Correlated intense X-ray and TeV activity of Mrk 501 in 1998 June

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ABSTRACT

We present exactly simultaneous X-ray and TeV monitoring with RXTE and HEGRA of the TeV blazar Mrk 501 during 15 days in 1998 June. After an initial period of very low flux at both wavelengths, the source underwent a remarkable flare in the TeV and X-ray energy bands, lasting for about six days and with a larger amplitude at TeV energies than in the X-ray band. At the peak of the TeV flare, rapid TeV flux variability on sub-hour timescales is found. Large spectral variations are observed at X-rays, with

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the 3–20 keV photon index of a pure power law continuum flattening from $\Gamma = 2.3$ to $\Gamma = 1.8$ on a timescale of 2–3 days. This implies that during the maximum of the TeV activity, the synchrotron peak shifted to energies $\gtrsim 50$ keV, a behavior similar to that observed during the longer-lasting, more intense flare in 1997 April. The TeV spectrum during the flare is described by a power law with photon index $\Gamma = 1.9$ and an exponential cutoff at $\sim 4$ TeV; an indication for spectral softening during the flare decay is observed in the TeV hardness ratios. Our results generally support a scenario where the TeV photons are emitted via inverse Compton scattering of ambient seed photons by the same electron population responsible for the synchrotron X-rays. The simultaneous spectral energy distributions (SEDs) can be fit with a one-zone synchrotron-self Compton model assuming a substantial increase of the magnetic field and the electron energy by a factor of 3 and 10, respectively.

**Subject Headings:** Galaxies:jets – X-rays:galaxies – Radiation mechanisms:non-thermal – BL Lacertae objects:Mrk 501 — Gamma rays:observations.

1. Introduction

BL Lacertae objects (BL Lacs) are radio-loud AGN dominated by non-thermal continuum emission from radio up to $\gamma$-rays (MeV to TeV energies) from a relativistic jet oriented at small angles to the observer (e.g., Urry & Padovani 1995). While the radio through UV/X-ray continuum is almost certainly due to synchrotron emission from relativistic electrons in the jet (Ulrich, Maraschi, & Urry 1997 and references therein), the origin of the luminous $\gamma$-ray radiation from BL Lacs is still uncertain. Possibilities include inverse Compton scattering of ambient photons off the jet electrons (Maraschi et al. 1992; Sikora, Begelman, & Rees 1994; Dermer et al. 1996), or hadronic processes (e.g. Dar & Laor 1997; Mannheim 1993).

A breakthrough was provided by the discovery of TeV emission from a handful of such sources, all characterized by a synchrotron peak at higher energies (High-energy peaked BL Lacs, or HBLs). One of these is Mrk 501 ($z=0.034$). This source came into much attention after it exhibited a prolonged period of intense TeV activity in 1997 (Catanese et al. 1997; Hayashida et al. 1998; Quinn et al. 1999; Aharonian et al. 1997,1999a-c; Djannati-Atai et al. 1999), accompanied by correlated X-ray emission on timescales of days. Interestingly, this exceptional TeV activity was accompanied by unusually hard X-ray emission up to $\gtrsim 100$ keV (Pian et al. 1998a; Catanese et al. 1997; Lamer & Wagner 1999; Krawczynski et al. 1999), unprecedented in this or any other BL Lac. The hard X-ray spectrum implied a shift toward higher energies of the synchrotron peak, usually located at UV/soft X-rays (e.g., Sambruna, Maraschi, & Urry 1996; Kataoka et al. 1999), by more than three decades, persistent over a timescale of $\sim 10$ days (Pian et al. 1998a). Further observations with *BeppoSAX* in April-May 1998 and in May 1999 during periods of TeV lower flux showed that the synchrotron peak had decreased to $\sim 20$ and 0.5 keV, respectively (Pian et al.
1998b, 1999). These secular variations of the synchrotron peak suggest a powerful mechanism of particle energization, operating over timescales of years.

Because of its bright TeV emission and unusual X-ray spectral properties, we selected Mrk 501 for an intensive monitoring in 1998 June using HEGRA and the Rossi X-ray Timing Explorer (RXTE), with a sampling designed to probe correlated variability at the two wavelengths on timescales of one day or shorter. Here we report the first results of the campaign, which is characterized by the detection of a strong flare at both TeV and X-ray energies after a period of very low activity. The structure of this paper is as follows. We describe the sampling and the observations in § 2, the X-ray and TeV light curves in § 3.1, and the TeV and X-ray spectra in §§ 3.2–3.3. Implications of the data are discussed in § 4.

2. Sampling and Data Analysis

The RXTE observations of Mrk 501 started June 14 and ended June 28, with a sampling of once per day. The exposure time, typically 2–7 ks during the first week of observations (as allowed by visibility), decreased to 0.5–1 ks during the latest period of the campaign, due to reduced visibility constraints. The total exposure in 1998 June was 45,184 s. The remaining 134 ks of the total allocated exposure were re-scheduled in 1998 July and August; these data will be presented in a future publication, together with simultaneous observations at longer wavelengths (Sambruna et al. 2000). The HEGRA observations started one day earlier and ended three days later than RXTE, with typical integration times of 1.5–2 hours per night, covering 100% of the RXTE exposure.

2.1. X-ray observations

The RXTE data were collected in the 2–60 keV band with the Proportional Counter Array (PCA; Jahoda et al. 1996) and in the 15–250 keV band with the High-Energy X-ray Timing Experiment (HEXTE; Rothschild et al. 1998). For the best signal-to-noise ratio, Standard-2 mode PCA data gathered with the top layer of the operating PCUs 0, 1, and 2 were analyzed. The data were extracted using the script REX which adopts standard screening criteria; the net exposure after screening in each Good Time Interval ranges from 0.2 to 6 ks (Table 2; see below). The background was evaluated using models and calibration files provided by the RXTE GOF for a “faint” source (less than 40 c/s/PCU), using pcabackest v.2.1b. Light curves were extracted in various energy ranges to study the energy-dependence of the flux variability; for simplicity, only the light curves in 2–4 keV and 10–20 keV (at the two extrema of the total energy range of the PCA) will be shown here.

The HEXTE data were extracted from both clusters for the same time periods as the PCA. Due to the weak nature of the hard X-ray flux, the data were combined into pre-flare (MJD 50980–988) and flare (MJD 50989–993) time intervals. In addition, the flare interval was further subdivided
into the rising portion (MJD 50989–990) and the rest of the flare containing the peak intensity. The source signal is detected to about 50 keV, and we present results from these average spectra only.

Response matrices for the PCA data were created with **PCARMF** v.3.5. Spectral analysis of the PCA and HEXTE data was performed within **XSPEC** v.10.0, using the latest released versions of the spectral response files. The fits were performed in the energy ranges 3–20 keV and 20–250 keV, where the calibrations are best known. The quoted uncertainties on the spectral parameters are 90% confidence for one parameter of interest ($\Delta \chi^2 = 2.7$).

### 2.2. TeV observations

The HEGRA Cherenkov telescope system (Daum et al. 1997; Konopelko et al. 1999) is located on the Roque de los Muchachos on the Canary Island of La Palma (lat. 28.8° N, long. 17.9° W, 2200 m a.s.l.). The Mrk 501 observations described in this paper were taken from June 14th, 1998 to July 3rd, 1998 and comprise 49 hours of best quality data. The analysis tools, the procedure of data cleaning and fine tuning of the Monte Carlo simulations, as well as the estimate of the systematic errors on the differential $\gamma$-ray energy spectra, were discussed in detail by Aharonian et al. (1999a,b).

The analysis uses the standard “loose” $\gamma$/hadron separation cuts which minimize systematic errors on flux and spectral estimates rather than yielding the optimal signal-to-noise ratio. A software requirement of two IACTs within 200 m from the shower axis, each with more than 40 photoelectrons per image and a “distance” parameter of smaller than 1.7° was used. Additionally, only events with a minimal stereo angle larger than 20° were admitted to the analysis. Integral fluxes above a certain energy threshold were obtained by integrating the differential energy spectra above the threshold energy, rather than by simply scaling detection rates. By this means integral fluxes were computed without assuming a certain source energy spectrum. For data runs during which the weather or the detector performance caused a Cosmic Ray detection rate deviating only slightly, i.e. less than 15% from the expectation value, the $\gamma$-ray detection rates and spectra were corrected accordingly. Spectral results above an energy threshold of 500 GeV were derived from the data of zenith angles smaller than 30° (39 hours of data). The determination of the diurnal integral flux estimates and the search for variability within individual nights use all data.

### 3. Results

#### 3.1. Light curves

Figure 1 shows the HEGRA and energy-dependent **RXTE** light curves re-binned on 1 day and 5408 s (~ one orbit), respectively. The PCA light curves were accumulated in the energy ranges
2–4 keV and 10–20 keV; for an assumed spectrum with a typical $\Gamma_{3–20 \text{ keV}} = 2.3$ (see below), their effective energies are 3 keV and 16 keV, respectively (not significantly dependent on the slope).

After a period of very low activity at both TeV and X-rays, a strong flare is apparent at all energies starting on day MJD 50989 and ending on day MJD 50994. At TeV energies, the flare has a broad base, lasting approximately six days, with a narrow “core” superposed, lasting two days (MJD 50991–992), and a total max/min amplitude of a factor $\sim 20$. The X-rays track well the structure of the TeV flare, although with lower amplitudes (factor 4 and 2 at hard and soft X-rays, respectively). A correlation analysis using both the Discrete Correlation Function and Modified Mean Deviation methods (Edelson & Krolik 1989; Hufnagel & Bregman 1992) confirm that there are no lags between the TeV and X-ray light curves, or between the soft and hard X-rays, larger than one day.

To explore correlations on short timescales, we examined light curves binned at 900 s in TeV and 300 s at X-rays (the best compromise between time resolution and adequate signal-to-noise ratio in both cases). Figure 2 shows the TeV and X-ray light curves for the day of the peak activity, i.e., MJD 50991, when intra-hour variability at TeV energies was detected. The TeV flux varied by a factor $\sim 2$, with the hypothesis of constant flux rejected at 99.4% confidence level according to the $\chi^2$ test. The doubling timescale of the TeV flux is well below 1 hour (approximately 20 min); to our knowledge, this is the shortest flux variability timescale found for Mrk 501 so far (e.g., Quinn et al. 1999), and comparable to Mrk 421 (Gaidos et al. 1996). Unfortunately, as Figure 2 shows, gaps in the RXTE sampling prevent us from commenting on sub-hour correlated variability at X-rays.

A very rapid X-ray flare, with an increase of the 2–10 keV flux by 60% in $< 600$ s, was recently detected from Mrk 501 with RXTE in 1998 May (Catanese & Sambruna 2000). This result, together with our evidence for fast TeV variability, shows that Mrk 501 can vary on the fastest timescales at both X-ray and TeV wavelengths as other TeV sources (Mrk 421; Maraschi et al. 1999), and calls for future dense X-ray/TeV monitorings, aimed at probing correlated variability on the shortest accessible timescales.

### 3.2. Simultaneous TeV and X-ray spectra

Because of the sampling, we are able to derive truly simultaneous X-ray and TeV spectra during the pre-flare and the flare states. The high-state spectra were accumulated during the days of maximum TeV activity, MJD 50991–992, while the pre-flare spectra were accumulated in the time interval MJD 50979–990. Table 1 reports the results of the spectral fitting of the simultaneous TeV and X-ray spectra, while the data are shown in Figure 3.

The HEGRA spectrum during the flare state was fitted over the energy range from 500 GeV to 20 TeV (above 10 TeV the evidence for emission is only marginal) with a power law plus an exponential cutoff, $\frac{dN}{dE} = N_0 \times \left(\frac{E}{\text{TeV}}\right)^{-\Gamma} \times e^{\left(-E/E_0\right)}$, with spectral parameters reported in Table 1 (with statistical uncertainties). The parameters $E_0$ and $\Gamma$ are strongly correlated: within
systematic errors the pairs of parameters \((\Gamma = 1.7; \ E_0 = 2.8 \ \text{TeV})\) and \((\Gamma = 2.2; \ E_0 = 6.6 \ \text{TeV})\) are also consistent with the data. Note that the spectral parameters we measure for the 1998 June outburst, i.e., a slope \(\Gamma = 1.9\) and cutoff energy \(E_0 = 4 \ \text{TeV}\), are very similar to those measured during the 1997 flaring phase (Aharonian et al. 1999a). For the pre-flare phase, the TeV-flux was too low to allow us to fit a power law model with an exponential cutoff (Table 1). A fit of a power law model to the ratio of the flare and the pre-flare spectra gives \((dN/dE)_{\text{flare}}/(dN/dE)_{\text{pre-flare}} \propto E^\beta\) with \(\beta = -0.17 \pm 0.19\), consistent within statistics with no spectral evolution.

The PCA spectra were fitted with a single power law with Galactic absorption, \(1.73 \times 10^{20} \ \text{cm}^{-2}\) (Elvis, Lockman, & Wilkes 1989). As can be seen from Table 1, this model provides an excellent fit to the X-ray spectra up to 20 keV, with the photon index flattening from \(\Gamma_{3-20 \ \text{keV}} = 2.21\) during the pre-flare state to \(\Gamma_{3-20 \ \text{keV}} = 1.89\) during the flare. No spectral breaks are required, i.e., there is no statistical improvement when a second power law is added to the fit. However, we can not exclude the presence of a spectral break at energies softer than sampled with the PCA, \(\sim 1-2 \ \text{keV}\), as indeed detected with BeppoSAX (Pian et al. 1998a).

The HEXTE data are fitted by a power law with a photon index consistent with the extrapolation of the PCA slope in both high and low states (Table 1). Indeed, fitting the PCA and HEXTE datasets together, we find that a single power law with a slope similar to the PCA slope describes well the 3–50 keV continuum during both the pre-flare and flare epochs. Given the large uncertainties of the HEXTE data, however, we can not rule out the presence of spectral breaks at energies \(\gtrsim 10-20 \ \text{keV}\), as indeed detected by BeppoSAX (Pian et al. 1998a,b).

3.3. X-ray and TeV spectral variability

We accumulated time-resolved PCA spectra for each data point of the X-ray light curves in Figure 1, and fitted them over the energy range 3–20 keV with a single power law plus Galactic absorption. The results of the fitting are reported in Table 2 (columns 3–5), together with the date of the spectrum (column 1) and its net exposure (column 2). The time progression of the PCA slope is plotted in Figure 1, intermediate panel. Large variability is readily apparent, with the photon index flattening from \(\Gamma_{3-20 \ \text{keV}} \sim 2.3\) to \(\Gamma_{3-20 \ \text{keV}} \sim 1.8\) with increasing flux. There is an indication that the X-ray continuum steepens during the decay stage of the flare.

The X-ray spectral variations follow a well-defined pattern with the intensity. This is illustrated in Figure 4, where the 3–20 keV photon index is plotted versus the 2–10 keV flux. The dotted lines mark the time progression of the slope during the flaring activity, and clearly show a “clock-wise” loop. This is similar to what was observed in other HBLs (PKS 2005–489, Perlman et al. 1999; PKS 2155–304, Sembay et al. 1992, Sambruna 1999; Mrk 421, Takahashi et al. 1996) and can be interpreted in terms of cooling of the synchrotron-emitting electrons in the jet (Kirk, Riegler, & Mastichiadis 1998).

The HEXTE spectrum accumulated at the beginning of the flare (see § 2) is fitted by a power
law with slope $\Gamma_{20-50 \text{ keV}} = 2.19 \pm 0.59$ and 20–50 keV flux $F_{20-50 \text{ keV}} = (5.3 \pm 1.6) \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$. During the peak and decreasing flare, $\Gamma_{20-50 \text{ keV}} = 1.86 \pm 0.28$ and $F_{20-50 \text{ keV}} = (1.1 \pm 0.2) \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$. Comparing to the pre-flare flux from Table 1, the source brightened by a factor $\sim 6$ during the TeV flare in the HEXTE band, with an indication of a hardening of the 20–50 keV continuum.

At TeV energies, given the limited signal-to-noise ratio in the pre-flare state, we investigated spectral variations by constructing hardness ratios. These are defined as the ratios of the flux in 2–9.7 TeV to the flux in 0.8–2 TeV (the lower bound is chosen to assure negligible systematic errors due to threshold effects and 2 TeV approximately equals the median energy of photons with energies above 0.8 TeV). The TeV hardness ratios are plotted versus the observation date in Figure 1, bottom panel, together with 1$\sigma$ uncertainties. It is apparent that, within statistical uncertainties, the hardness ratios in the pre-flare state (MJD 50979–990) and flare state (MJD 50991–992) are very similar, despite that the absolute fluxes differ by one order of magnitude. Intriguingly, the spectrum seems to soften substantially during the decay stage, although the limited statistical significance of about 2$\sigma$ prevents us from drawing firmer conclusions.

4. Discussion

Since the typical flux variability timescale of Mrk 501 in TeV $\gamma$-rays and X-rays can be much less than one day, it is important to have truly simultaneous observations in both bands. It is also important to have reasonably continuous sampling on timescales of at least one day in order to have an accurate picture of the dynamics of the source. For this reason, we conducted a 15-day TeV/X-ray monitoring with diurnal RXTE observations exactly in the HEGRA visibility windows. After 10 days of quiescence, the source exhibited a strong flare at both TeV and X-rays lasting six days, with a flux exceeding the pre-flare level by a factor of $\sim 20$ at TeV energies during a 2-day maximum, and with lower amplitudes (factor 2–4) at X-rays. We also report the first detection of TeV flux variability on sub-hour timescales in Mrk 501 ($\S$ 3.1).

By chance, our multiwavelength campaign in 1998 June coincided with the only high TeV activity of the source during that year. Luckily, we were able to follow the evolution of the TeV flare not only during the pre-flare and flare stage but also during the decay stage. The TeV spectrum during the flare is similar to the spectra observed in 1997, suggesting that the flaring episode we witnessed in 1998 June was a scaled-down version of the longer-lasting 1997 flare. This conclusion is bolstered by the strong spectral variations we observe in the X-rays. Our RXTE observations show that the X-ray continuum in 3–20 keV flattened by $\Delta \Gamma_{3-20 \text{ keV}} \sim 0.5$ from the beginning of the campaign ($\Gamma_{3-20 \text{ keV}} = 2.3$) to the flare maximum ($\Gamma_{3-20 \text{ keV}} = 1.8$). Interestingly, at the peak of the TeV flare the X-ray slope was similar to the 2–10 keV slope measured in 1997 April, May, and July with BeppoSAX and RXTE (Pian et al. 1998a; Lamer & Wagner 1999; Krawczynski et al. 1999). This implies a similar shift of the synchrotron peak frequency at higher energies, $\gtrsim 50$ keV (Figure 3). While in April 1997 the X-ray continuum flattened by 0.4 within approximately
two weeks, we see here a comparable flattening within only $\sim 2-3$ days. Note that large changes of the position of the synchrotron peak are relatively rare. Besides Mrk 501, they were observed to-date only in two HBLs, 1ES 2344+514 (Giommi, Padovani, & Perlman 1999) and 1ES 1426+428 (Ghisellini, Tagliaferri, & Giommi 1999), but not in Mrk 421, PKS 2155–304, or any other BL Lac. Our observations provide the first evidence that in Mrk 501 the synchrotron peak may change on relatively short timescales ($\sim$ a few days).

Several models have been suggested to explain the TeV radiation from blazars. A popular scenario are the leptonic models, where TeV $\gamma$-rays are produced via inverse Compton scattering of directly accelerated electrons on external and/or internal photons (e.g., Sikora 1997). For Mrk 501, an object without strong broad line emission, the synchrotron self-Compton (SSC) model is almost commonly accepted as the most probable explanation for the observed X-ray/TeV-$\gamma$-ray emission (e.g., Tavecchio et al. 1998; Kataoka et al. 1999). Presently, the SSC model is the only model (at least in its simplified, “one-zone” version) which has been developed to a level which allows conclusive predictions which can be compared with experimental results. In particular, the SSC scenario is able to give satisfactory fits to both the X-ray and the TeV spectra (Pian et al. 1998a; Hillas 1999; Krawczynski et al. 1999). We used the code developed by Coppi (1992) to fit our simultaneous SEDs in Figure 3, assuming emission from a one-zone, homogeneous region and incorporating Klein-Nishina effects. The key parameters used in this model are the Doppler factor $\delta_j$ of the relativistic plasma, the radius $R$ of the emission region, the magnetic field $B$, and the electrons’ maximum energy $E_{\text{max}}$.

The results of the fits are shown in Figure 3 as solid lines, and the parameters’ values are reported in the caption. As discussed further below, the models were computed without correcting for the extragalactic extinction of TeV photons due to $\gamma/\gamma$ pair production with the photons of the Diffuse Extragalactic Background Radiation (e.g. Gould & Schrédor 1966). In the lower panel, we plot the ratio of the data and best-fit model between the high-state and pre-flare. The latter plot emphasizes that, while the TeV spectra of both states are quite similar, the X-ray spectra of the pre-flare and the flare state are significantly different. In SSC models the hardening of the X-ray spectrum during the flare can be attributed to a shift of the peak frequency $\nu_s$ of the synchrotron radiation, $\nu_s \propto B \times E_{\text{max}}^2$. Assuming an increase of both the magnetic field and the maximum energy during the flare, the dramatic changes of the X-ray spectrum are readily explained (see Figure 3). While the increase of magnetic field does not affect the $\gamma$-ray spectrum, the increase of $E_{\text{max}}$ does make the inverse Compton (IC) spectrum harder. However, since the $\gamma$-rays are produced in the Klein-Nishina regime, this effect is less pronounced in IC than in the synchrotron radiation component. The fits shown in Figure 3 correspond to the following model parameters: $B=0.03$ G, $E_{\text{max}} = 2$ TeV (exponential cutoff energy), $R = 4 \times 10^{16}$ cm for pre-flare state, and $B=0.1$ G, $E_{\text{max}} = 20$ TeV, $R = 2.7 \times 10^{15}$ cm for the flare state. For both cases a Doppler factor of $\delta_j = 25$ is assumed. Note that the latter value of the Doppler factor implies that internal absorption of the TeV $\gamma$-rays by lower frequency photons can be completely neglected (e.g. Celotti, Fabian, & Rees 1998). Furthermore, the chosen Doppler factor and radius of the emitting volume in the
flaring state imply time variability down to $t = R/(c \delta_j) = 1$ hour which agrees with the observed flux variability following from Figure 2. For the flare state with good statistics up to $\sim 10$ TeV, the model over-predicts the TeV flux above $\sim 5$ TeV, in particular by a factor of $\sim 2.5$ at 10 TeV. This discrepancy should not be overemphasized, but could well be the result of intergalactic extinction due to $\gamma/\gamma$ pair production.

In summary, we have performed a 2-week monitoring campaign of the HBL Mrk 501 in 1998 June with HEGRA and RXTE, with a sampling designed to probe TeV/X-ray correlation on timescales of several hours. We detected a strong flare at both wavelengths, rising from a period of very low activity, well correlated at TeV and X-rays on time scales of $\lesssim 1$ day, accompanied by large ($\Delta \Gamma_{3-20 \text{ keV}} \sim 0.5$) spectral variability at X-rays. Our results support an interpretation in terms of a canonical synchrotron-self Compton scenario. Future campaigns with a more intensive sampling designed to probe correlation on shorter time scales at both X-ray and TeV energies are needed to set more stringent constraints on the radiative processes which play an important role in the evolution of the flare.

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Figure Captions

- Figure 1: Multiwavelength light curves of Mrk 501 in 1998 June, as measured with HEGRA and *RXTE*, binned at 1 day and 5408 s (one orbit), respectively (top panel). The HEGRA flux units are $10^{-12}$ ph cm$^{-2}$ s$^{-1}$, the *RXTE* data are in c s$^{-1}$. The HEGRA light curve was arbitrarily shifted by +1.5 in logarithmic units for clarity of presentation. A strong flare is detected at both TeV and X-rays, with increasing amplitude for increasing energy. The flare was accompanied by large spectral variations at X-rays (middle panel), with flatter slope with increasing flux. Within the statistical errors, the TeV spectrum was rather hard during the whole pre-flare and flare phases, as shown by the TeV hardness ratios in the bottom panel (upper limits are on 1σ confidence limit to facilitate the comparison with the error bars of the flux estimates). There is an indication of spectral softening during the decay stage of the flare.

- Figure 2: TeV and X-ray light curves (binned at 900 s and 300 s, respectively) of Mrk 501 during the day of maximum TeV activity in 1998 June. Significant variability of a factor $\sim2$ on $\sim20$ min timescale is detected at TeV energies. Unfortunately, gaps are present in the *RXTE* monitoring and we can not comment on correlated X-ray variability on these short timescales.

- Figure 3: Spectral energy distributions of Mrk 501 in 1998 June during the peak of the TeV/X-ray flare (filled dots) and during the pre-flare state (open dots). Only the PCA data are plotted for clarity (Table 1). The solid lines are fits to the spectra with an homogeneous SSC model (Coppi 1992), with the following fitted parameters: $B=0.03$ G, $E_{\text{max}}=2$ TeV, $R=4 \times 10^{16}$ cm for the pre-flare state; $B=0.1$ G, $E_{\text{max}}=20$ TeV, $R=2.7 \times 10^{15}$ cm for the high state. The bottom panel shows the ratios of the model spectra and data for the flare and pre-flare states.

- Figure 4: Plot of the X-ray 3–20 keV slope versus the observed 2–10 keV flux, from fits to the time-resolved PCA spectra (Table 2). The trend of flattening slope with increasing flux is apparent. The dotted lines mark the time progression of the slope, which appears to follow a “clock-wise” pattern during the flare. This behavior is consistent with the X-ray flare being due to electron cooling (Kirk et al. 1998).
Table 1: Simultaneous average TeV and X-ray spectra

| State | \( N_0 \) | \( \Gamma \) | \( E_0 \) (TeV) | \( F \) \((10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1})\) | \( \chi^2/\text{dofs} \) |
|-------|---------|---------|----------------|----------------|------------------|
| **A) TeV** | | | | | |
| Flare | 7.9 ± 1.0 | 1.92 ± 0.3 | 4.0^{+1.45}_{-0.90} | ... | 0.54/13 |
| Pre-flare | 0.5 ± 0.1 | 2.31 ± 0.20 | ... | ... | 1.4/9 |
| **B) X-ray** | | | | | |
| Flare PCA | ... | 1.89 ± 0.02 | ... | 18.5 ± 0.9 | 0.75/42 |
| Flare HEXTE | ... | 2.19 ± 0.29 | ... | 7.5 ± 1.1 | 1.04/69 |
| Pre-flare PCA | ... | 2.21 ± 0.02 | ... | 0.7 ± 0.1 | 0.85/41 |
| Pre-flare HEXTE | ... | 2.30 ± 0.45 | ... | 1.8 ± 0.4 | 0.87/69 |

**Notes:**

a=High state corresponds to the time interval MJD 50991–992. Low state corresponds to MJD 50979–987;
b=Normalization of the power law, in \( 10^{-11} \) ph cm\(^{-2}\) s\(^{-1}\) TeV\(^{-1}\) for the HEGRA data;
c=Observed flux in 2–10 keV (PCA) and 20–50 keV (HEXTE);
d=Fits with a power law plus exponential cutoff: \( dN/dE=N_0 \times (E/\text{TeV})^{-\Gamma} \times e^{-(E/E_0)} \). Errors on parameters are statistical;
e=Fits with a single power law plus Galactic absorption, \( N_H = 1.73 \times 10^{20} \) cm\(^{-2}\) (Elvis et al. 1989).
Table 2: X-ray spectral variability

| Start Date (MJD-50000) | Net Exp. (s) | $\Gamma_{3-20 \text{ keV}}$ | $\chi^2$ (for 42 dofs) | $F_{2-10 \text{ keV}}$ ($10^{-11}$ erg cm$^{-2}$ s$^{-1}$) |
|------------------------|-------------|-----------------|----------------|-----------------|
| 978.9                  | 3168        | 2.29 ± 0.04     | 0.55           | 5.91            |
| 979.9                  | 3312        | 2.27 ± 0.04     | 0.72           | 6.05            |
| 980.9                  | 6304        | 2.31 ± 0.03     | 0.57           | 6.04            |
| 981.9                  | 6320        | 2.17 ± 0.03     | 0.84           | 7.13            |
| 982.9                  | 3488        | 2.22 ± 0.04     | 0.66           | 6.29            |
| 983.0                  | 4144        | 2.23 ± 0.04     | 0.46           | 6.41            |
| 983.9                  | 6192        | 2.21 ± 0.03     | 0.73           | 8.41            |
| 984.0                  | 1328        | 2.19 ± 0.06     | 0.70           | 6.58            |
| 984.9                  | 5040        | 2.16 ± 0.03     | 0.70           | 6.08            |
| 985.1                  | 464         | 2.26 ± 0.10     | 0.68           | 6.02            |
| 985.9                  | 3024        | 2.19 ± 0.04     | 0.71           | 6.47            |
| 986.0                  | 352         | 2.07 ± 0.11     | 0.77           | 6.43            |
| 986.1                  | 528         | 2.25 ± 0.09     | 0.78           | 6.45            |
| 986.9                  | 384         | 2.21 ± 0.10     | 0.68           | 6.71            |
| 987.1                  | 480         | 2.36 ± 0.10     | 0.78           | 6.76            |
| 987.9                  | 1536        | 2.28 ± 0.06     | 1.04           | 7.05            |
| 988.0                  | 592         | 2.20 ± 0.08     | 0.71           | 7.29            |
| 988.9                  | 1152        | 2.06 ± 0.04     | 0.71           | 10.8            |
| 989.0                  | 912         | 2.06 ± 0.04     | 0.60           | 11.4            |
| 989.9                  | 1296        | 1.96 ± 0.03     | 0.65           | 12.1            |
| 990.0                  | 208         | 2.03 ± 0.08     | 0.52           | 11.3            |
| 990.0                  | 512         | 2.06 ± 0.06     | 0.74           | 11.3            |
| 990.9                  | 1392        | 1.89 ± 0.02     | 1.46           | 16.9            |
| 991.0                  | 656         | 1.86 ± 0.03     | 0.99           | 18.1            |
| 991.9                  | 432         | 1.91 ± 0.03     | 0.52           | 20.5            |
| 992.0                  | 512         | 1.93 ± 0.04     | 0.65           | 20.0            |
| 992.9                  | 528         | 2.01 ± 0.04     | 0.47           | 15.4            |
| 993.0                  | 736         | 2.08 ± 0.04     | 0.82           | 15.4            |

Notes:

a= Fits to the PCA data in 3–20 keV with a single power law plus Galactic $N_H$ ($1.73 \times 10^{20}$ cm$^{-2}$).

Errors are 90% confidence for one parameter of interest ($\Delta \chi^2 = 2.7$).

b= High $\chi^2$ is due to instrumental absorption features in the residuals around 4.8 keV (Xenon edge) and 8.5 keV (unknown origin).
\[ \log_{10}(\nu/\text{Hz}) \]

\[ \log_{10}(\text{Flare/Pre-Flare}) \]

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