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Study of the variable VHE emission from Markarian 501 with the MAGIC telescope

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Abstract: The blazar Markarian 501 (Mrk 501) was observed at energies above 100 GeV with the MAGIC Telescope from May through July 2005. The high sensitivity of the instrument enabled the determination of the flux and spectrum of the source on a night-by-night basis. Throughout our observational campaign, the flux from Mrk 501 was found to vary by an order of magnitude and to be correlated with spectral changes. Intra-night flux variability with flux-doubling times down to 2 minutes was also observed. These are the fastest flux variations ever observed in Mrk 501. The strength of variability is increased with the energy of the gamma-ray photons, regardless whether the source is in active or quiescent state. The energy spectra were found to harden significantly with increasing flux and a spectral peak clearly showed up during very active states. The details of this unprecedented spectral and temporal analysis of Mrk 501 observations are reported and the implications of these results are discussed.

Introduction

Mrk 501 is one of the closest known TeV blazars ($z = 0.031$). Since its detection in the TeV band [1] it underwent states of high emission characterized by large amplitude and rapid variability at both the X-ray (keV) and VHE (GeV/TeV) energies. Strong constraints on leptonic models and on acceleration processes in the jets can be derived from the study of the flux and spectrum variability [2, 3, 4]. The observation of trends in the evolution of the flare along different energies would shed light on the interplay between the acceleration and energy loss timescales of the electrons [5].

Observations and results

The MAGIC (Major Atmospheric Gamma-ray Imaging Cherenkov) Telescope [6] observed Mrk 501 during 30 nights between May and July 2005 [7]. The source was observed pointing directly at the object (ON-data). The background was estimated from nearby off-source observations (OFF-data) recorded in different nights. Hillas image parameters [8] were calculated and for γ/hadron separation both dynamical cuts and Random Forest method have been used[9].

Finally the image parameter *Alpha* was calculated for the ON and OFF data. *Alpha* is used to extract the γ signal that should show up as an excess at small *Alpha* values. The energy of the events was estimated using a parameterization of the image parameters and was double-checked with a Random Forest technique. The source showed large flux variations during consecutive nights and it was in a very active state in the nights of June $30^{\rm th}$ (MJD 53551.905, 1.09 hours observation time) and July $9^{\rm th}$ (MJD 53560.906, 0.76 hours observation

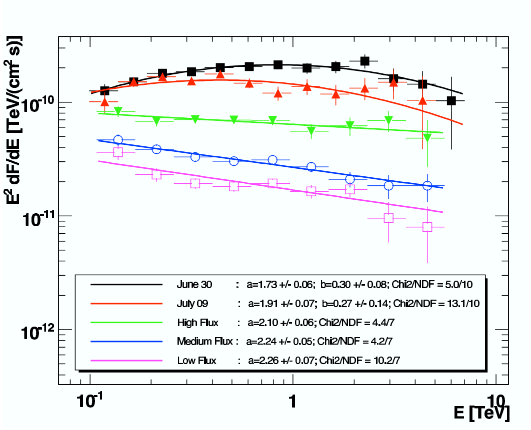

Figure 1: Energy spectra of Mrk 501 for the flaring nights of June 30$^{\rm th}$ (black squares) and July 9$^{\rm th}$ (red up-triangles) and for the three data sets which group nights according to whether their integral flux above 150 GeV, $F_{\rm 150GeV}$ (measured in Crab Units), was high (1.0 C.U. $<$ $F_{\rm 150GeV}$; green down triangles), medium (0.5 C.U. $<$ $F_{\rm 150GeV}$ $<$ 1.0 C.U.; blue open circles), or low ($F_{\rm 150GeV}$ $<$ 0.5 C.U.; pink open squares). Lines show best fits using log-parabolic (for flare nights) and power-law (for high/medium/low levels) functions. The spectra are corrected for EBL extinction using [10]'s 'Low' EBL model.

time). The flux in the VHE γ-ray region, exceeded 3 Crab Units (C.U.$= (3.2 \pm 0.1) \times 10^{-10} {\rm cm}^{-2} {\rm s}^{-1}$ at $E > 0.15\,{\rm TeV}$), with a variation of up to a factor of six respect to the previous nights. No significant flux variation was recorded in the X-ray (RXTE/ASM) and optical band.

The high flux of the source in the flaring nights gave the opportunity to split the data and to measure spectrum and light curve (LC) for each night. The spectral analysis was performed in the $0.1-3$ TeV range. The resulting differential spectra (EBL corrected) for the flaring nights and for three different flux levels during different nights are shown in Fig.1. Most of the data are well described by a simple power-law, but during the two flaring nights the spectra exhibit a curved shape that is better described by a log-parabolic fit [11]:

$$\frac{dF}{dE} = K_0 \left(\frac{E}{300\,{\rm GeV}} \right)^{-a-bLog_{10}(E/300\,{\rm GeV})} \qquad (1)$$

where K_0 is the normalization factor, a the spectral index at 300 GeV and b the curvature parameter. The parameters of the fit are reported in the inset of the figure. The data show a hardening of the spectra with increasing flux. Besides the data from the flaring nights suggest the presence of a spectral peak located at $0.85 \pm 0.13\,{\rm TeV}$ and $0.44 \pm 0.08\,{\rm TeV}$ for June 30 and July 9 respectively.

The integral fluxes above $150\,{\rm GeV}$ have been divided in 2 minutes time bins, resulting in the light curves in Fig.2. The source shows a intra-night flux variation on both nights, with a well defined rebrightening in the night of 9 July, lasting $\sim$20 minutes. The large flux of the source in these two nights, allowed the analysis of the intra-night flux variations at different energy bins. The amplitude and rise/fall times of the flare peaks was estimated fitting the LC with an exponential variation on the stable emission, using the function F(t) [12]:

$$F(t) = a + \frac{b}{2^{-(t-t_0)/c} + 2^{(t-t_0)/d}} \qquad (2)$$

c and d are respectively related to the doubling rise time and the halving fall time. Within this model we fix a to the 'stable' flux value at the time of the flare (the horizontal black dashed lines in Fig. 2. t_0 is set to the time corresponding to the point with the highest value in the LC; b, c, d are left free to vary. The parameters c and d can be converted into characteristic rise/fall times by the factor $1/\ln 2$. The computed rise/fall times are of the order $\sim$ 2 minutes; these are the shortest variation timescales observed in Mrk 501.

Discussion

The VHE γ-ray emission of blazars is usually interpreted as the inverse Compton scattering of soft photons by electrons accelerated in a jet which moves at relativistic speed towards the observer. In such a scenario the time variability is dominated by the intrinsic cooling and acceleration timescales and the short timescale of the observed flux variation on Mrk 501 can constrain the parameters of the emitting region.

Time variability

From the variability time it is possible to establish a lower limit on the Doppler factor δ. Since the γs

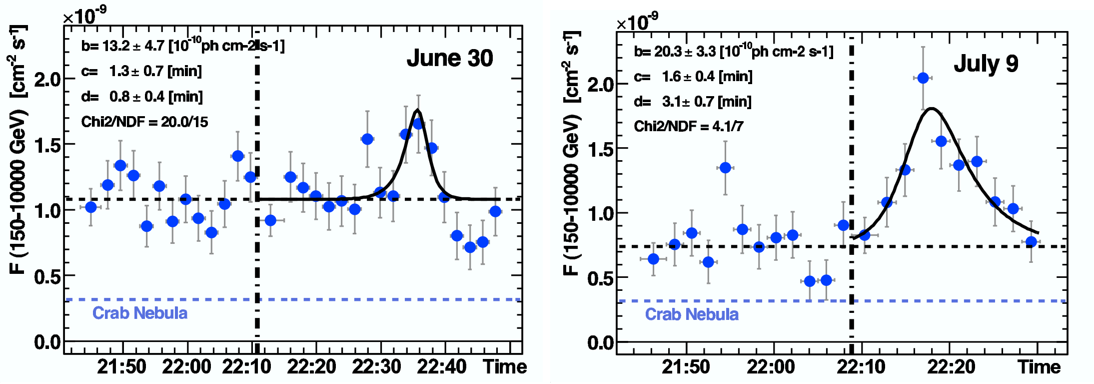

Figure 2: Light curves for the nights of June 30 (left) and July 9 (right) for energy $> 150\,\mathrm{GeV}$ represented in 2-minutes time bins. The Crab integral flux level above 150 GeV is reported for reference. The horizontal black dashed line represents the average of the 'stable' emission. The solid black curve represents the best-fit flare model from eq.2. The insets report the fit parameters.

observed in the VHE range have not been absorbed by $\gamma + \gamma \rightarrow e^+ + e^-$, the optical depth is lower than unity, $\tau_{\gamma\gamma} < 1$ [13] [4]. The optical depth depends on the source dimensions, on the target photons density and on the cross section of the pair production process.

The characteristic times that can affect the light curve shape are the electrons acceleration and cooling times and the time related to the source dimension (R/c). The symmetric shape of the measured light curves is a hint that the flux variations depends mainly on the R/c time. So we can assume $t'_{var} \sim R'/c$ in the source frame.

The constrain on the doppler factor is then

$$\delta \geq \left[\frac{\sigma_T d_L^2 (1+z)^{2\alpha}}{5hc^2} \frac{1}{t_{var}} F(\nu_0) \right]^{1/(4+2\alpha)} \qquad (3)$$

where σ_T is the Thompson cross section for the electron, d_L is the *luminousity distance*, α the spectral index for the target photons, z the redshift and $F(\nu_0)$ the observed flux of target photons. Assuming $\alpha = 0.5$, $E_\gamma = 1\,\mathrm{TeV}$ and $t_{var} = 5\,\mathrm{min}$ we obtain a lower limit $\delta > 16$.

Time lags

The flare in the night of 10 July has shown an evident intranight variation. The integral LC has been divided in four different energy ranges ($0.15 - 0.25\,\mathrm{TeV}$, $0.25 - 0.6\,\mathrm{TeV}$, $0.6 - 1.2\,\mathrm{TeV}$ and $1.2 - 10\,\mathrm{TeV}$) as shown in Fig.3. The fit has been performed assuming a symmetric flare, i.e. $c = d$ in equation 2 and it results in a shift between the highest an the lower energies peaks of $4 \pm 1\,\mathrm{min}$. The combined fit gave $\chi^2/NDF = 14.0/12$ $(\mathrm{probability}\, p = 0.3)$. The significance of this time shift has been evaluated performing the same fit using a common t_0 for all LCs, resulting in a $\chi^2/NDF = 26.6/15\,(p = 0.04)$ which implies that the time shift is more probable. The observed time lag should be given by the difference between the acceleration times of electrons in the blob, at energies $0.25\,\mathrm{TeV}$ and $1.2\,\mathrm{TeV}$ (Δt_{acc}):

$$\Delta t_\gamma^{obs} = \Delta t_{acc}/\delta \qquad (4)$$

where t_γ^{obs} is the observed delay and t_{acc} is related to the electron energy in the blob frame:

$$t_{acc} \simeq 0.1 \frac{E'_e}{\xi B}\,\mathrm{s} \qquad (5)$$

with B expressed in Gauss and E'_e in TeV and ξ is called *acceleration efficiency*. By this way it is possible to derive the acceleration efficiency by substituting the quantity E'_e/t_{acc} with $\Delta E'_e/\Delta t_{acc} = \Delta E_\gamma^{obs}/(\Delta t_\gamma^{obs}\delta^2)$ so that we have:

$$\xi \simeq 0.1 \frac{\Delta E_\gamma^{obs}}{B\, \Delta t_\gamma^{obs}\, \delta^2} \qquad (6)$$

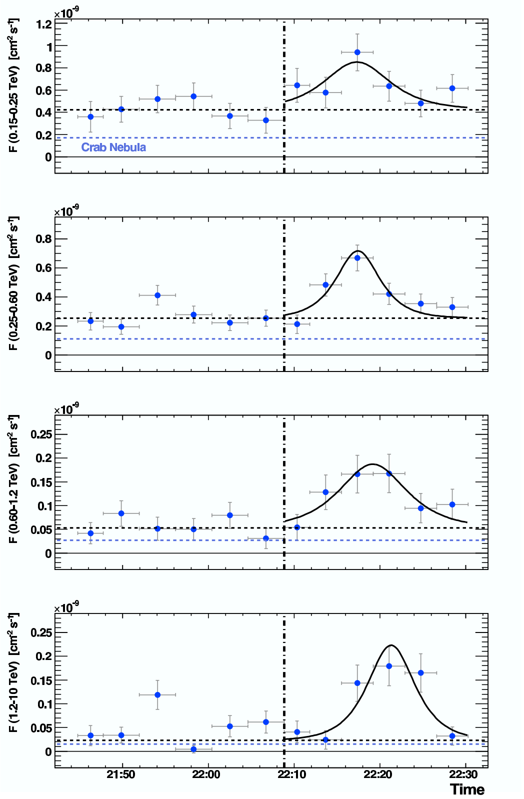

Figure 3: Light curves for the night of July 9 divided in four energy bands $0.15 - 0.25\,\mathrm{TeV}$, $0.25 - 0.6\,\mathrm{TeV}$, $0.6 - 1.2\,\mathrm{TeV}$ and $1.2 - 10\,\mathrm{TeV}$. The vertical dashed line divide the LC in 'stable' and 'flare' regions. In the 'flare' region the fit described in the text is superimposed.

Using the lower limit computed above and a magnetic field of magnitude 0.5 G, with a time delay of 4 minutes between $1.2\,\mathrm{TeV}$ and $0.25\,\mathrm{TeV}$, we obtain $\xi \sim 3 \times 10^{-6}$. It should be noted that this relatively inefficient acceleration of the electrons in the jet has been obtained by a model-independent derivation of the doppler factor, assuming that the observed time lag is related to the acceleration times of electrons at different energies.

Conclusions

A study of the time variability in the flux of the nearby blazar Mrk 501 has been performed with the MAGIC telescope above $100\,\mathrm{GeV}$ during the period between June and July 2005. For the June 30^{th} and July 9^{th} nights the analysis shows an active state with flux-doubling time of $\sim 2\,\mathrm{min}$.

A lower limit on the Doppler factor has been derived, without any assumption on the model, from the observed time variability. From the observed energy-dependent time lag a limit on the acceleration efficiency of electrons has been inferred.

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