . \quad (1)$$

The first term accounts for a 50% uncertainty in flux normalization, while the second accounts for a possible systematic error in the spectral index. A more detailed evaluation of these systematic errors is currently underway, however such corrections will have minimal impact on the IR upper limits derived in this paper.

It will be assumed that the number density of IR photons can be effectively characterized by a power law in energy with an arbitrary normalization and spectral index for the energy range that is of interest:

$$n(\epsilon) = \rho_0\left(\frac{\epsilon}{1\ \text{eV}}\right)^{\beta} . \quad (2)$$

If the true number density differed significantly from this form and if the Whipple data indicated attenuation due to the IR background (since one considers the maximum possible level of IR consistent with the data when computing an upper limit), one would expect to see evidence of structure in these data points. No evidence for this is present in the data between ~0.5 and ~4 TeV. The lack of excess above ~5 TeV might have several possible causes: (1) It may be due to additional systematic effects (such as biases in image selection procedures) associated with the analysis of higher energy events from sources with hard spectra; (2) It may be due to effects unrelated to attenuation by the IR background, such as changes in the true source spectrum; or (3) It may represent real IR attenuation, which must in this case be seen as only modest additional attenuation to that which would be indicated by the possible mismatch between the EGRET spectrum and the lower energy Whipple data. For these reasons, the lack of excess above ~5 TeV will be ignored in this analysis. Even if the third possibility is correct, it will make only minor difference in the upper limit that will be derived. It should also be noted that a further assumption is that the EGRET data points are unaffected by γ-γ attenuation on background radiation fields. However, this assumption is well justified based on the direct experimental limits on the background flux of ultraviolet photons (Lieu et al. 1993) which are relevant for GeV gamma-ray interactions.

Calculation of the optical depth due to γ-γ absorption has been detailed by numerous authors (e.g., Nikishov 1962; Gould & Schréder 1967; Stecker & de Jager 1993). Since the optical depth for IR attenuation, τ, is directly proportional to the number density, it will be convenient to define

$$\tau \equiv \rho_0 \tau' . \quad (3)$$

For the redshift of Mrk 421 (0.031), τ' was computed for a range of possible values of β. The following parameterization was then derived:

$$\tau' = aE_{\text{TeV}}^{\beta-1} , \quad (4)$$

where

$$a = 0.26 \exp(-3.37\beta + 1.76\beta^2 - 0.369\beta^3 + 0.0299\beta^4) . \quad (5)$$

This is valid for the range $0.1 < E_{\text{TeV}} < 10$, $0 < \beta < 5$. Therefore, assuming the inherent Mrk spectrum is a power law, the detected flux at a given energy will be

$$\Phi(E) = \Phi_0 E^{-\alpha} e^{-\rho_0 \tau'(\beta)} . \quad (6)$$

In fact, the upper limits that will be derived will be valid even if the Mrk spectrum is not a power law, so long as the photon flux does not increase more with energy than the power-law fit allowed by the EGRET data points. A χ^2 fit can now be performed on the combined EGRET and (conservatively adjusted) Whipple data based on the above formula for the four-dimensional space defined by Φ_0, α, ρ_0, and β. The minimum χ^2 was found to correspond to the values

$$\begin{aligned} \Phi_0 &= 2.41 \times 10^{-8}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{GeV}^{-1} , \\ \alpha &= 1.57 , \\ \rho_0 &= 0.046\ \text{cm}^{-3}\ \text{eV}^{-1} , \\ \beta &= 1.2 . \end{aligned} \quad (7)$$

The corresponding χ^2 was 8.5 for 8 degrees of freedom. The upper limit to the background IR flux was then derived by first varying all four parameters until the χ^2 for the fit changes from its minimum value by 9.5, corresponding to a 95% confidence level. Maximum values of the parameter ρ_0 which lie along this contour are plotted in Figure 3 (*solid line*) as a function of IR spectral index β. For comparison, minimum values of ρ_0 are also plotted in this figure (*dashed line*). Note that these minimum values are negative, further demonstrating that the data only yields an upper limit.

Since the IR threshold energy for the γ-γ interactions is approximately $\epsilon_{\text{thresh}}(\text{eV}) \sim 0.5/E_{\text{TeV}}$, where E_{TeV} is the energy of the high-energy gamma ray, the range of IR photon energies relevant to the Whipple data extends from ~0.1 eV to above ~1.0 eV. Given the values of ρ_0 and β defined by the solid line

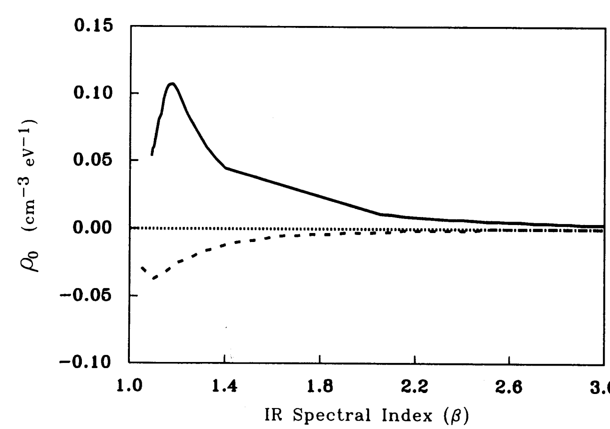

FIG. 3.—Maximum (*solid line*) and minimum (*dashed line*) allowed values of the background IR number density, ρ_0, which lie along the 95% C.L. contour as a function of spectral index β. The negative values of ρ_0 confirms that the data only provides an upper limit.

TABLE 1

INFRARED ENERGY DENSITY UPPER LIMITS BASED ON EGRET AND WHIPPLE DATA

E_{TeV}	ϵ (eV)	IR Energy Density Upper Limit (95% C.L.) (eV cm^{-3})
0.5......	1.0	0.11
1.0......	0.5	0.06
5.0......	0.1	0.04

of Figure 3, an upper limit to the energy density of IR photons in this energy range can be derived. The dotted lines in Figure 1 shows limits derived assuming values for β of 1.2 (peak of Fig. 3), 2, and 3. Note that these values of β refer to the cumulative number density spectrum of the IR background and should not be used to imply limits on any separate components which may possess various spectral slopes. Given that the shape of the background IR energy spectrum is not known, the bold, dashed line in Figure 1 gives the upper bound derived from choosing the most conservative combinations of ρ_0 and β at each energy. These results are summarized in Table 1.

These are currently the most restrictive limits in the wavelength range of 10–12 μm. Improvement of these limits must be based on reducing the uncertainty in the extrapolated spectrum. Given that the EGRET data on Mrk 421 used in this analysis was accumulated over 70 days of observation, a significant reduction in the error bars and/or an extension of the GeV spectral measurements to higher energies cannot be expected over the remaining lifetime of that experiment. The most promising hope therefore seems to be further measurements of the spectrum in the regime below $\sim$100 GeV, which should be achievable with the next generation of experiments. The potential sensitivity of this approach to bounding the IR background could well rival that of any nonterrestrial experiment.

5. CONCLUSIONS

Numerous mechanisms may be responsible for the presence of background IR fields. No firm prediction for the spectrum and intensity level exists, however, various cosmological models would leave distinct signatures. There is therefore cause for considerable interest in studies of this energy range. Satellite experiments are starting to probe part of this regime, but will be limited by the ability to accurately model and subtract local sources of IR. Attenuation of high-energy gamma rays by the reaction $\gamma + \gamma \rightarrow e^+ + e^-$ promises to be a highly sensitive probe of background IR fields. Current observations of the AGN Mrk 421 by the EGRET and Whipple experiments yield upper limits which are competitive with satellite and rocket-based observations, and provide the best constraints in the IR energy regime of 0.1–0.3 eV (λ = 10–12 μm). These constraints are presently limited by the uncertainty of extrapolating the source spectrum from 5 to 500 GeV. Observations in the regime less than 100 GeV would significantly improve these limits, allowing for a wide range of IR production models to be constrained. Observations of several AGN spectra attenuating in overlapping energy regimes might provide a means of better determining the IR flux and spectrum, however this is not possible based on a single attenuation measurement.

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