GAMMA-RAY OBSERVATIONS CONSTRAIN THE INTERGALACTIC INFRARED RADIATION DENSITY

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ABSTRACT

We have used the recent γ-ray observations of Mrk421 to place theoretically significant constraints on the intergalactic IR radiation field (IIRF). Our 2σ upper limits are $\sim 10^{-8}$ w m^{-2} sr^{-1} for the 1 to 5μm range, consistent with normal galactic IR production. They rule out exotic mechanisms proposed to produce a larger IIRF.

INTRODUCTION

Stecker, De Jager and Salamon 1992 (SDS), following the strong detection of the blazar 3C279 at energies of 0.1 to 5 GeV by the EGRET team (Hartman, *et al.* 1992) proposed a unique way of using ground-based TeV observations (Weekes 1988) of blazars to probe the IIRF by looking for γ-ray absorption in the spectra of these objects above 0.1 TeV. The absorption is the result of the TeV γ-rays interacting with IIRF photons to produce high energy electron-positron pairs. Observations of nearby sources in the TeV energy range can be used to determine important new upper limits on the strength of the intergalactic infrared radiation field, since interactions with the cosmic microwave background radiation will not produce a break in the spectrum of a low redshift source below an energy of $\sim$ 100 TeV (Fazio and Stecker 1970). We thus deem of particular importance the discovery that the relatively nearby (z=0.031) BL Lac object Mk421 has a hard, roughly E^{-2} spectrum extending to the TeV energy range (Lin, *et al.* 1992; Punch, *et al.* 1992) where the pair production process involving infrared photons becomes relevant. The TeV spectrum obtained by the Whipple Observatory group is consistent with a perfect $E^{-2.06}$ power-law, showing no absorption out to an energy of at least 3 TeV (Mohanty, *et al.* 1993.) It is this lack of absorption which we use here to put upper limits on the extragalactic infrared energy density in the $\sim$ 0.2 to 1 eV energy range ($\sim$ 1 μm to 5 μm).

THE INTERGALACTIC INFRARED BACKGROUND RADIATION FIELD

A theoretical upper limit for the infrared energy density from starlight in normal galaxies was given by Stecker, Puget and Fazio (1977) (solid line in Figure 1). Figure 1 also shows estimates of the intergalactic IR and optical radiation densities which were obtained by Yoshii and Takahara (1988) and Tyson (1990), based on galaxy counts and other modelling considerations. Tyson (1990) gives a "lower limit" estimate at 2.2μm (the left hand "X" on Figure 1). Estimates by Cowie, *et al.* (1990) based on a K band deep galaxy survey are also shown, as are direct observational upper limits obtained by Matsumoto, et al. (1988) and Dube, et al.

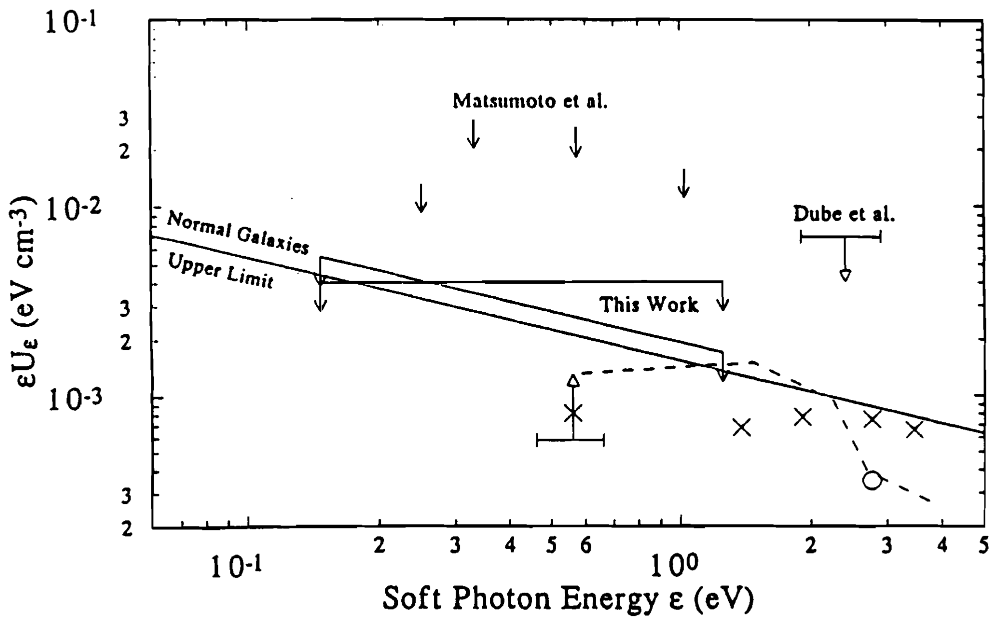

Figure 1: The extragalactic infrared photon density versus energy. The spectrum corresponding to the maximum contribution from normal galaxies (Stecker, *et al.* 1977) is shown as a solid line. The upper limits of Dube *et al.* (1979) and Matsumoto, *et al.* (1988) are also shown. The model estimates by Tyson (1990) are shown as crosses and that of Yoshii and Takahara (1988) by an open circle. Estimates by Cowie, *et al.* (1990) are shown by the dashed line. Our 2σ upper limits are shown by the upper-limit envelopes labled "This Work". The slanted line with upper limit arrows is for $\alpha = 2.55$; the horizontal line with upper limit arrows is for $\alpha = 2.0$.

THE ABSORPTION OF TeV PHOTONS BY INFRARED PHOTONS

Consider the interaction of a TeV γ-ray of energy $E(z) = (1+z)E$ with a soft photon of energy $\epsilon(z) = (1+z)\epsilon$ at a redshift of z, where E and ϵ are the presently observed (z=0) photon energies. Pair production is expected above the threshold energy condition $E\epsilon(1+z)^2x > 2(mc^2)^2$, where $x = (1-\cos\theta)$ and θ is the angle between the photon directions. The cross section is given by (Heitler 1960)

$$\sigma[E(z),\epsilon(z),x] = 1.25\times10^{-25}(1-\beta^2)\left[2\beta(\beta^2-2)+(3-\beta^4)\ln(\frac{1+\beta}{1-\beta})\right] \text{ cm}^2 \quad (1)$$

where $\beta = (1-2(mc^2)^2/(E\epsilon x(1+z)^2))^{1/2}$. For γ-rays in the TeV energy range, this cross section is maximized when the soft photon energy is in the infrared range:

$$\epsilon(E) \simeq \frac{2(mc^2)^2}{E} \simeq 0.5(\frac{1\text{ TeV}}{E}) \text{ eV} \quad (2)$$

For a ~ 1 TeV γ-ray, this corresponds to a soft photon wavelength near the K-band ($\sim 2\mu$m). Thus, infrared photons with wavelengths around 2μm will contribute most to the absorption of TeV γ-rays. If the photons with energy ϵ have a number density $n(\epsilon)d\epsilon$ cm^{-3}, the optical depth for Mrk421 γ-rays will be

$$\tau(E) = \frac{c}{H_o} \int_0^{0.031} dz\,(1+z)^{1/2} \int_0^2 \frac{x}{2} \int_{\epsilon_1}^{\infty} d\epsilon\, n(\epsilon)\sigma\left[2x\epsilon E(1+z)^2\right] \tag{3}$$

where $\epsilon_1 = 2m^2c^4/Ex(1+z)^2$ (Stecker 1971). We assume $H_o \approx 75$ km/s/Mpc and $z = 0.031$ is the redshift of Mk421. (Here we have assumed that $\Omega = 1$. For $\Omega z << 1$, the first integrand will be approximately $(1+z)$ rather than $(1+z)^{1/2}$.)

We can now use the new data on the TeV energy spectrum from Mrk421 in order to put limits on τ, and therefore to put limits on the infrared radiation density. For a low redshift source ($z \ll 1$) such as Mk421, the calculation of the optical depth, τ, simplifies considerably. Taking the soft photon spectrum as $n(\epsilon) = \kappa\epsilon^{-\alpha}$, for small redshifts , z,

$$\tau(E) = \frac{2^\alpha cz}{(\alpha+1)H_o}\left(\frac{2(mc^2)^2}{E}\right)n\left[\frac{2(mc^2)^2}{E}\right] \int_1^{\infty} u^{-\alpha}\, du\, \sigma[\beta = \sqrt{1-1/u}] \tag{4}$$

For normal galaxies (Stecker *et al.* 1977) with $n(\epsilon) = \kappa_1\epsilon^{-2.55}$, in units of eV^{-1}cm^{-3} with ϵ in eV, we find

$$\tau(E) = 143\kappa_1 E_{TeV}^{1.55} \tag{5}$$

and, for ϵu_ϵ as constant (or $n(\epsilon) = \kappa_2\epsilon^{-2}$), we find that

$$\tau(E) = 120\kappa_2 E_{TeV}. \tag{6}$$

Expressions (5) and (6) for $\tau(E)$ should roughly hold up to $E \sim 10$ TeV.

A total of 11 well detected spectral points are available: five from EGRET (see Lin *et al.* 1992), and six from Whipple group (see Mohanty *et al.* 1993.) The spectral index found by EGRET is 1.96$\pm$ 0.14, which is consistent with the Whipple group index of 2.25$\pm$ 0.19 (statistical) $\pm$ 0.3 (systematic), within measurement errors. Mohanty *et al.* (1993) were able to fit a single power law between the two data sets

$$dN/dE = (1.02 \pm 0.14) \times 10^{-11} E^{-2.06\pm0.04} \text{ photons/cm}^2\text{/s/TeV} \tag{7}$$

We generalized this fit to include absorption by assuming spectra of the form

$$dN/dE = KE^{-\Gamma}\exp\left(-\tau(E)\right) \tag{8}$$

with K, Γ and κ as free parameters. Then the best χ^2 fit is for

$$dN/dE = (1.11 \pm 0.21) \times 10^{-11} E_{TeV}^{-2.04\pm0.04}\exp\left(-\tau(E)\right) \tag{9}$$

where $\tau(E) = 0.048E_{TeV}$ (for $\alpha = 2$) and $\tau(E) = 0.043E_{TeV}^{1.55}$ (for $\alpha = 2.55$) (again valid only up to $E \sim 10$ TeV) with a minimum $\chi^2_8 = 4.9$ for $11 - 3 = 8$ degrees of freedom for both models for $n(\epsilon)$. The χ^2 increases to only 5.4 for $\tau(E) = 0$ (no absorption.) Thus, the optimal values of τ obtained above are not significant, which implies no evidence for absorption. The upper limits on τ are obtained by allowing all free parameters to vary simultaneously, which allows us to construct confidence ellipsoids. The 1σ and 2σ upper limits on κ_1 in Eq. (5) (i.e. for $\alpha = 2.55$) are $\kappa_1 < 9\times10^{-4}$ and $\kappa_1 < 1.9\times10^{-3}$ respectively, whereas the corresponding numbers for κ_2 in Equation (6) (i.e. for $\alpha = 2$) are $\kappa_2 < 2.1\times10^{-3}$ and $\kappa_2 < 4.0\times10^{-3}$ respectively. The 2σ or 95% upper limits on $\tau(E)$ are then $\tau(E) < 0.27E_{\rm TeV}^{1.55}$, which implies $n(\epsilon) < 1.9\times10^{-3}\epsilon^{-2.55}$ eV^{-1}cm^{-3} for $\alpha = 2.55$. For $\alpha = 2$ we find $\tau(E) < 0.48E_{\rm TeV}$, which implies $n(\epsilon) < 4.0\times10^{-3}\epsilon^{-2}$ eV^{-1}cm^{-3}. If systematic errors should exist which were comparable to the statistical errors, they would raise our upper limits by less than a factor of two.

DISCUSSION AND CONCLUSIONS

Our new 95% CL upper limits are indicated as the two lines with upper limit arrows at their ends marked "This Work" on Figure 1. These results are consistent with the theoretical upper limit for starlight from normal galaxies given by Stecker, *et al.* (1977) and theoretical estimates of the IIRF obtained from galaxy counts in optical and infrared by Cowie, *et al.* (1990), Tyson (1990) and Yoshii and Takahara (1988).

Our upper limit IR fluxes as shown in Figure 1 are quite conservative. Fluxes at these densities would produce noticable absorption features in the TeV spectrum of Mrk421 which are not seen in the Whipple observations of Mohanty *et al.*(1993) as shown in Figure 2. These constraints on the IIRF rule out various exotic mechanisms for producing larger fluxes, such as some exploding star, decaying particle, massive object and black hole models (Carr 1988). They are consistent with the extragalactic near infrared background originating from ordinary stellar processes in galaxies.

It would appear (see Figure 1) that the background flux in the 1 to 5 μm range is expected to be of the order of $\sim 10^{-9}$ to $\sim 10^{-8}$ w m^{-2} sr^{-1}. Such a flux may be eventually detectable with the DIRBE experiment on COBE, provided that the foreground radiation from zodiacal light can be modeled well enough to be subtracted out (Mather, 1982).

The fact that the Whipple team did not detect the much brighter EGRET source 3C279 at TeV energies (Vacanti, *et al.* 1990, Kerrick, *et al.* 1993) is consistent with absorption by an IIRF within our limits, because this source is at a much higher redshift of 0.54 (see SDS). The TeV detection of other sources in the redshift range ~ 0.15 to ~ 0.25, where SDS estimate that $\tau \sim 1$ (SDS; Stecker 1992), or greater, should show the effect of absorption. Thus, spectral measurements of blazars in the TeV range should eventually lead to a determination of the IIRF (SDS).

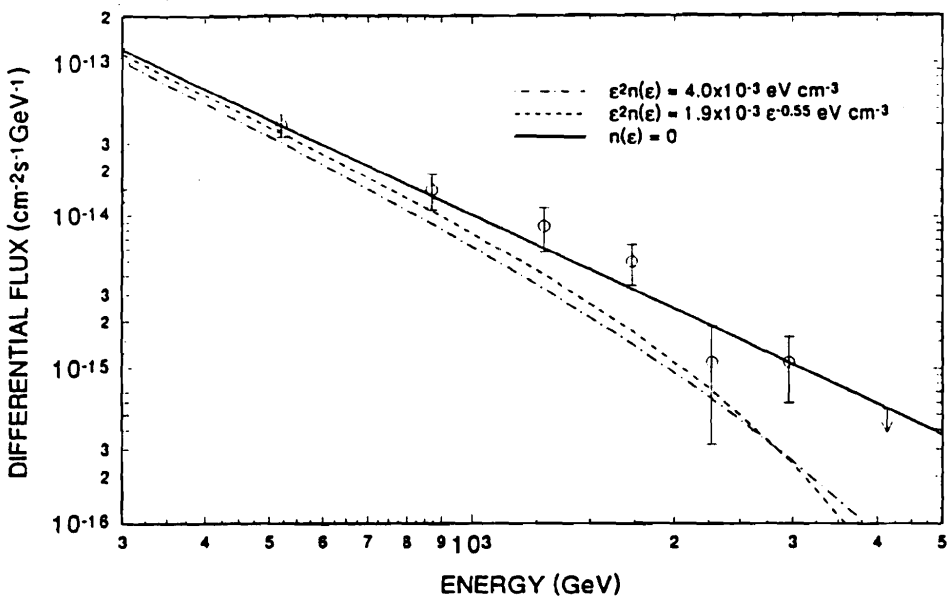

Figure 2: The portion of the Mrk421 differential γ-ray photon energy spectrum observed by the Whipple team (Mohanty *et al.*1993) compared to theoretical spectra corresponding to no absorption and absorption by our two 2σ upper limit infrared fluxes.

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