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THE TeV GAMMA-RAY SPECTRUM OF MARKARIAN 421 DURING AN INTENSE FLARE

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ABSTRACT

We present the gamma-ray spectrum of the BL Lacertae object, Markarian 421, above 500 GeV during its most intense recorded TeV flare, on 1996 May 7. The spectrum is well fitted by a power law with an exponent of $-2.56 \pm 0.07 \pm 0.1$ (statistical and systematic errors). The spectrum extends above 5 TeV with no evidence for a cutoff, favoring determinations of the extragalactic infrared energy density that do not produce a sharp cutoff at these energies.

Subject headings: BL Lacertae objects: individual (Markarian 421) — gamma rays: observations

1. INTRODUCTION

The Whipple Observatory's 10 m gamma-ray telescope has now detected two extragalactic sources of more than 300 GeV photons: Markarian 421 (Punch et al. 1992) and Markarian 501 (Quinn et al. 1996). Both objects belong to the BL Lacertae (BL Lac) class of active galactic nuclei (AGNs) that itself is a subset of the broader blazar class that includes not only BL Lac objects, but core-dominated flat-spectrum radio quasars and highly polarized and optically violent, variable quasars. Nearly all of the AGNs detected by the EGRET instrument at energies greater than 100 MeV (Thompson et al. 1995, 1996; von Montigny et al. 1995) belong to the blazar class.

In a common view of AGNs, blazars have relativistic jets whose axes make a small angle to the line of sight to the earth (e.g., Blandford & Königl 1979). Evidence for this interpretation comes directly, in some cases, from observations of apparent superluminal motion of radio-emitting blobs. Indirect evidence comes from arguments that relativistic beaming is necessary to avoid absorption of the highest energy radiation by pair production on low-energy photon fields within the jet.

In previous papers, the Whipple Collaboration has reported on several aspects of the very high energy (VHE) emission from Mrk 421. Correlations in the time variations in intensity of X-ray and TeV gamma-ray emission were reported by Macomb et al. (1995). Correlated time variations extending to optical wavelengths, as well as X-rays, were recently reported by Buckley et al. (1996). Variability of the source at TeV energies on timescales as short as 30 minutes was observed in May 1996 (Gaidos et al. 1996). Eight days prior to this flare, the most intense flare yet recorded by the Whipple Observatory instrument was observed. More than 1000 gamma rays were collected during a 3 hr observation, and the source reached an intensity ~10 times that of the Crab Nebula. The energy spectrum of Mrk 421 during this intense flare is the subject of this letter. Because of the strength of the flare and recent improvements in our technique for extracting spectra (Mohanty et al. 1997), the shape of that spectrum is much better determined than that previously reported by the Whipple group (Mohanty et al. 1993). This result provides an important constraint to determinations of the density of extragalactic infrared photons.

Gould & Schréder (1967) first proposed that the extragalactic infrared photon density could be determined through a study of the spectra of cosmologically distant sources of VHE radiation. The infrared photons absorb VHE radiation via the pair production process. Cosmological factors that enhance the absorption effects were first discussed by Stecker (1969). What is required for this determination are sources of VHE radiation whose unabsorbed spectra can reasonably be inferred. The discovery of intense 100 MeV radiation from 3C 279 (Hartman et al. 1992) and the probability of even higher energy sources reaching into the VHE range made this a realistic possibility (Stecker, de Jager, & Salamon 1992). The discovery of Mrk 421 as a TeV gamma-ray source (Punch et al. 1992) and the preliminary estimate of its spectrum, given by Mohanty et al. (1993), have led to a number of estimates of that density. It is interesting to note that although this is an indirect technique for determining the extragalactic infrared photon density, it is nevertheless superior, so far, to direct measurements by rockets and satellite experiments owing to the difficulties these encounter in subtracting contributions from local galactic infrared sources.

Stecker & de Jager (1993) first used the data of Mohanty et al. (1993) to derive an upper limit on the extragalactic infrared photon density. Biller et al. (1995) derived higher upper limits on the infrared photon density under the assumption that absorption effects were already at work at energies between the energy region covered by EGRET and that covered by the Whipple instrument. On the other hand, de Jager, Stecker, & Salamon (1994) derived a much lower measurement of the density by integrating the Mohanty et al. (1993) spectrum. Bond, Carr, & Hogan (1986) pointed out that the epoch of galaxy formation affects the extragalactic infrared photon density. Various scenarios for early galaxy formation have been examined in detail by MacMinn & Primack (1996). For many scenarios appreciable absorption (i.e., $\gtrsim 20\%$) occurs at ener-

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gies as low as 100 GeV for a source at a redshift of 0.2 (MacMinn & Primack 1996; Stecker & de Jager 1996).

The observations and method of spectral analysis are presented in § 2 and § 3, respectively. In a concluding section the shape of the spectrum, well fitted with a simple power law, is discussed in the context of various determinations of the extragalactic infrared photon density.

2. OBSERVATIONS

A camera (Cawley et al. 1990) consisting of 109 fast photomultipliers with a pixel size of 0°.25 in the focal plane of the 10 m gamma-ray telescope of the Whipple Observatory is used to image Cerenkov radiation from air showers. Individual air shower images are characterized by parameters that determine their shape, orientation and location in the field of view, and energy. Monte Carlo simulations and frequent observations of the Crab Nebula over several years (Weekes et al. 1993) have led to efficient use of these parameters in selecting gamma-ray induced air showers in the presence of a background of cosmic-ray air showers (Reynolds et al. 1993).

The details of the data-taking procedure for Mrk 421 are described in Schubnell et al. (1996). During routine monitoring of Mrk 421 in the 1996 May observing period, the gamma-ray telescope recorded a dramatic flare (Gaidos et al. 1996) that produced the largest instantaneous flux ever recorded from any source in the current VHE gamma-ray catalog. The source flux was observed to increase monotonically during the first 2 hr of observation, beginning at a rate nearly twice that of the highest previously observed flare (Kerrick et al. 1995). For the last hour of observation the flux was approximately constant at a value of ~15 gamma rays per minute, 10 times that of the steady rate from the Crab Nebula above 400 GeV.

3. ANALYSIS AND RESULTS

One of the inherent strengths of the atmospheric Cerenkov technique is that the energy of the shower-initiating gamma ray may be determined from observations of the intensity of the Cerenkov light reaching a single imaging detector. The location of the image centroid relative to the direction to the gamma-ray source measures the impact parameter of the shower axis relative to the telescope. For centroid values in the range 0°.6–1°.0 the impact parameter is such that the shower front is sampled in a relatively flat region of the lateral distribution of Cerenkov light, where the amount of light is proportional to the energy of the primary gamma ray. With this restriction on centroid values the energy resolution is well described by a simple Gaussian in the log (base 10) of the energy with a standard deviation of 0.16, independent of energy (see Fig. 1*a*).

Since the 1991 publication of a spectrum from the Crab Nebula (Vacanti et al. 1991) much effort has been spent on refining techniques whereby spectra may be extracted from observations using the Whipple Observatory gamma-ray telescope. These efforts have resulted in a spectrum for the Crab Nebula (Hillas et al. 1997) that is extremely close to the original Vacanti et al. (1991) estimate, although with much better justification. We now feel confident in applying these methods to extracting spectra for other objects, in particular to Mrk 421 during the recent intense flare.

The details of our spectral analysis procedures are explained in Mohanty et al. (1997). In that paper two methods are described. The methods use completely independent shower-simulation programs and different approaches in determining the overall gain of the Cerenkov telescope. The two methods give good agreement on the spectrum of the Crab Nebula in the energy range 500 GeV to 8 TeV (Hillas et al. 1997).

For the determination of the energy spectrum we have followed method 1 of Mohanty et al. (1997). This method uses data binned in equal increments of the logarithm of the estimated energy, and collection areas as calculated from simulations. In this method the collection area is somewhat modified by the form of the primary gamma-ray energy spectrum. The flux in each bin is the net gamma rays divided by the modified collection area, the time of observation, and the width of the bin. A least-squares technique may then be used to derive the

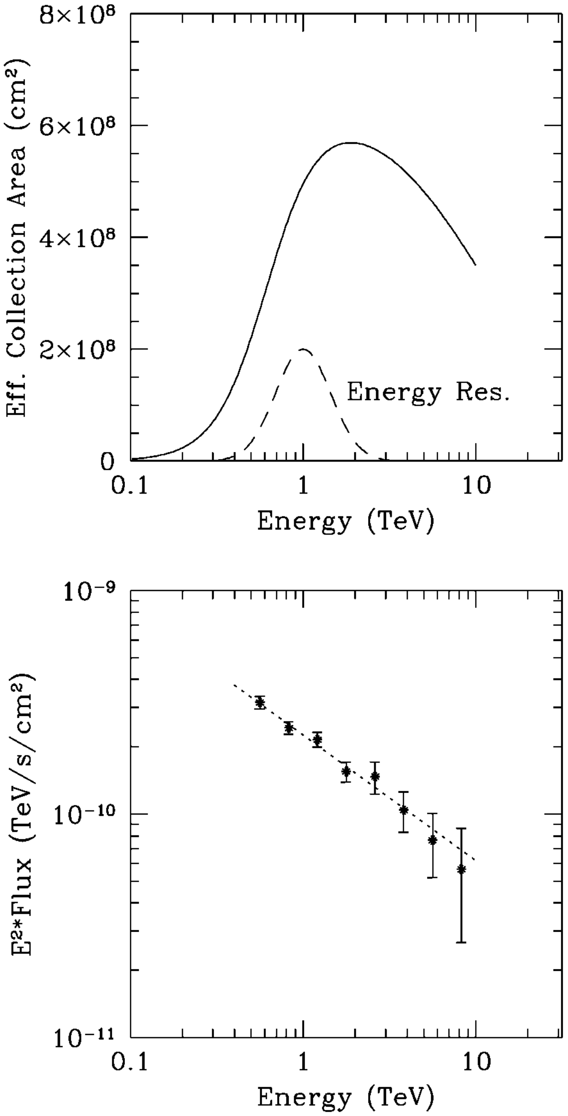

FIG. 1.—(*a*) Modified collection area of the Whipple Observatory 10 m gamma-ray telescope as a function of primary gamma-ray energy. For method 1 of Mohanty et al. (1997) the collection area (the "modified collection area") is slightly modified by the slope of the primary energy spectrum and the curve given above is appropriate for a primary gamma-ray energy spectrum with an energy exponent of −2.5. Also shown in the figure is the energy resolution of the instrument. The resolution function is well described by a Gaussian in the log (base 10) of the energy, approximately independent of energy, with a σ of 0.16. (*b*) Gamma-ray energy spectrum of Markarian 421 on 1996 May 7. The photon flux has been multiplied by E^2. The best-fit power law to the data has a slope of −2.56 (*dashed line*).

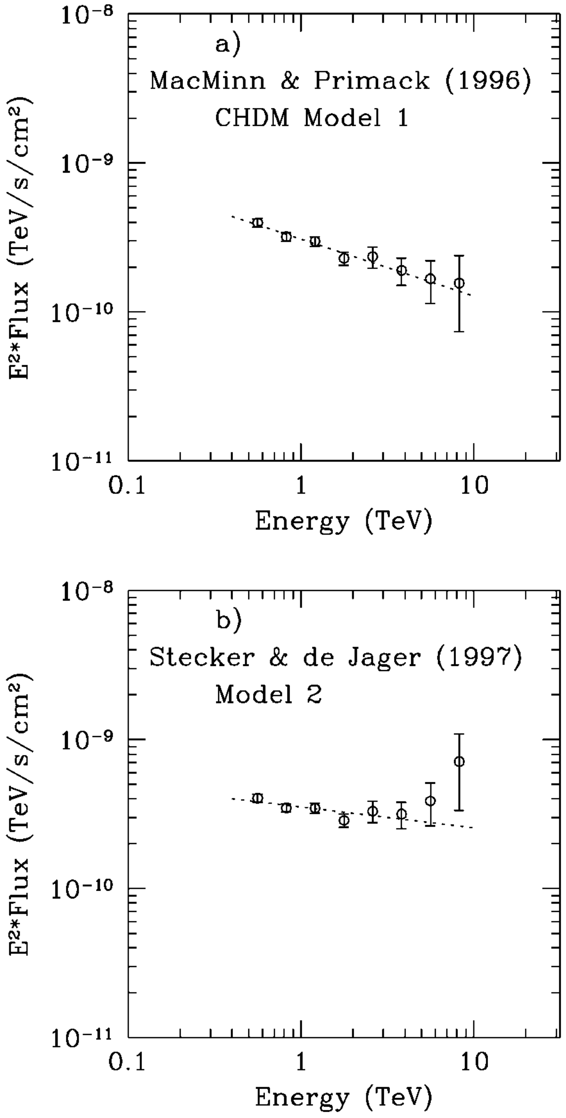

FIG. 2.—Energy spectrum of Mrk 421 on 1996 May 7 corrected for pair production absorption according to various models; the flux has been multiplied by E^2. (*a*) Correction according to model 1 of the cold/hot dark matter scenario of galaxy formation of MacMinn & Primack (1996). (*b*) Correction according to model 2 of Stecker & de Jager (1997). The dashed lines indicate the best power-law fit for each case.

best values for a flux constant and the exponent of an assumed power-law energy spectrum.

In Figure 1*a* the modified collection area of the telescope derived from simulations (Mohanty et al. 1997) is shown as a function of the primary gamma-ray energy. The curve shown assumes a power-law spectrum with energy exponent of −2.5.

The energy bins associated with the data were chosen a priori to be $\frac{1}{6}$ of a decade to match the width of the energy resolution. Eight bins were used; the lowest bin, which was judged to be free from increased systematic errors due to uncertainties in threshold, was centered at $E = 560$ GeV; the highest bin was centered at 8.3 TeV. A total of 842 showers were selected as gamma-ray candidates using the so-called extended supercuts procedure (Mohanty et al. 1997). The background was determined from five different off-source runs taken earlier in 1996; the runs were chosen to span zenith angle ranges and sky conditions closely matched to that during the flare. The total background for the eight bins was 127; thus the 842 showers are approximately 85% pure gamma rays.

The resulting flux values are plotted in Figure 1*b*. A simple power law is an excellent fit to the data with a total χ^2 of 1.94 for 6 degrees of freedom (dof). The best-fit differential photon spectrum is

$$F(E) = (2.24 \pm 0.12 \pm 0.7) \times 10^{-10} E^{-2.56 \pm 0.07 \pm 0.1}$$

photons s^{-1} cm^{-2} TeV^{-1}, where E is in TeV. Two errors are given for each of the two parameters; the first is statistical, the second is systematic. The statistical errors are determined by requiring an increase in χ^2 of 2.3 (Avni 1976). (If one is only interested in the slope of the power law and not the flux constant, then the statistical error on the energy exponent is reduced to ±0.05.) Method 2 from Mohanty et al. (1997), applied to the same flare data, gives a flux constant and an exponent that agree well with the above values.

4. DISCUSSION AND CONCLUSIONS

This same method of analysis has been applied to all of the Whipple observations of Mrk 421 during its 1995–1996 observing season. When the data from the night of May 7 (the night of the flare) are excluded, a power-law fit with an energy exponent -2.96 ± 0.22 results (Zweerink 1997). Although this value differs only by 1.8 σ from the exponent during the flare state, it does suggest the possibility of spectral hardening during the strong flare of 1996 May 7.

The HEGRA atmospheric Cerenkov group has recently reported on the spectrum of Mrk 421 above 1 TeV obtained during the 1994–1995 observing season (Petry et al. 1996). Their power-law fit, with energy exponent of -3.6 ± 1.0, was obtained for data in which the average Mrk 421 intensity was ~0.5 that of the Crab, i.e., the intensity of Mrk 421 was less than $\frac{1}{10}$ that of the flare reported here.

As mentioned in § 1, the VHE gamma-ray spectra of blazars may be used to constrain the density of intergalactic infrared radiation that acts as an absorber via the photon-photon pair production process (Gould & Schréder 1967; Stecker et al. 1992). In an effort to quantify what constraints our data impose on the density, we have corrected our flux values according to various prescriptions of that absorption. Our data, which extend in an apparently unbroken power law to energies beyond 5 TeV, appear to rule out extreme forms of the absorption that predict a sharp cutoff. For example, de Jager et al. (1994) give an early prescription for the energy-dependent optical depth, $\tau(E)$, as $\tau = 0.112E^{1.55}$. When this amount of absorption is removed from our data points, the resulting spectrum is not well fitted by a simple power law (χ^2 value of 12.7 for 6 dof; less than 5% likely), and the spectrum flattens with increasing energy, something that is judged unlikely by us on physical grounds.

More recent prescriptions for the energy-dependent optical depth give acceptable fits. Two of these are shown in Figure 2. Any of the models of MacMinn & Primack (1996) would produce acceptable χ^2 fits; the model illustrated in Figure 2*a* is model 1 of their cold/hot dark matter scenario of galaxy formation. The fit to our flux values corrected for this amount of absorption has a χ^2 value of 1.9 (6 dof). The latest calculation by Stecker & de Jager (1997) of the pair production absorption (model 2 in their paper) produces the corrected flux values and fit ($\chi^2 = 5.5$) shown in Figure 2*b*. Their model 1 gives an even better fit with a total $\chi^2 = 2.6$. Further detailed analysis of these observations and the limits that they place on the extragalactic infrared photon density will be presented in a paper in preparation (Biller et al. 1997).

To make further progress in determining the density of intergalactic infrared photons one needs not only observations of the nearby TeV sources (Mrk 421 and Mrk 501) but observations on sources at greater redshifts. It is important also to recognize that for many scenarios (see Fig. 3 in MacMinn & Primack 1996) the absorption acts over a wide range of energies. Even for a nearby source like Mrk 421 one must go to energies below 30 GeV before the absorption is negligible. Thus one's ability to discriminate between various determinations of the intergalactic infrared density will be enhanced considerably when detectors with a dynamic range extending to much lower energies become operative.

The observation of correlated variability during the 1996 May flare can also be used to constrain the physical properties of the region emitting the VHE gamma rays. For instance, an upper limit on the magnetic field strength can be derived from the maximum observed gamma-ray energy and from the shape of the X-ray spectrum. For Mrk 421, the spectral energy distribution is typically observed to roll over in the X-ray band (Takahashi et al. 1996). This break is usually attributed to the maximum energy of the synchrotron component of the emission spectrum, $E_{\rm syn,max}$. If the X-ray photons are produced by synchrotron radiation of nonthermal electrons within the jet, this maximum energy is related to the magnetic field strength B (measured in the jet frame), the Doppler factor of the jet δ and the maximum electron Lorentz factor $\gamma_{e,\rm max}$ (also measured in the bulk frame; Sikora, Begelman, & Rees 1994) by

$$E_{\rm syn,max}\ {\rm keV} \approx 1.2 \times 10^{-11}\delta\gamma^2_{e,\rm max}B\ {\rm G}. \qquad (1)$$

If the VHE emission arises from inverse Compton scattering of low-energy photons from the same nonthermal electrons that produce the synchrotron emission, then regardless of the nature of the seed photons we have the kinematic limit on the electron Lorentz factor $\delta\gamma_{\rm max} > E_{\rm C,max}/m_e c^2$ or

$$\gamma_{e,\rm max} \gtrsim 2 \times 10^6 \delta^{-1}\frac{E_{\rm C,max}}{1\ {\rm TeV}}, \qquad (2)$$

where $E_{\rm C,max}$ is the maximum energy of the inverse Compton photons.

Combining equations (1) and (2) one obtains an upper limit on the magnetic field strength (e.g., Buckley et al. 1997):

$$B \lesssim 2.2\ {\rm G}\left(\frac{E_{\rm syn,max}}{10\ {\rm keV}}\right)\left(\frac{\delta}{10}\right)\left(\frac{E_{\rm C,max}}{1\ {\rm TeV}}\right)^{-2}. \qquad (3)$$

In this Letter we present evidence for significant detection of gamma-ray emission at energies above 5 TeV. Previous low-elevation observations of Mrk 421 by the Whipple collaboration during a time of its flaring (Krennrich et al. 1997) further support the absence of any cutoff in the TeV regime. If the cutoff in the synchrotron spectrum is less than 10 keV (Takahashi et al. 1996) then a limit $B \lesssim 0.1(\delta/10) \lesssim 0.1$ G is obtained if we further assume the value of δ given in Gaidos et al. (1996). However, simultaneous X-ray data taken with the *Rossi X-Ray Timing Explorer* by Schubnell et al. (1997) indicate the possibility of an X-ray cutoff greater than 10 keV; if this is correct then the limit on the magnetic field in the jet during the time of this strong flare will be higher in direct proportion to the energy of the X-ray cutoff.

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