

# THE TeV ENERGY SPECTRUM OF MARKARIAN 501 MEASURED WITH THE STEREOSCOPIC TELESCOPE SYSTEM OF HEGRA DURING 1998 AND 1999

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Received 2000 May 16; accepted 2000 August 7

## ABSTRACT

During 1997, the BL Lac object Mrk 501 went into an extraordinary state of high X-ray and TeV gamma-ray activity, lasting more than 6 months. In this paper we report on the TeV emission characteristics of the source in the subsequent years of 1998 and 1999 as measured with the stereoscopic Cherenkov telescope system of the High-Energy Gamma-Ray Astronomy (HEGRA; La Palma, Canary Islands). Our observations reveal a 1998–1999 mean emission level at 1 TeV of  $\frac{1}{3}$  of the flux of the Crab Nebula, a factor of 10 lower than during the year of 1997. A data set of 122 observation hours with the HEGRA telescope system makes it possible to assess for the first time the Mrk 501 TeV energy spectrum for a mean flux level substantially below that of the Crab Nebula with reasonable statistical accuracy. Excluding the data of a strong flare, we find evidence that the 1998–1999 low-flux spectrum is substantially softer (by  $0.44 \pm 0.1_{\text{stat}}$  in spectral index) than the 1997 time-averaged spectrum. The 500 GeV to  $\approx 10$  TeV energy spectrum can well be described by a power-law model with exponential cutoff:  $dN/dE \propto E^{-\alpha} \exp(-E/E_0)$ , with  $\alpha = 2.31 \pm 0.22_{\text{stat}}$  and  $E_0 = 5.1(^{+7.8}_{-2.3})_{\text{stat}}$  TeV. Within statistical accuracy, a pure power-law model also gives an acceptable fit to the data:  $dN/dE \propto E^{-\Gamma}$ , with  $\Gamma = 2.76 \pm 0.08_{\text{stat}}$ . After presenting the 1998–1999 TeV characteristics of the source, we discuss the implications of the results.

*Subject headings:* BL Lacertae objects: individual (Markarian 501) — galaxies: jets — gamma rays: observations

## 1. INTRODUCTION

During the years of its discovery as a TeV source, the BL Lac object Mrk 501 showed modest integral fluxes: during 1995, about 1/12 of the Crab flux above 300 GeV (Quinn et al. 1996) and during 1996, about one-third of the Crab flux above 1.5 TeV (Bradbury et al. 1997). In the year 1997 the source went into a state of surprisingly high activity in the X-ray (Pian et al. 1998) and TeV energy bands (Samuelson et al. 1998; Aharonian et al. 1999a; Djannati-Atai et al.

1999). During more than 6 months, the source showed a succession of very strong flares with an average differential flux at 1 TeV approximately 3 times higher than the flux of the Crab Nebula.

The extraordinary high TeV emission level as well as the significant improvement of detectors and analysis methods made it possible to study the temporal and spectral TeV characteristics of a BL Lac object with unprecedented detail. The measurements with the stereoscopic Cherenkov telescope system of the High-Energy Gamma-Ray Astronomy (HEGRA) revealed that while the TeV flux varied by factors of up to 30, the TeV spectrum remained surprisingly stable. With a typical statistical accuracy ( $1\sigma$ ) of the diurnal spectral indices between 0.1 and 0.3, no spectral variability could be ascertained with a statistical significance exceeding  $3\sigma$  (Aharonian et al. 1999a). Furthermore, dividing the data into groups according to the flux level at 2 TeV did not reveal any evidence for a flux-hardness correlation (statistical accuracy of the 1–10 TeV spectral indices  $\lesssim 0.05$ ).

The excellent gamma-ray statistics combined with the 20% energy resolution of the HEGRA instrument resulted in the first detection of gamma rays from an extragalactic source well beyond 10 TeV and the first high-accuracy measurement of an exponential cutoff in the energy region above 5 TeV, well into the exponential regime (Aharonian

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et al. 1999b). From 500 GeV to  $\approx 20$  TeV, the differential photon spectrum could be approximated by a power law with an exponential cutoff:

$$dN/dE = N_0(E/1 \text{ TeV})^{-\alpha} \exp(-E/E_0), \quad (1)$$

with  $N_0 = (108 \pm 2_{\text{stat}} \pm 2.1_{\text{syst}}) \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$ ,  $\alpha = 1.92 \pm 0.03_{\text{stat}} \pm 0.20_{\text{syst}}$ , and  $E_0 = 6.2 \pm 0.4_{\text{stat}} (+2.9_{\text{syst}}) \text{ TeV}$ .

Note that the stability of the 1997 TeV spectrum has been a matter of debate. The Cherenkov Array at Themis (CAT) group reported evidence for a flux-hardness correlation in their 1997 Mrk 501 data set: the spectrum of the 3 days with maximum greater than 250 GeV flux in their data set seemed to be harder than the spectrum during the rest of the 1997 observations on a statistically significant level, although they did not report an estimate of the systematic uncertainty in this result (Djannati-Atai et al. 1999). The apparent contradiction between the HEGRA and CAT results could be explained by the following two facts: (1) since the CAT flux-hardness correlation stems from the energy range below 1 TeV while the HEGRA constraints on the correlation are strongest at energies above 1 TeV, the results could indicate a stronger flux-hardness correlation below 1 TeV than above 1 TeV (Djannati-Atai et al. 1999); and (2) since the evidence for the flux-hardness correlation is based on the detection of a harder spectrum for a small number of observation nights (3 nights), it could well be that the flux-hardness relation found for these days does not represent the behavior of the source during the full 1997 flaring phase. While there are no HEGRA observations for the strongest flare in the CAT data sample (1997 April 16), the HEGRA data of the day with the second highest TeV emission in the CAT data sample (1997 April 13) also indicated a harder than average spectrum: the 1–5 TeV photon index of  $1.87 \pm 0.14_{\text{stat}}$  deviated by  $2.7 \sigma$  from the 1997 mean photon index of 2.25 (Aharonian et al. 1999a). Therefore, a harder than average spectrum for at least 2 of the 3 CAT nights is consistent with the HEGRA observations even if the spectrum hardened as much above 1 TeV as it did below 1 TeV. Note that the HEGRA observations of several later 1997 flares with comparable and higher flux levels than that of April 13 did not show such a trend of spectral hardening.

In this paper we present HEGRA observations of Mrk 501 during the years 1998 and 1999 and show how the energy spectrum evolved in the years following the 1997 flaring phase. After describing the telescope system as well as the data set in § 2, we report on the 1998 and 1999 Mrk 501 light curve and energy spectrum in § 3. In § 4 we discuss possible implications of the results.

## 2. THE HEGRA CHERENKOV TELESCOPE SYSTEM AND THE DATA SAMPLE

The HEGRA collaboration operates six imaging atmospheric Cherenkov telescopes located on the Roque de los Muchachos on the Canary Island of La Palma, at 2200 m above sea level. In this paper we present the 1998–1999 Mrk 501 data taken with the HEGRA Cherenkov telescope system (Konopelko et al. 1999a). The system consists of five telescopes (CT2–CT6) that are operated as a single detector for the stereoscopic detection of air showers induced by primary gamma rays in the atmosphere. The telescope system has been taking data since 1996, initially with three

and later four telescopes, and since fall 1998 as a complete five-telescope system. With an energy threshold of 500 GeV, the telescope system achieves an angular resolution of  $0.1^\circ$  and an energy resolution of 20% for individual photons, as well as an approximate energy flux sensitivity  $\nu F_\nu$  at 1 TeV of  $10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1}$  ( $S/N = 5 \sigma$ ) for 1 hr of observation time. Note that most of the data presented in this paper were taken with the four-telescope system. The telescope CT2 was undergoing significant hardware modifications. The results presented in the following are based on 126 hr of data acquired between 1998 February 28 and 1999 July 7 with Mrk 501 altitudes above  $60^\circ$ . The search of intraday flux variability makes use of an additional 27 hr of data with Mrk 501 altitudes between  $45^\circ$  and  $60^\circ$ . The standard data quality criteria, analysis tools, and “loose” selection cuts for spectral studies described in detail in Aharonian et al. (1999a, 1999b) were applied.

## 3. EXPERIMENTAL RESULTS

Figure 1 shows the diurnal averages of the Mrk 501 integral fluxes above 1 TeV as measured during 1998 and 1999. Compared to 1997, when diurnal averages of up to  $\approx 178 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$  (corresponding to 10 crab units; 1 crab unit equals  $17.5 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ ) and a mean greater than 1 TeV integral flux of  $64 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$  (3.7 crab units) were observed, a striking decrease in flaring activity can clearly be recognized. Only one flare with a peak flux substantially surpassing the flux level of the Crab Nebula was detected, on 1998 June 26/27 (MJD 50,991) and June

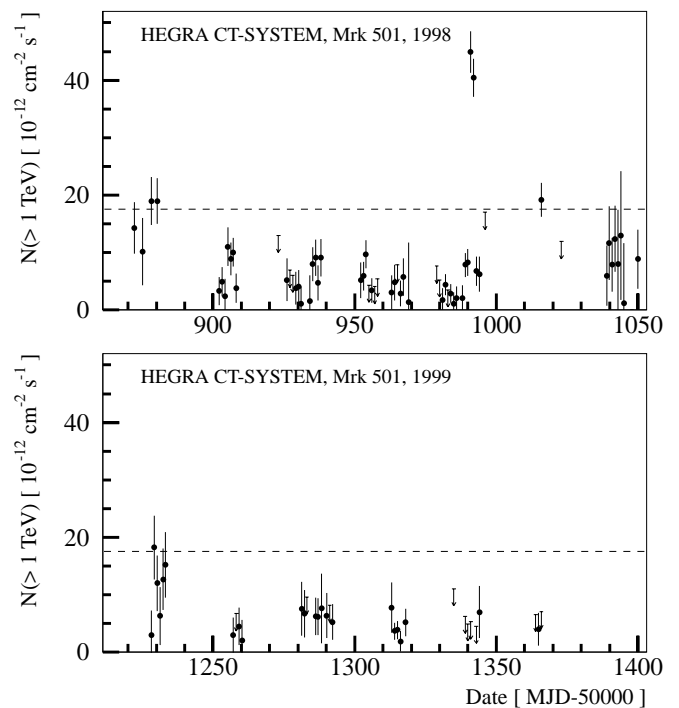


FIG. 1.—The 1998 and 1999 light curves of Mrk 501 as measured with the HEGRA telescope system. Dashed line indicates the steady emission level of the Crab Nebula. Each data point is a diurnal average. Note that during 1997 the source reached greater than 1 TeV integral flux levels of about 10 crab units: HEGRA detected a maximum flux of  $(178 \pm 10_{\text{stat}}) \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$  on 1997 June 26. The 1997 mean greater than 1 TeV flux level was  $64 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$  (3.7 crab units). Upper limits are given at the  $2 \sigma$  confidence level.

27/28 (MJD 50,992). The mean greater than 1 TeV integral flux of the 1998–1999 data sample without the 1998 June flare was  $(4.8 \pm 0.3_{\text{stat}}) \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ , a factor of 13 lower than that of 1997.

The 1998 June flare and the correlated X-ray activity have been discussed in detail by Sambruna et al. (2000). For the day of maximum emission, June 26/27, we found evidence on the 99.4% confidence level that the flux increased and decreased by a factor of 2 within a time interval of 1 hr. The spectrum of the 2 days with maximum emission seemed to be softer than that of the 1997 observations, but the difference was not statistically significant. A fit of a power law with an exponential cutoff yielded the parameters [see eq. (1)]  $N_0 = (79 \pm 10_{\text{stat}}) \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$ ,  $\alpha = 1.92 \pm 0.30_{\text{stat}}$ , and  $E_0 = 4.0^{+1.45}_{-0.90}_{\text{stat}} \text{ TeV}$ . For the remaining days of the 1998–1999 observations, we did not find additional evidence for intraday variability. For the typical diurnal observation times of about 1.5 hr, the  $2\sigma$  (S/N) flux sensitivity threshold was approximately one-sixth of the Crab flux. For 36% (63%) of the days with observations, we found an excess with more than  $2\sigma$  ( $1\sigma$ ) statistical significance. For 12% of the nights, the Mrk 501 flux was clearly below the sensitivity threshold for diurnal observations, and an event deficit rather than an event excess was found in the signal region.

We determined a “low-flux” TeV energy spectrum of Mrk 501 by analyzing 122 hr of 1998–1999 data, excluding the 4 hr of data taken during the 1998 flare. Here we combine data of the two years to increase the statistical accuracy of the resulting spectrum. Analyzing the two years independently yields a very similar fitted mean flux at 1 TeV for both data sets and, within the large statistical errors, no significant difference in spectral shape. The 1998–1999 low-flux spectrum combined with the results of the fits discussed in the following are shown in Figure 2.

A fit of a power-law model with an exponential cutoff yields the parameter values [see eq. (1)]  $N_0 = (10.1 \pm 1.9_{\text{stat}}) \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$ ,  $\alpha = 2.31 \pm 0.22_{\text{stat}}$ , and  $E_0 = 5.1^{+7.8}_{-2.3}_{\text{stat}} \text{ TeV}$ , with a reduced  $\chi^2$  value of 0.71 for 13 degrees of freedom (dof) (the negative flux estimates corresponding to the flux upper limits in Fig. 2 are included in the fit). Within statistical errors, a pure power-law model

$$dN/dE = N_0(E/1 \text{ TeV})^{-\Gamma} \quad (2)$$

also yields an acceptable fit, with  $N_0 = (8.4 \pm 0.5_{\text{stat}}) \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$ ,  $\Gamma = 2.76 \pm 0.08$ , and a slightly larger reduced  $\chi^2$  value of 0.92 for 14 dof. The systematic error in the absolute flux is 25%, due to uncertainty in the absolute energy scale. Systematic uncertainty in the shape of the spectrum is relevant only for energies below 1 TeV

and corresponds to an uncertainty of a power-law spectral index of 0.05 (see the shaded area in Fig. 2). The results of the fits to the Mrk 501 spectra are summarized in Table 1.

The fit results indicate that the 1998–1999 low-flux spectrum is softer than the 1997 time-averaged spectrum. The parameterization of equation (1) is not suited to assessing the statistical significance of the spectral steepening since the fit parameters  $\alpha$  and  $E_0$  are strongly correlated and hence the statistical errors in both parameters are large. A fit to the ratio of the two spectra shows that indeed the spectrum softened significantly:  $(dN/dE)_{(1998-1999 \text{ low-flux})}/(dN/dE)_{(1997)} \propto E^\gamma$ , with  $\gamma = -0.44 \pm 0.10_{\text{stat}}$ . The systematic error  $\Delta\gamma_{\text{syst}}$  in the change in spectral index from year to year is smaller than the error in the shape of individual spectra since several contributions to the systematic error affect all measured spectra in the same way. We estimate that  $\Delta\gamma_{\text{syst}} \lesssim 0.05$ ; i.e., it is smaller than the statistical error in  $\gamma$  of 0.1. This latter conclusion is substantiated by observations of the persistent TeV-emitter Crab Nebula (Aharonian et al. 2000). The spectral index determined for

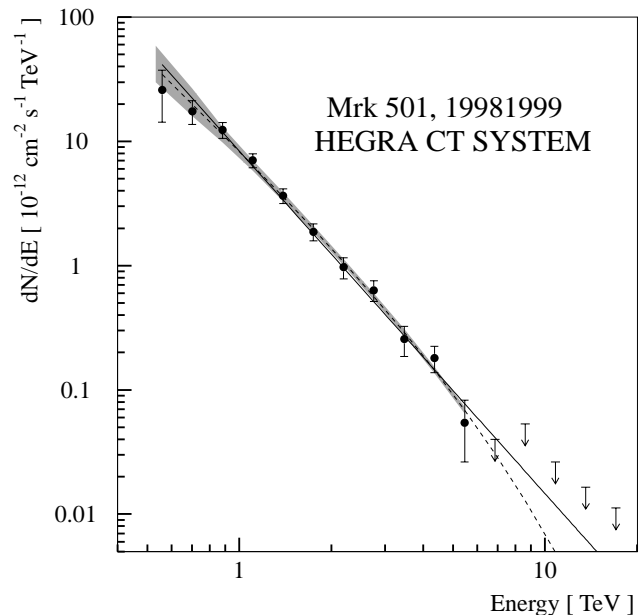


FIG. 2.—Figure shows the 1998–1999 low-flux spectrum measured with the HEGRA telescope system. Systematic error in the curvature of the spectrum is given by the shaded region. The additional uncertainty of 15% in the absolute energy scale is not shown here. Solid and dashed lines give the fit results of a pure power-law model and a power-law plus exponential cutoff model, respectively (see text). Upper limits are given at the  $2\sigma$  confidence level.

TABLE 1  
RESULTS OF MRK 501 SPECTRAL FITS

Data Sample	$N_0^{a,b}$	$\Gamma^a$	$\alpha^a$	$E_0^a$	$\chi^2/\text{dof}$
1997 .....	$108 \pm 2$	...	$1.92 \pm 0.03$	$6.2 \pm 0.4$	1.66/14
1998 June flare .....	$79 \pm 10$	...	$1.92 \pm 0.30$	$4.0^{+1.45}_{-0.90}$	0.54/13
1998–1999 low-flux .....	$8.4 \pm 0.5$	$2.76 \pm 0.08$	...	...	0.92/14
	$10.1 \pm 1.9$	...	$2.31 \pm 0.22$	$5.1^{+7.8}_{-2.3}$	0.71/13

NOTE.—Statistical errors only. See text for systematic errors.

<sup>a</sup> Model parameters of eqs. (1) and (2).

<sup>b</sup> Flux normalization constant in units of  $10^{-12} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$ .

the two Crab observation periods 1997–1998 and 1998–1999 differs by only  $0.02 \pm 0.07_{\text{stat}}$ . Given the statistical errors on the low-flux spectrum, it is not possible to decide which one of the two parameters,  $E_0$  or  $\alpha$ , actually changed. Fixing  $E_0$  to the 1997 value of 6.2 TeV gives a 1998–1999 photon index of  $\alpha = 2.36 \pm 0.10_{\text{stat}}$ , i.e., a value 0.44 softer than that of the 1997 energy spectrum. Fixing  $\alpha$  to the 1997 value of 1.92 gives a 1998–1999 high-energy cutoff of  $E_0 = (2.61^{+0.44}_{-0.38})_{\text{stat}}$  TeV, i.e., a value reduced by 3.6 TeV compared to the 1997 data.

The upper panel of Figure 3 compares the spectral energy distributions as measured during 1997, during the 1998 flare, and during the 1998–1999 low-flux phases. The results of the  $dN/dE \propto E^{-\alpha} \exp(-E/E_0)$  fits to the data are shown by the solid lines and the fitted spectral shapes for the 1997 data and 1998 flare data are compared to that of the 1998–1999 low-flux data by the dashed and dotted lines, respectively. The lower two panels of Figure 3 show the ratios of the 1998–1999 low-flux spectrum and the 1997 spectrum and 1998 flare spectrum, respectively. While the 1998–1999 low-flux spectrum is significantly softer than the 1997 spectrum, its shape does not differ significantly from the 1998 flare spectrum: the fit of a power law to the flux ratio gives

$$(dN/dE)(1998-1999 \text{ low-flux})/(dN/dE)(1998 \text{ June flare}) \propto E^\gamma, \text{ with } \gamma = -0.21 \pm 0.12_{\text{stat}}.$$

#### 4. DISCUSSION

In this paper we present the TeV characteristics of Mrk 501 in the years of 1998–1999 following the major 1997 outburst phase. We assess for the first time the TeV energy spectrum of the source for a mean flux at 1 TeV well below the flux of the Crab Nebula. This spectrum complements the high-flux spectra measured so far in the sense that the Mrk 501 spectrum has now been determined for flux levels between 1/3 crab units (this paper) and  $\simeq 10$  crab units (Aharonian et al. 1999a). Although the 1997 spectra were determined for a range of absolute fluxes differing by more than a factor of 5 (yet at 1 TeV by a factor of at least 2 higher compared with the flux of the 1998–1999 low-flux data sample), we did not detect any evidence for spectral variability. In contrast we find evidence that the 1998–1999 low-flux spectrum is substantially softer (0.44 in spectral index) than the 1997 spectra.

The synchrotron self-Compton (SSC) mechanism is widely believed to be responsible for the nonthermal X-ray and TeV gamma-ray emission in BL Lac objects (Ulrich, Maraschi, & Urry 1997). A high-energy population of electrons embedded in a relativistic jet approaching the observer with a speed close to the speed of light emits X-rays as synchrotron radiation and TeV gamma-rays as inverse Compton radiation resulting from interactions of electrons with lower energy synchrotron photons. The recent observations of X-ray and TeV gamma-ray flares correlated to within less than half a day for Mrk 501 (Krawczynski et al. 2000) as well as for the other well-studied TeV-emitting BL Lac object, Mrk 421 (Maraschi et al. 1999; Takahashi, Madejski, & Kubo 1999), are naturally explained in the SSC scenario and strongly support this model. More detailed theoretical work is needed to decide whether the multiwavelength data could reasonably be described with alternative models assuming that the nonthermal emission of Mrk 501 is produced by hadronic interactions of a highly relativistic outflow that sweeps up ambient matter (Pohl & Schlickeiser 2000), by interactions of high-energy protons with gas clouds moving across the jet (Dar & Laor 1997), or by interactions of extremely high energy protons with ambient photons (Mannheim 1998), with the magnetic field (Aharonian 2000), or with both (Mücke & Protheroe 2000). Note that in the proton-synchrotron model, the stable spectral shape is explained by the self-regulated synchrotron cutoff, while steepening in the low-flux state could be explained by the drop of the acceleration rate of protons (Aharonian 2000). While the interpretation of TeV gamma-ray spectra is hampered by the unknown modification of the spectrum due to intergalactic extinction, as discussed, e.g., by Aharonian et al. (1999b), the temporal evolution of the gamma-ray flux and the spectral shape is free of this uncertainty and should be explained by models of the origin of the TeV radiation.

Assuming for the time being that the mechanism responsible for the X-ray and TeV gamma-ray emission has been identified, a next step concerns the understanding of how the emission region(s) is (are) embedded in the jet, how an emission region evolves with time, and where the energy that is ultimately converted into the observed nonthermal X-ray and gamma-ray radiation comes from. Within SSC models, the stability of the TeV energy spectrum during the

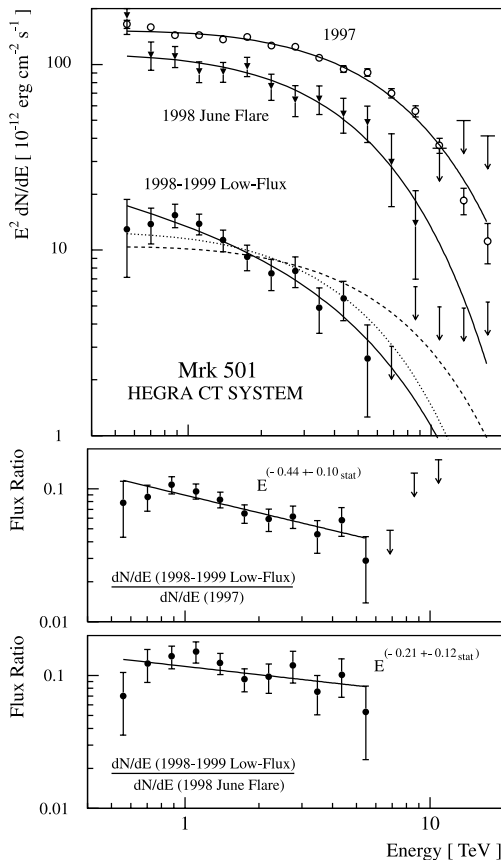


FIG. 3.—Upper panel shows the spectral energy distributions measured during 1997, the 1998 flare, and the 1998–1999 low-flux period. Solid lines show the fit results  $dN/dE \propto E^{-\alpha} \exp(-E/E_0)$ , with the pairs  $(\alpha, E_0)$  of (1.9, 6.2 TeV) for 1997, (1.9, 4.0 TeV) for 1998 flare, and (2.3, 5.1 TeV) for 1998–1999 low-flux data samples. Dashed and dotted lines show the shapes of 1997 spectrum and 1998 flare spectrum overlaid on the 1998–1999 low-flux spectrum. Lower two panels show the ratios  $r(E)$  of the 1998–1999 low-flux and the 1997 and 1998 flare spectra, respectively, as well as the results of power-law fits  $r(E) \propto E^\gamma$ . All upper limits are given at the  $2\sigma$  confidence level.

1997 flares can be explained by a spectrum of accelerated electrons (and possibly positrons) that is stable throughout the whole flaring phase (Aharonian et al. 1999a; Konopelko et al. 1999b; Krawczynski et al. 2000). The steepening of the TeV energy spectrum reported in this paper can be accounted for by, e.g., (1) a steepening of the spectrum of accelerated particles streaming into the emission region; (2) the shift of the break in the electron spectrum (caused by the synchrotron and inverse Compton cooling of the electrons or by a lower energy cutoff of the spectrum of accelerated particles) toward lower energies; or (3) a shift of the maximum energy of accelerated particles toward lower energies. Detailed modeling of the now available very detailed multiwavelength data on Mrk 501 as given, e.g., by Pian et al. (1998), Djannati-Atai et al. (1999), Krawczynski

et al. (2000), and Sambruna et al. (2000) should make it possible to identify the origin of the spectral curvature observed at X-ray and TeV energies during 1997 and to determine which properties of the emission region(s) changed from 1997 to 1998–1999.

The support of the German Ministry for Research and Technology BMBF and of the Spanish Research Council CYCIT is gratefully acknowledged. G. P. R. acknowledges receipt of a Humboldt fellowship. We thank the Instituto de Astrofísica de Canarias for the use of the site and for supplying excellent working conditions at La Palma. We gratefully acknowledge the technical support staff of the Heidelberg, Kiel, Munich, and Yerevan Institutes.

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