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Letter to the Editor

Markarian 501 in X-ray bright state – RXTE observations

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Abstract. Mrk 501 has been in a state of very high flux in X-rays and VHE γ-rays during 1997. In July 1997 near its hitherto maximum X-ray brightness intense multifrequency observations of Mrk 501 have been performed at radio, near infrared, optical, X-ray, and VHE γ-ray frequencies.

Here we report on *Rossi X-ray Timing Explorer* (RXTE) observations carried out in 1997 between July 11 and July 16. The X-ray spectrum has been well detected up to 100 keV and is best described by a broken power law with spectral indices α_1 = 0.70 and α_2 = 0.94 below and above the break energy of $E_{\rm break}$ = 5.8 keV.

The X-ray flux from Mrk 501 declined and flared by $\sim$ 30% within about 3 days each, showing an unusual anti-correlation between flux and spectral hardening of both power law components. The break energy remained constant.

The observed broad band and X-ray spectra confirm recent observations, that the synchrotron component in Mrk 501 can extend up to energies of 100 keV with the maximum power being emitted at hard X-rays. On longer time-scales the cut-off frequency of the synchrotron spectrum changes by more than two orders of magnitude.

Key words: galaxies: active – BL Lacertae objects: individual: Mrk 501 – X-rays: galaxies

1. Introduction

Markarian 501 is the second closest (z=0.034) BL Lacertae object. From its quiescent state radio to X-ray energy distribution ($\alpha_{\rm rx} \approx 0.62$, $f_\nu \propto \nu^{-\alpha}$) it can be described as intermediate between X-ray bright BL Lacs (XBLs) and radio bright objects (RBLs). The object usually displays a relatively steep X-ray spectrum (e.g. α_x = 1.77 observed by ROSAT in 1991) indicating that the energy loss dominated high energy part of the synchrotron spectrum is observed in X-rays (Lamer et al. 1996). X-ray spectra with α_x significantly less than unity, as required for the maximum of the synchrotron power output to be at hard X-rays, have not been measured during earlier observations (1975-1990, Ciliegi et al. 1995). The 1 keV flux densities measured in these observations vary by a factor of $\sim$ 3.

In 1995 Mrk 501 was detected as a source of TeV gamma-rays by the *Whipple* team (Quinn et al. 1996) for the first time. Its flux level corresponded to 8% of that of the Crab Nebula. The detection was confirmed by the HEGRA collaboration (Bradbury et al. 1997). A recent compilation of TeV observations of Mrk 501 (Protheroe et al. 1997) shows the source at very high level with flares up to 10 Crab throughout the entire observing season of 1997 well into the July observations presented here.

A similar brightening of Mrk 501 during 1997 has been observed in X-rays by the RXTE All Sky Monitor (ASM), the

Table 1. Observation log

ObsID	start [MJD-50000.0]	end	exposure [sec] PCA	HEXTE[a]
20421-01-01-01	640.9746	640.9916	1456	873
20421-01-01-00	641.1764	641.1916	1296	1709
20421-01-02-01	641.9740	641.9918	1520	640
20421-01-02-00	642.1519	642.1919	2688	1771
20421-01-03-01	642.9733	642.9918	1584	971
20421-01-03-00	643.1520	643.1920	2880	1843
20421-01-04-01	643.9526	643.9922	1616	1078
20421-01-04-00	644.1526	644.1923	3152	996
20421-01-05-01	644.9530	644.9922	1744	1129
20421-01-05-00	645.1530	645.1922	3376	2135

[a] added exposures of clusters A and B

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Table 2. Results of broken power law fits to the individual spectra

MJD	duration [days]	α_1 ($E < E_{\rm break}$)	$\pm(1\sigma)$	$E_{\rm break}$ [keV]	$\pm(1\sigma)$	α_2 ($E > E_{\rm break}$)	$\pm(1\sigma)$	1 keV norm [(cm^2 s keV)$^{-1}$]	$\pm(1\sigma)$	χ^2 (d.o.f)
50640.9831	0.0170	0.756	0.015	5.519	0.149	1.054	0.008	0.1702	0.0030	1.03 (224)
50641.1840	0.0152	0.767	0.013	5.984	0.186	1.028	0.009	0.1666	0.0030	1.04 (224)
50641.9829	0.0178	0.664	0.016	5.380	0.148	0.962	0.007	0.1400	0.0030	1.04 (224)
50642.1719	0.0400	0.687	0.010	5.856	0.143	0.922	0.006	0.1421	0.0020	0.95 (224)
50642.9826	0.0185	0.653	0.014	5.621	0.189	0.889	0.008	0.1306	0.0026	0.96 (224)
50643.1720	0.0400	0.669	0.011	5.604	0.152	0.893	0.006	0.1227	0.0020	1.11 (224)
50643.9724	0.0396	0.674	0.015	5.546	0.161	0.944	0.007	0.1381	0.0030	0.98 (224)
50644.1725	0.0396	0.722	0.009	5.889	0.131	0.956	0.005	0.1555	0.0018	0.98 (224)
50644.9726	0.0393	0.746	0.010	5.981	0.140	1.029	0.007	0.1803	0.0032	0.97 (224)
50645.1726	0.0393	0.730	0.008	5.724	0.090	1.035	0.005	0.1780	0.0020	1.02 (224)
integral spectrum		0.702	0.019	5.576	0.208	0.960	0.005	0.1510	0.0040	0.98[a] (224)

[a] 1% systematic error allowed

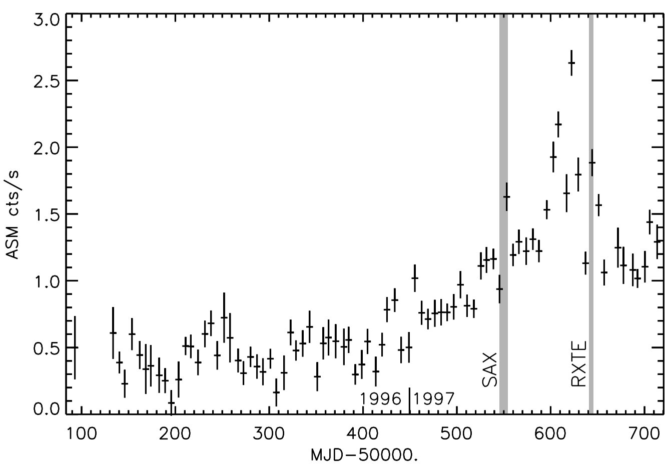

Fig. 1. RXTE ASM light curve of Mrk 501 during 1996 and 1997 with the epochs of pointed observations with SAX and RXTE marked by the shaded bars.

peak brightness in June 1997 being $\sim$ 40 mCrab (Fig. 1). The TeV and ASM (2-10 keV) light curves show similar flaring activity during 1997, the correlated X-ray and VHE gamma-ray variability will be discussed in a forthcoming paper.

At the onset of this high activity in April 1997 observations with the SAX satellite were carried out (Pian et al. 1997). They find Mrk 501 with an unusually hard X-ray spectrum, extending up to photon energies of 100 keV with the hardest spectrum observed on 16 April, when the source was brightest.

2. Observations and data analysis

The bright X-ray state of Mrk 501 in June/July 1997 triggered intense multi-frequency observations from radio to VHE gamma-rays. Here we report on RXTE observations between 11 July and 16 July 1997 resulting in 21300 seconds of good data in 10 pointings (Table 1).

We have used `ftools 4.0` for the reduction of the PCA and HEXTE data. PCA good times have been selected from the standard 2 mode data sets using the following criteria: target elevation $> 10°$, pointing offset $< 0.01°$, and all 5 PCUs switched on. For the resulting intervals spectra and light curves were extracted using all Xenon layers. The corresponding PCA background spectra and light curves were derived with `pcabackest 1.5`.

After applying the above elevation and offset criteria, HEXTE spectra and light curves have been binned and background subtracted using the off-source looking intervals.

Spectral fitting was performed with `XSPEC 10.0` using the latest detector response matrix from 26 August 1997 for PCA and the response files from 20 March 1997 for HEXTE. The PCA spectra in the PHA channel range 3-60 (2.5-27 keV) and the spectra from both HEXTE clusters in the channel range 15-100 (15-100 keV) were combined for each of the 10 pointings and then fitted with single and broken power law spectra. The uncertainty in the absolute flux calibration of the HEXTE instrument, mainly due to uncorrected dead-time effects (see Rothschild et al. 1997), was accounted for by allowing for a scaling factor between the PCA and HEXTE spectra. Setting PCA to 1.0, the mean best fit value for the HEXTE normalization was 0.65.

The absorbing column density on the line of sight to Mrk 501 was fixed to $2.87 \cdot 10^{20}{\rm cm}^{-2}$ as derived from the ROSAT spectrum (Lamer et al. 1996). This value is larger than the galactic value as derived from 21 cm H I measurements ($1.73 \cdot 10^{20}{\rm cm}^{-2}$, Stark et al. 1992). However, the effect of this difference on the spectral results in the RXTE energy range is negligible. Note that Pian et al. 1997 used the galactic H I column density $N_{\rm H}$ $=1.73 \cdot 10^{20}{\rm cm}^{-2}$ for the spectral fits to the SAX data and that the uncertainty in the $N_{\rm H}$ value towards the source may have a significant effect on the spectral indices measured with the LECS instrument at the softest X-ray energies.

3. Spectra and variability

Single power law models with N_H fixed to any reasonable value do not yield acceptable fits to the data of any pointing, whereas

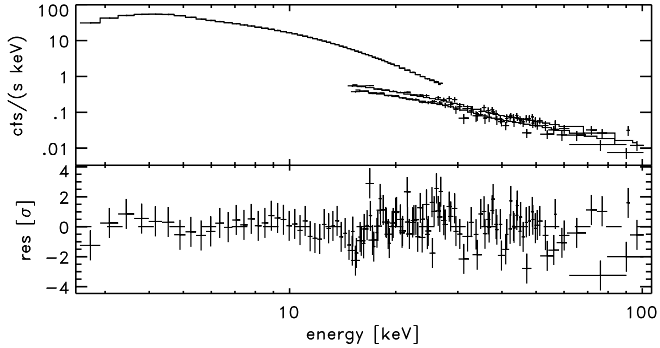

Fig. 2. Top panel: PCA and HEXTE countrate spectra of the entire observation fitted with a broken power law model (see Table 2 for the model parameters). Bottom panel: Fit residuals with 1% systematic uncertainty allowed.

broken power law models with break energies between 5.5 and 6.0 keV give excellent fits to the individual spectra (see Table 2). Below the break point the model spectra are exceptionally hard with energy indices ranging from 0.65 to 0.77. In fact an X-ray synchrotron spectrum of this hardness has never been observed in any other XBL (Ciliegi et al. 1995, Lamer at al. 1996). The spectrum measured on 16 April 1997 by SAX in about the same energy band (2.14-10 keV) is even slightly harder (α = 0.59, Pian et al. 1997). As the PCA has no sensitivity below 2 keV, we are not able to verify the break at $\sim$ 2 keV in the SAX spectrum.

Above the break point the PCA spectrum steepens by up to 0.3 in energy index. In some of the spectra α_2 exceeds unity, indicating that the maximum of the synchrotron power output is reached in the hard X-ray range. However, there is no evidence for further steepening of the spectrum up to 100 keV.

During the RXTE observations the PCA count-rate varied by $\sim$ 30%, but in contrast to the results from the April 1997 SAX observations an anti-correlation of flux and spectral hardness was observed both below and above the spectral break. Such an anti-correlation has never been reported in Mrk 501 and is quite unusual for X-ray BL Lac objects altogether. Pian et al. found a spectral hardening by $\Delta\alpha$ = 0.32 in the SAX MECS 2-10 keV band during an increase of the flux in this energy band by a factor of 2.4.

The large degree of spectral variability and its anti-correlation with total flux implies great differences between the light curves in the individual X-ray energy bands. We hence derived light curves for seven and four different channel ranges of the PCA and HEXTE detectors, respectively (Figs. 3 and 4). The light curves in the softer bands show a decline by 20% over 3 days with a well defined minimum at MJD 50643.2 and a subsequent increase by 30% during the following 2 days. On the other hand the hardest bands are dominated by a feature with a broad maximum around MJD 50642. A smooth transition with superpositions of both morphologies is observed in the intermediate energy bands. The independent variability of soft and hard X-rays requires the existence of at least two emission components which is not evident from the X-ray spectrum alone.

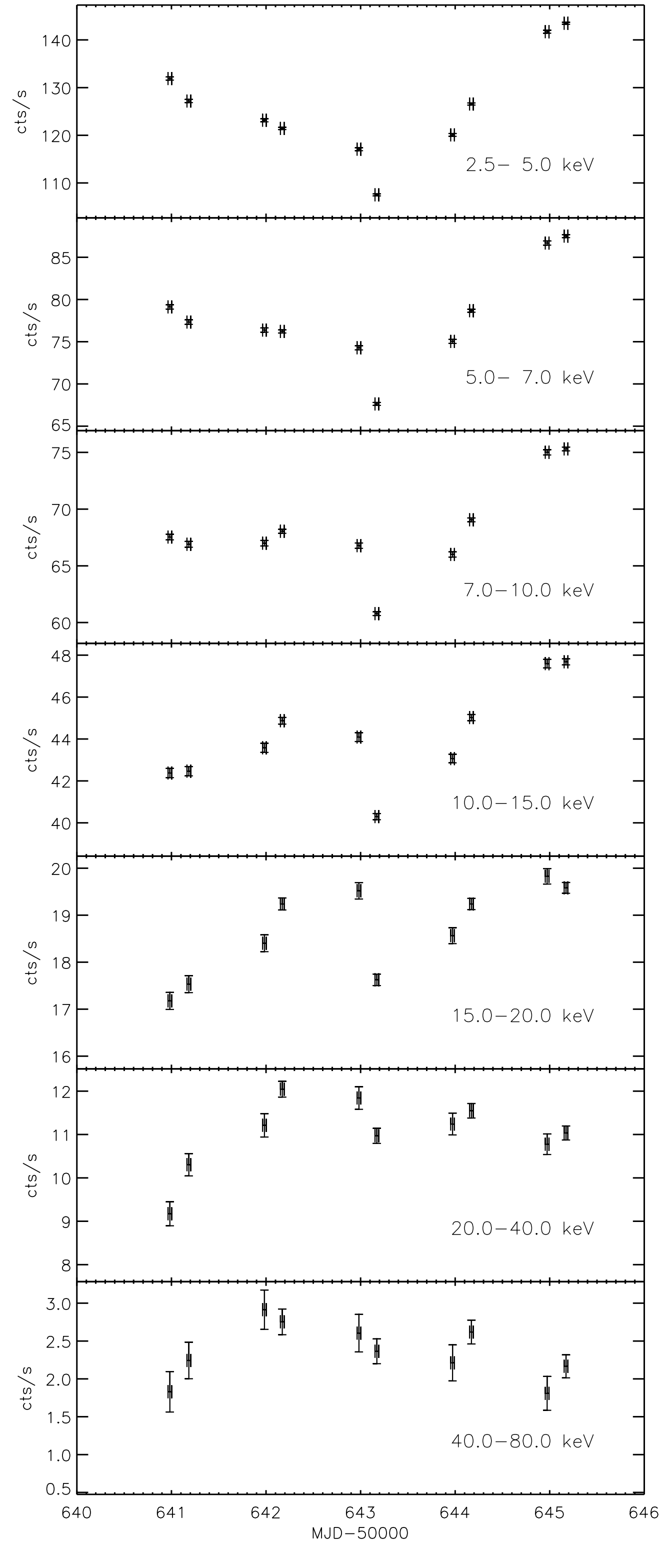

Fig. 3. Background subtracted PCA light curves in different energy bands.

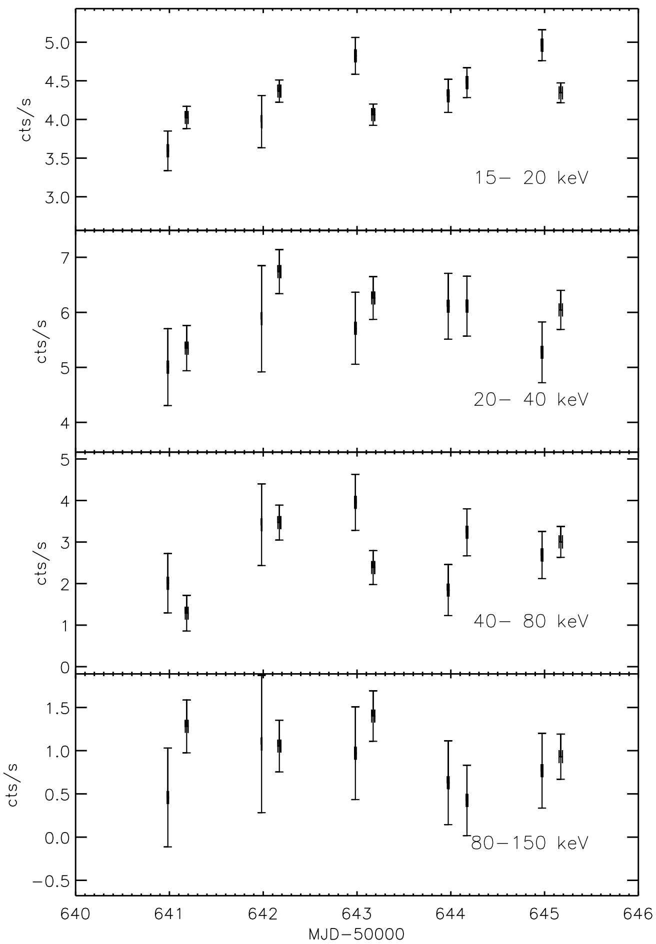

Fig. 4. Background subtracted HEXTE light curves in different energy bands, the count-rates of clusters A and B have been added. Note the good agreement of the PCA and HEXTE light curves in the 3 energy bands between 15 and 80 keV.

The sharpest feature in the 2-20 keV lightcurves is a decrease in flux by 10% within 4.5 hours. In an EXOSAT ME lightcurve (0.7-8 keV, Giommi et al. 1990) similar timescales and amplitudes have been found. In an investgation of the spectral variability of 6 BL Lac objects Giommi et al. found tight correlations of flux and spectral hardness for any of the objects, including Mrk 501. This highlights the peculiarity of the spectral variability reported here.

4. Conclusions

Our RXTE observations from July 1997 show that the period of increased X-ray brightness continued throughout 1997 and was not limited to a short flare in April. The object clearly was in a long-lasting high-state in 1997 rather than exhibiting a short, spectacular X-ray flare during the epoch of the SAX observations. We confirm the extraordinary hard X-ray spectrum which extends up to 100 keV. The peak of the synchrotron emission is observed in the hard X-rays, more than 2 orders of magnitude higher than in earlier observations (e.g. by ROSAT in 1991, Lamer et al. 1996).

During the RXTE observations in July the total flux and the spectral hardness show an anti-correlation. This is a very unusual spectral behaviour for any BL Lac object, it has not been observed previously in Mrk 501 and is in marked contrast to the fact that the SAX observations of Pian et al. showed a flatter spectrum during the brighter stage (there are only two different brightness and spectral levels in the SAX data set rather than a well-established correlation). The flux-spectral index relations should hence not be regarded as universal and viable models should explain both kinds of behaviour.

The broken power law (or gradual steepening of the spectrum) is consistent with synchrotron cooling of a single component and does not require the superposition of different particle distributions. A homogeneous jet and a magnetic field of 0.4G are capable of producing the integrated spectral signature. We have found rather dramatic spectral differences in the light curves which cannot be explained by a single population but requires the contributions of at least two, if not more spectral components. This illustrates the great importance of well-sampled monitoring with instruments covering a wide spectral range.

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