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Study of Markarian 421 in the γ-ray energy range 30-100 TeV

THE EAS-TOP COLLABORATION*

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The active galactic nucleus Markarian 421 (Mrk 421) is studied through the EAS-TOP extensive air shower array in the γ-ray energy ranges 20-50 TeV and 80-120 TeV. No evidence of d.c. emission is found in both datasets: the 90% flux limits are $\Phi(>25 \text{ TeV}) < 1.3 \cdot 10^{-13}$ cm^{-2} s^{-1} and $\Phi(>90 \text{ TeV}) < 2.5 \cdot 10^{-14}$ cm^{-2} s^{-1}. A straight power law extrapolation up to $E_0 \approx 10^{15}$ eV of the spectrum obtained from the observations by the EGRET and Whipple experiments - above 100 MeV and 0.5 TeV respectively - is excluded with a confidence level >99.99%, as expected from the absorption of VHE γ-rays by the 2.7K cosmic microwave background radiation. An indication (at $\approx$ 90% c.l.) of a steepening of the spectrum, with respect to such extrapolation, at γ-ray energies lower than expected from the 2.7K cutoff is derived. This could be due either to a break in the source spectrum or to the absorption of VHE γ-rays by intergalactic infrared photons of wavelength $\approx$ 100 μm.

1. INTRODUCTION

AGNs are generally recognized as the best candidates for cosmic rays acceleration at the highest energies. This has to be investigated through the study of possible emission in different components, i.e. gamma-rays, neutrinos, cosmic rays (the latter at EHE, at which they are nearly not deflected). Significant results have been obtained in gamma-rays: at GeV energies by the satellites (the EGRET experiment on the Compton Gamma Ray Observatory [1]), and at TeV by the ground-based atmospheric Cherenkov detectors (Whipple [2,3], HEGRA [4,5], CAT [6], Telescope array [7]). The extension of these measurements to higher energies has therefore the main aim of defining the source spectrum, expected to be a power law. Moreover, it can probe the intergalactic low energy background radiation - the cosmic microwave background at 2.7K (CMBR) [8] and the intergalactic infrared radiation fields (IIRF) [9,10].

An optimal candidate for such a study is Markarian 421, observed with high statistical significance (and therefore with well measured fluxes) both at GeV energies by EGRET [11] and at TeV by the Whipple atmospheric Cherenkov light detector up to $\approx$ 10 TeV [2,12–14], the data being well fitted by a single power law spectrum. At γ-ray energies above Cherenkov measurements, upper limits have been given in refs. [15–21].

In the present note we report on the observations performed by the EAS-TOP extensive air shower array [18–20] which is sensitive in the energy range 80-120 TeV, i.e. around the CMBR cutoff, and, through lower energy events, in the 20-50 TeV interval, which is below the CMBR cutoff and is therefore interesting in view of the possible absorption of VHE γ-rays by intergalactic infrared photons of wavelength $\lambda \approx 100$ μm.

2. THE EXPERIMENT AND THE DATA

The EAS-TOP extensive air shower array is located at Campo Imperatore (2005 m a.s.l., INFN

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Table 1
Expected and measured events for TR_0 and TR_1 trigger condition (see text for the definition).

	Expected source contribution		Observations		
	Without CMBR cutoff (a)	With CMBR cutoff (b)	ON	<OFF>	ON-<OFF>
TR_0	7440	3372	11597932	11599310	-1378±3679
TR_1	1181	331	125148	125559	-411±382

National Gran Sasso Laboratories, lat. 42.5° N, long. 13.5° E). The detector of the electromagnetic component [22] consists of 35 modules of scintillator 10 m^2 each, spread over an area of $\approx 10^5$ m^2.

Different selection criteria are applied to the data in order to investigate different primary energies. In the present analysis we use showers with $\geq$ 4 modules fired, without core location (TR_0 events), and showers with $\geq$ 7 modules fired and core located inside the edges of the array (TR_1 events). The typical triggering primary energies in the angular window $\theta \leq 40^o$ are 25 and 90 TeV. The angular resolutions are respectively $\sigma_\theta=2.5^o$ (taking into account the uncertainty in core location) and $\sigma_\theta=0.83^o\pm0.10^o$ (which includes systematic effects and is obtained by the measurement of the shape of the Moon shadow on the flux of primary cosmic rays [18,23]).

The search is performed by means of the ON-OFF technique (details about the procedure, a study of the background stability, the calculations of the array effective area, energy thresholds and reported upper limits are discussed in refs. [18,19]). The number of counts from the source direction (ON) is compared with the number of counts from six OFF-source cells located in the same declination band and next to the ON source bin. The used angular bins are: $\Delta\delta = 1.5^o$ (with efficiency for a point source signal $\epsilon = 0.9$) for TR_1 and $\Delta\delta = 4.0^o$ for TR_0 ($\epsilon = 0.7$), while $\Delta\alpha = \Delta\delta/\cos\delta = 1.9^0$ and 5.1^0 respectively.

Data have been collected between 1992 and 1997 for a total observation time $T_{obs} = 2.95 \cdot 10^7$ s both for the ON and the OFF sources.

3. RESULTS AND CONCLUSIONS

The number of on- and off-source events measured for both trigger conditions is shown in Table 1: ON and <OFF> counts are compatible within 1 s.d. in both energy ranges. Assuming a source spectrum $\propto E^{-2}$, the 90% c.l. flux upper limits are:

$$\Phi(> 25\ TeV) < 1.3 \cdot 10^{-13} cm^{-2} s^{-1}$$

$$\Phi(> 90\ TeV) < 2.5 \cdot 10^{-14} cm^{-2} s^{-1}$$

The data are compared with the expectations from the extrapolation of the source spectrum fitting the EGRET-Whipple data [11,12]:

$$\frac{dN}{dE} = (1.02 \pm 0.14) 10^{-11}\ E^{-2.06\pm0.04} / cm^2 s TeV \quad (1)$$

The EGRET and Whipple observations were not simultaneous: the excellent fit of the data to a single power-law over the whole energy range guarantees to some extent the good determination and the stability of the spectrum. Moreover, the Whipple data are relative to Mrk 421 in a low state of emission, while in high state the flux can increase by a factor up to ≈ 5 [14]: the usage of spectrum (1) is then quite conservative.

The extrapolation of expression (1) is performed:
a) as a single power law spectrum up to 10^{15} eV;
b) as in a), including the absorption from the CMBR.

The number of events expected under both hypothesis for the two trigger conditions are given in Table 1. Comparing them with the observed rates, we conclude:

(i) concerning the straight power law extrapolation of spectrum (1), the number of observed TR_0 events, is not compatible with the expected one at 98% c.l. Considering TR_1 data, the incompatibility between observation and expectation is at 99.99% c.l. Hypothesis (a) is then excluded with high confidence level.

(ii) Concerning hypothesis (b), which includes the CMBR cutoff, and considering TR_0 events, the level of incompatibility between the number of observed events and of the expected ones is at 72% c.l. From TR_1, observation and expectation are not compatible at 82% c.l. By combining the significance of the two results, we obtain that the rejection c.l. of hypothesis b) is 90%. This is not compelling, but it represents an indication either of a break in the Mrk 421 spectrum at γ-ray energies $10 < E_\gamma < 30$ TeV, or of the presence of a $\lambda \approx 100$ μm IIRF. Under the second hypothesis - which is considered more favored [24] - assuming an absorption length $l_{abs}(\gamma_{30TeV} - \gamma_{IIRF}) = \frac{1}{\sigma n_{IIRF}} \approx d_{Mrk421}$, and a $\epsilon^{-\nu}$ power law spectrum for the IIRF [24], a lower limit to the background photon density in the wavelength range $\lambda \approx 50 - 300\mu$m (IR energy $\epsilon \approx 0.03 - 0.004$ eV) can be set (see fig. 1). Such a lower limit is consistent with the estimates of Mac Minn and Primack [26] based on different models of galaxy formation.

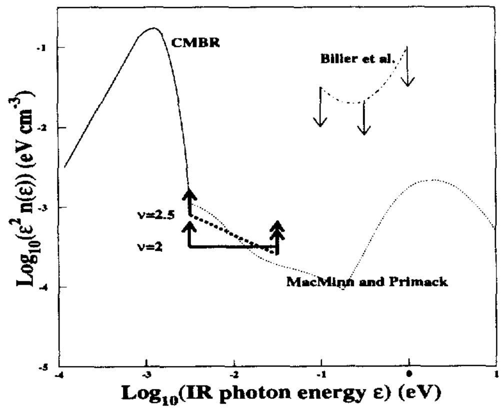

Figure 1. *The extragalactic photon density versus photon energy ϵ. The CMBR (continuous line) and the estimation of the infrared background by MacMinn and Primack [26] (dotted line) are shown. The upper limits by Biller et al. [25] (dash-dotted line) and by the present work (thick continuous and dashed lines, corresponding to two different values of the power-law index ν of the IIRF) are drawn.*

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