

DISCOVERY OF SPECTRAL VARIABILITY OF MARKARIAN 421 AT TeV ENERGIES

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ABSTRACT

The detection of spectral variability of the γ -ray blazar Mrk 421 at TeV energies is reported. Observations with the Whipple Observatory 10 m γ -ray telescope taken in 2000/2001 revealed exceptionally strong and long-lasting flaring activity. Flaring levels of 0.4–13 times that of the Crab Nebula flux provided sufficient statistics for a detailed study of the energy spectrum between 380 GeV and 8.2 TeV as a function of the flux level. These spectra are well described by a power law with an exponential cutoff: $dN/dE \propto E^{-\alpha} e^{-E/E_0} \text{ m}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$. There is no evidence for variation in the cutoff energy with flux, and all spectra are consistent with an average value for the cutoff energy of 4.3 TeV. The spectral index varies between $1.89 \pm 0.04_{\text{stat}} \pm 0.05_{\text{syst}}$ in a high flux state and $2.72 \pm 0.11_{\text{stat}} \pm 0.05_{\text{syst}}$ in a low state. The correlation between spectral index and flux is tight when averaging over the total 2000/2001 data set. Spectral measurements of Mrk 421 from previous years (1995/1996 and 1999) by the Whipple collaboration are consistent with this flux–spectral index correlation, which suggests that this may be a constant or a long-term property of the source. If a similar flux–spectral index correlation were found for other γ -ray blazars, this universal property could help disentangle the intrinsic emission mechanism from external absorption effects.

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

1. INTRODUCTION

The discovery of more than 70 active galactic nuclei (AGNs) by the EGRET γ -ray detector (Hartman et al. 1999) operating at $E > 30$ MeV gave a fresh perspective on the AGN phenomenon, particularly relevant to understanding the intrinsic properties of their jets. EGRET-detected AGNs are typically radio-loud and show a second peak in their νF_ν distribution at GeV energies. Blazars detected at TeV energies have a primary peak

at X-ray energies and a second component at TeV energies. Both types are γ -ray blazars, and the commonly accepted model is that they have their jet oriented toward the observer revealing emission regions that are strongly Doppler-boosted. Relativistic boosting gives rise to large flux variations (Catanese et al. 1997) and short-timescale phenomena (Gaidos et al. 1996). Two AGNs (Mrk 421 and Mrk 501) show emission extending to energies greater than 10 TeV (Aharonian et al. 1999; Krennrich et al. 2001).

Since the discovery of TeV γ -rays from the blazars Mrk 421 (Punch et al. 1992) and Mrk 501 (Quinn et al. 1996), these objects played a significant role in discussions involving the emission processes in AGN jets and attenuation effects of TeV γ -rays propagating over extragalactic distances. Both blazars exhibit episodes of strong flaring activity, providing good statistics for detailed measurements of their average energy spectra from 260 GeV up to 17 TeV using ground-based γ -ray telescopes. Mrk 421 and Mrk 501 are at approximately the same distance ($z = 0.031$ and $z = 0.034$, respectively). Since the level of attenuation of γ -rays by the diffuse extragalactic background light (EBL) via pair creation (Nikishov 1962; Gould & Schröder 1967; Stecker, De Jager, & Salamon 1992) depends on the distance of the source to the observer, it could cause a common spectral feature in the energy spectra of Mrk 421 and Mrk 501.

Measurements by the Whipple collaboration (Samuelson et al. 1998; Krennrich et al. 2001) imply that the energy spectra of both Mrk 501 and Mrk 421 require a curved fit parameterization, e.g., a power law with an exponential cutoff with cutoff energies of $4.6 \pm 0.8_{\text{stat}}$ TeV and $4.3 \pm 0.3_{\text{stat}}(-1.4 + 1.7)_{\text{syst}}$ TeV (“stat” means statistical error, “syst” means systematic error), respectively. Data from the HEGRA collaboration suggest that the cutoff energy of Mrk 501 is $6.2 \pm 0.4_{\text{stat}}(-1.5 +$

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2.9)_{sys} TeV (Aharonian et al. 1999, 2001) and that Mrk 421 has a cutoff energy of $4.2(+0.6 - 0.4)$ _{stat} TeV (Kohnle et al. 2001). The results from the two groups may be consistent given systematic uncertainties. The interpretation of the origin of the cutoff requires a better understanding of the emission process in γ -ray blazars as a class of objects. Making progress in unraveling the emission process in blazars from external attenuation effects requires two types of key observations.

The first is contemporaneous multiwavelength observations at X-ray and TeV energies (see Buckley et al. 1996 and Krawczynski et al. 2002). These constrain the emission process by simultaneously probing the synchrotron emission and the mechanism responsible for the γ -ray component, e.g., the inverse Compton (IC) scattering process (Maraschi, Ghisellini, & Celotti 1992; Marscher & Travis 1996). There are also competing models that assume that the high-energy emission arises from protons (Mannheim 1998; Mücke & Protheroe 2001; Aharonian 2000).

The second is the study of γ -ray spectral variability as a function of flux and time. Spectral variability is directly tied to the emission process at the source, whereas external absorption by the EBL is a universal feature that is independent of the flux level. Thus, by studying the spectral variability, we are able to disentangle these two effects. In synchrotron-Compton models, spectral variability could be explained by cooling of electrons in the jet, causing a shift of the break in the electron spectrum, or by variations of the maximum energy of accelerated electrons. Spectral variability may also be a key to the understanding of the energy dissipation processes in the vicinity of a supermassive black hole powering the jet.

Some evidence for spectral variability has been reported by Djannati-Ataï et al. (1999) and Krawczynski et al. (2001) for Mrk 501; however, the effect was not highly statistically significant ($\approx 4\sigma$) and precluded detailed studies. In fact, the spectral index of Mrk 501 turned out to be surprisingly stable during observations of a strong outburst in 1997 (Aharonian et al. 1999), although the flux varied by a factor of 30.

In this Letter, we present the discovery of the spectral variability of Mrk 421 at TeV energies based on data taken with the Whipple Observatory 10 m γ -ray telescope. We show that Mrk 421 exhibits a remarkable flux–spectral index correlation that appears to be stable, averaged over timescales of months to several years.

2. OBSERVATIONS AND DATA ANALYSIS

The observations were made with the Whipple Observatory 10 m γ -ray telescope using the GRANITE-III high-resolution camera (Finley et al. 2001). The high sensitivity of the telescope for point sources in the energy range from ≈ 200 GeV to greater than 20 TeV permits the measurement of energy spectra of γ -ray sources with fluxes above 1 crab on timescales as short as 30 minutes (1 crab is defined as the differential flux of the Crab Nebula at 1 TeV in units of photons $m^{-2} s^{-1} TeV^{-1}$).

Mrk 421 was more active in the 2000/2001 observing season than in previous years. Unusually high flaring states ranging from 0.4 to 13 crab, lasting for a period of approximately 5 months, provided a wealth of statistics for studies of spectral variability. The data used for the analysis in this Letter were collected on 2000 November 28 and December 4–6, 22, 27, and 28–29 and 2001 January 20–21, 24–25, and 30–31, February 1–3, 19, and 27–29, March 19, 22–23, 26–27, and 30, and April 13. These data are an extension to the data set published in Krennrich et al. (2001) and include observations of

the source in a lower flux state. A total of 49.93 hr of on-source observation time with zenith angles less than $\approx 35^\circ$ has been used in this study.

The γ -ray rate of the 107 individual on-source runs varies from 0.4 to 18.0 γ minute⁻¹. The background from cosmic-ray-induced showers has been estimated for each on-source run individually by using a matching off-source run also taken during the 2000/2001 season. A good match requires that both runs cover a similar zenith angle range and that the on-source and off-source runs show good agreement in the distribution of the parameter associated with the alignment of the image in the focal plane, for values of the parameter outside the γ -ray fiducial region. In some runs, a normalization factor between the on-source and off-source samples was applied to ensure that the off-source samples accurately represented the background in the on-source region. This procedure has been tested as a function of the total light intensity of the γ -ray image to minimize a possible systematic bias. Uncertainties in the spectral index, α , due to the method of background estimation are typically $\Delta\alpha < 0.1$ in the spectral index for individual runs and $\Delta\alpha < 0.05$ for sets of five or more runs.

In a search for yearly trends in a flux–spectral index correlation, we also include previously published data from 1995 and 1996 (Krennrich et al. 1999a). In addition, we derive a spectrum for observations taken in 1999 May–June using the GRANITE-III 331 pixel camera (Krennrich et al. 1999b; Le Bohec et al. 2000; Finley et al. 2001). The data consist of 33 on-source and 33 matched off-source runs from 1999 May 6–7, 9–10, 11, and 16–18 and 1999 June 5–8.

The analysis methods for the 2000/2001 observations, γ -ray selection, and energy estimate are based on the method described in Mohanty et al. (1998), and their application has been described in Krennrich et al. (2001). These γ -ray selection criteria are derived from parameter distributions of simulated γ -ray showers as a function of their total light intensity in the camera. We set these criteria so that they retain 90% of the γ -ray images whose centroids are within 0.4 – 1.0 of the center of the camera. To avoid the difficulties of modeling the trigger electronics, we apply an additional cut requiring that a signal of at least 15.1, 13.6, and 12.1 photoelectrons are present in the three highest camera pixels, respectively. In this analysis, we have increased the lowest energy point of our spectral measurements from 260 to 380 GeV, to minimize the systematic uncertainties inherent at low energies.

3. RESULTS: SPECTRAL VARIABILITY AS A FUNCTION OF FLUX

The data were divided a priori into eight independent subsets with comparable numbers of excess events and average γ -ray rates ranging from 3.3 to 16.0 γ minute⁻¹. In Figure 1, we show the corresponding energy spectra. For clarity of presentation, we have combined set II+ III and set VI+VII, respectively. Progressive hardening of the spectra is apparent to the eye when comparing the spectra toward increasing flux levels. We have attempted to fit the individual spectra by a simple power law. These fits result in unacceptable goodness-of-fit (χ^2) values for sets I–IV; hence, the power-law hypothesis is rejected (also see Table 1).

For comparison with previous papers (Krennrich et al. 1999a, 2001) and the results from other groups (Piron et al. 2001; Bazer-Bachi et al. 2001), we also fitted the data using a parabolic function: $dN/dE \propto E^{-\alpha-\beta \log E} m^{-1} s^{-1} TeV^{-1}$. The results in Table 2 have acceptable goodness-of-fit (χ^2) values. The

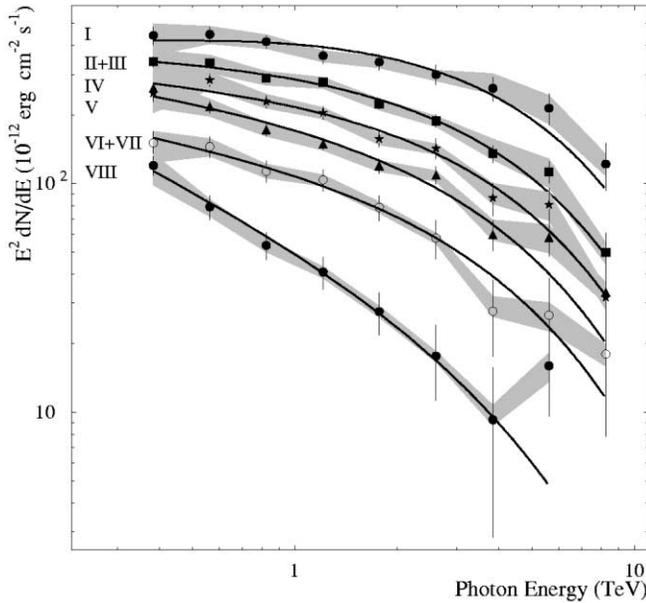


FIG. 1.—Mrk 421 spectra at different flux levels averaged for data over the 2000/2001 season. The spectra have been fitted by a power law with a fixed exponential cutoff at 4.3 TeV (Krennrich et al. 2001). The fits produce acceptable goodness-of-fit (χ^2) values. The shaded areas indicate the systematic errors on the flux measurements.

spectrum hardens with increasing flux, whereas the curvature term shows no significant dependence on flux. In a previous paper (Krennrich et al. 2001) describing the average energy spectrum of Mrk 421 in a high flaring state in 2001, the best fit to the energy spectrum was achieved by using a power law with an exponential cutoff:

$$dN/dE \propto E^{-\alpha} e^{-E/E_0} \text{ m}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}. \quad (1)$$

The results for fits of this form are provided in Table 3 and exhibit acceptable goodness-of-fit values for all spectra. Since the spectral index and cutoff energy E_0 are correlated, we also present the uncertainty of E_0 when accounting for this correlation, as shown in parentheses in Table 3. These uncertainties are the extrema of E_0 of the 1σ error ellipse¹⁷ that result from plotting the minimizing function χ^2 as a function of spectral index α versus cutoff energy E_0 .

Figure 2 shows the derived cutoff energies for the individual data sets (I–VIII) at different flux levels in units of crab. No evidence for variability in the cutoff energy is suggested by the data (the probability for the hypothesis of a fixed cutoff energy is $P = 0.98$). However, it is important to realize that the statistical uncertainties in the cutoff energy are strongly correlated with the spectral index and that the error bars on E_0 are typically of magnitude 1–3 TeV. Therefore, we cannot exclude variability in the cutoff energy at the few TeV level. Instruments that extend to significantly lower energies and provide better sensitivity at higher energies are required to reduce the uncertainties in the cutoff energy. In addition, our measurement of the cutoff energy has systematic uncertainties, e.g., the absolute energy scale, that can also be improved with the

¹⁷ As calculated by MINUIT, Version 94.1, CERN Program Library entry D506. We also compared MINUIT with the method given by Avni (1976) giving consistent results.

TABLE 1
FITS TO THE SPECTRA OF MRK 421: POWER LAW^a

Set	α	χ^2/dof^b
I	2.31 ± 0.04	1.57
II	2.47 ± 0.03	3.70
III	2.43 ± 0.03	5.47
IV	2.48 ± 0.06	3.86
V	2.56 ± 0.05	0.91
VI	2.57 ± 0.04	0.82
VII	2.60 ± 0.06	1.28
VIII	2.95 ± 0.10	0.32

^a $dN/dE \propto E^{-\alpha}$ (in units of $\text{m}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$)

^b Results from the fits for the energy spectra of Mrk 421, using a power law.

next generation of γ -ray instruments (the VERITAS project; Weekes et al. 2002).

Hence, for the remainder of this Letter, we adopt a parameterization (see eq. [2]) with a fixed cutoff energy of $E_0 = 4.3$ TeV, the same cutoff energy that was derived for the average spectrum of Mrk 421 in a high flaring state (Krennrich et al. 2001):

$$dN/dE \propto E^{-\alpha} e^{-E/E_0} \text{ m}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}, \quad (2)$$

with $E_0 = 4.3 \pm 0.3_{\text{stat}} (-1.4 + 1.7)_{\text{syst}}$ TeV.

As can be seen from Table 3, the spectra corresponding to different flux levels are well fitted by this parameterization but show significant variation in the spectral index α . We find that the energy spectra exhibit spectral variability from $\alpha = 1.89 \pm 0.04_{\text{stat}} \pm 0.05_{\text{syst}}$ up to $\alpha = 2.72 \pm 0.11_{\text{stat}} \pm 0.05_{\text{syst}}$. The systematic uncertainties, which are indicated by the shaded areas in Figure 1, have been derived as in Krennrich et al. (2001) by varying cut efficiencies, the angular resolution cut, and the software trigger threshold. In addition, uncertainties due to the method of background matching are included. Other potential sources of systematic uncertainties such as throughput variations (light throughput of the atmosphere, mirror reflectivity, and gain variations of the telescope; S. LeBohec & J. Holder 2002, in preparation), elevation dependence, and a varying signal-to-background ratio have been studied. No systematic dependence of the spectral index with these variables was found.

Figure 3 shows the spectral index as a function of the absolute γ -ray flux in units of crab. Variability of the spectral index is apparent, and therefore the hypothesis that the spectral index is constant can be excluded at the $P = 9.5 \times 10^{-14}$ level. The correlation between spectral index and flux indicates substantial spectral hardening with increasing flux. If we fit the

TABLE 2
FITS TO THE SPECTRA OF MRK 421: POWER LAW WITH CURVATURE

Set	Parabolic ^a α	β	χ^2/dof^b
I	2.22 ± 0.05	0.27 ± 0.10	0.40
II	2.39 ± 0.04	0.34 ± 0.09	1.53
III	2.29 ± 0.04	0.45 ± 0.09	0.91
IV	2.38 ± 0.05	0.45 ± 0.11	1.08
V	2.51 ± 0.06	0.20 ± 0.13	0.63
VI	2.55 ± 0.05	0.13 ± 0.12	0.75
VII	2.53 ± 0.08	0.49 ± 0.21	0.32
VIII	2.95 ± 0.09	-0.16 ± 0.29	0.32

^a $dN/dE \propto E^{-\alpha-\beta \log E}$ (in units of $\text{m}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$).

^b Results from the fits using a power-law fit including curvature.

TABLE 3
 FITS TO ENERGY SPECTRA OF MRK 421 AT VARIOUS FLUX LEVELS IN 2001:
 POWER LAW INCLUDING EXPONENTIAL CUTOFF

Set	Power Law Exp. Cutoff ^a α	E_0 ^b	χ^2/dof^c	Exp. Cutoff (4.3 TeV) ^d α	χ^2/dof^c
I.....	2.07 ± 0.09	$7.89 \pm 2.65^{(+4.1)}_{(-2.1)}$	0.23	1.89 ± 0.04	1.04
II.....	2.20 ± 0.08	$6.18 \pm 1.76^{(+2.4)}_{(-1.5)}$	1.75	2.08 ± 0.04	2.13
III.....	2.02 ± 0.08	$4.40 \pm 0.86^{(+1.0)}_{(-0.8)}$	0.30	2.01 ± 0.04	0.34
IV.....	2.12 ± 0.09	$4.64 \pm 1.27^{(+1.7)}_{(-1.1)}$	1.28	2.10 ± 0.04	1.30
V.....	2.36 ± 0.11	$8.41 \pm 4.61^{(+10.3)}_{(-3.2)}$	0.46	2.19 ± 0.06	0.83
VI.....	2.46 ± 0.09	$15.29 \pm 12.26^{(+100.4)}_{(-7.5)}$	0.71	2.23 ± 0.06	1.69
VII.....	2.22 ± 0.19	$3.77 \pm 2.02^{(+3.4)}_{(-1.4)}$	0.43	2.26 ± 0.07	0.44
VIII.....	2.95 ± 0.10	$25,977 \pm 84,528^{(+10,712)}_{(-50,301)}$	0.38	2.72 ± 0.11	0.81

^a $dN/dE \propto E^{-\alpha} e^{-E/E_0}$ (in units of $\text{m}^{-2} \text{s}^{-1} \text{TeV}^{-1}$).

^b Cutoff energy E_0 (in units of TeV).

^c Results from the fits using a power-law fit with an exponential cutoff.

^d $dN/dE \propto E^{-\alpha} e^{-E/E_0}$ (in units of $\text{m}^{-2} \text{s}^{-1} \text{TeV}^{-1}$); $E_0 = 4.3 \text{ TeV}$ fixed.

spectral index as a function of flux Φ in units of crab with a second-order polynomial, we get

$$\alpha(\Phi) = -2.66(\pm 0.01) + 0.123(\pm 0.030)(\Phi/\text{crab}) - 0.0056(\pm 0.00230)(\Phi/\text{crab})^2,$$

which provides a $\chi^2 = 13.92$ for 5 degrees of freedom (dof; $P = 1.61 \times 10^{-2}$).

4. DISCUSSION

Strong and extended flaring of Mrk 421 allows us to study the spectral variability of this source as a function of flux. Averaged over the time period of 2000 November 28 to 2001 April 13, the data show a clear flux–spectral index correlation, with the spectral index varying between 1.89 ± 0.04 in a high state and 2.72 ± 0.11 in a low state.

Whether or not this correlation is maintained in different epochs outside of the 2000/2001 observing period can be addressed using previously published results and archival data

from the Whipple collaboration. Figure 3 also shows results from the average spectrum in 1995/1996 in a high state (Krennrich et al. 1999a) and the average spectrum from 1999 May 6 through June 8. The data points from 1995/1996 and from 1999 fall into place with the flux–spectral index correlation as observed for the 2000/2001 data alone. This indicates that the correlation between spectral index and flux holds true when averaging over timescales of months to 5 years.

Spectral hardening during flares has also been observed for Mrk 421 in X-rays by Fossati et al. (2000) using *BeppoSAX* data during X-ray flares in 1997 and 1998. In X-rays, the effect of spectral hardening has been interpreted as a shift of the synchrotron peak toward higher frequencies. The flux–spectral index correlation seen in the TeV spectra could also be interpreted as a shift of the high-energy peak toward higher frequencies. The shape of spectrum I in Figure 1 suggests that the peak in νF_ν is at a few hundred GeV, significantly above

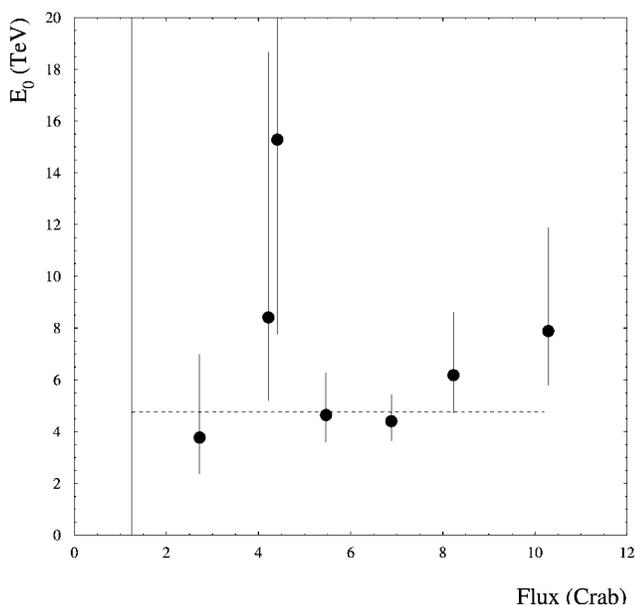


FIG. 2.—Cutoff energy E_0 plotted as a function of flux in units of crab (defined in text) for various flaring states (data sets I–VIII) of the 2000/2001 season. No significant variability of the cutoff energy is seen in the data. Note that the point at the lowest flux level has a large statistical uncertainty so that it is off the plot, only showing its error bar.

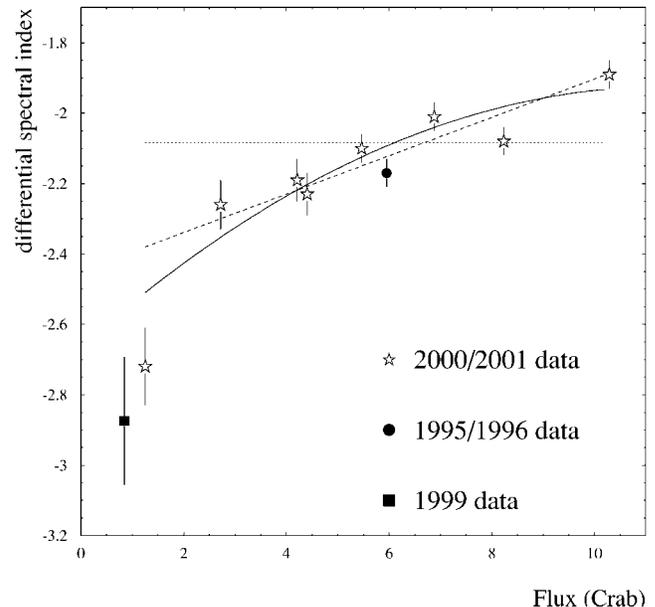


FIG. 3.—Stars showing the spectral index of Mrk 421 as a function of flux (in units of crab) for the 2000–2001 data set. The hypothesis of a constant spectral index (*dotted line*) is rejected, whereas the data are better fitted by a linear relation ($P = 5 \times 10^{-3}$). A second-order polynomial (*solid line*) gives a better but still marginal fit ($P = 1.6 \times 10^{-2}$). In addition, we show results for Whipple 1995/1996 data (*filled circle*) from Krennrich et al. (1999a) and data taken during 1999 May–June (*filled square*).

previous levels (Maraschi et al. 1999). The spectral hardening is most evident at energies below 2 TeV; it is not uniform.

Strong spectral hardening at lower energies might be expected in the IC scenario in which the IC peak shifts toward higher energies as the flux increases. Conversely, at the higher energies, spectral softening occurs as a result of either a terminating particle distribution in energy, the falling cross section due to the Klein-Nishina effect, or external attenuation effects from the EBL or nearby radiation fields. If the changes are due

to a shifting IC peak energy, the flux value would be closely tied to the spectral index, as seen here. Further studies of spectral variability on short timescales (hours to days) will be presented in a follow-up paper.

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