Study of Flux and Spectral Variations in the VHE Emission from the Blazar Markarian 501

David Paneque
on behalf of the MAGIC collaboration


OUTLINE

1- Motivation to observe Mrk 501

2- Highlights from the Mrk 501 observations performed with MAGIC in June-July 2005 (details in the paper)

3- Conclusions and outlook
1- Motivation to observe Mrk 501 (again…)

The physics related to Mrk 501 (and AGNs in general) is not yet understood, despite these guys have been studied for >= 10 years (see talks from Monday; Padovani, Celotti…)

Culprits

1 - Time evolving broad band spectra

Coordination of instruments covering different energies needed

2 - Poor sensitivity to study high energy part (E>1 GeV)

Large observation times (with EGRET and “old” IACTs) were required to have a decent signal to make physics. Most of our HBL’s knowledge relates to the high state

Current experimental data allows for a big inter-model and intra-model degeneracy

More and “higher quality” data required to constrain models
1- Motivation to observe Mrk 501 (again…)

Present and near future:

New Generation of IACTs came online (low Eth, high sensitivity)
GLAST in operation next year (~25 more sensitive than EGRET)

Excellent laboratory for studying High Energy blazar emission

Strong gamma ray source (0.2-0.5 crabs in low state)
$z = 0.034$; low EBL absorption, we see "almost" intrinsic features

Things we know about Mrk 501 (and HBLs in general)

Dominant gamma-ray emission mechanism is believed to have a leptonic origin (SSC, EC), at least in high (flaring) state
- Fast variations (few hours in VHE)
- X rays- Gamma-rays correlation (in general)
2- Analysis of the MAGIC data (24 nights, 32.2 h)

*June-July 2005*

Flux and spectra determined on a night-by-night basis

<table>
<thead>
<tr>
<th>Obs. Nights</th>
<th>Gamma-Flux</th>
<th>Power Law fit to spectra</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MJD</strong></td>
<td><strong>$T_{obs}$</strong></td>
<td><strong>$ZA$</strong></td>
</tr>
<tr>
<td>53518.980</td>
<td>0.75</td>
<td>19.10-28.95</td>
</tr>
<tr>
<td>53521.966</td>
<td>1.85</td>
<td>9.97-30.10</td>
</tr>
<tr>
<td>53524.969</td>
<td>0.58</td>
<td>19.18-27.73</td>
</tr>
<tr>
<td>53526.975</td>
<td>0.98</td>
<td>9.96-28.94</td>
</tr>
<tr>
<td>53530.973</td>
<td>0.47</td>
<td>15.22-22.32</td>
</tr>
<tr>
<td>53531.959</td>
<td>0.90</td>
<td>15.21-25.15</td>
</tr>
<tr>
<td>53532.936</td>
<td>0.53</td>
<td>23.80-30.11</td>
</tr>
<tr>
<td>53533.933</td>
<td>1.63</td>
<td>12.85-30.09</td>
</tr>
<tr>
<td>53534.940</td>
<td>2.07</td>
<td>9.95-30.09</td>
</tr>
<tr>
<td>53535.934</td>
<td>3.43</td>
<td>9.95-30.07</td>
</tr>
<tr>
<td>53536.947</td>
<td>2.68</td>
<td>9.95-29.93</td>
</tr>
<tr>
<td>53537.971</td>
<td>3.08</td>
<td>9.95-30.10</td>
</tr>
<tr>
<td>53548.931</td>
<td>0.87</td>
<td>9.98-20.68</td>
</tr>
<tr>
<td>53551.905</td>
<td>1.09</td>
<td>12.86-25.15</td>
</tr>
<tr>
<td>53554.906</td>
<td>0.68</td>
<td>15.21-22.32</td>
</tr>
<tr>
<td>53555.914</td>
<td>0.44</td>
<td>12.85-22.32</td>
</tr>
<tr>
<td>53557.916</td>
<td>0.54</td>
<td>12.84-19.06</td>
</tr>
<tr>
<td>53559.920</td>
<td>0.58</td>
<td>9.94-17.22</td>
</tr>
<tr>
<td>53560.906</td>
<td>0.76</td>
<td>9.96-19.07</td>
</tr>
<tr>
<td>53562.911</td>
<td>1.63</td>
<td>9.94-16.79</td>
</tr>
<tr>
<td>53563.921</td>
<td>0.85</td>
<td>9.94-15.16</td>
</tr>
<tr>
<td>53564.917</td>
<td>0.91</td>
<td>9.94-15.18</td>
</tr>
<tr>
<td>53565.920</td>
<td>2.57</td>
<td>9.95-28.93</td>
</tr>
<tr>
<td>53566.953</td>
<td>1.91</td>
<td>9.99-30.10</td>
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2.1- Light curves (LCs): Gamma, X-rays, Optical

- **MAGIC**
  - Clear variability in gamma-rays

- **RXTE ASM**

- **KVA**
  - June 2005
  - July 2005
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- MAGIC
  \[<F_\gamma>_{\text{Mrk}501} \sim 0.5 \text{ crab (‘low’)}\]
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- KVA
  June 2005
  July 2005
2.1- Light curves (LCs): **Gamma, X-rays, Optical**

- **MAGIC**
  - June 30
  - $\left< F_\gamma \right>_{\text{Mrk 501}} \sim 0.5 \text{ crab (‘low’)}$
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- **RXTE ASM**

- **KVA**
  - June 2005
  - July 2005

Highest VHE activity during MAGIC obs.
2.2- Intra-night flux variations \((E > 150 \text{ GeV})\)

June 30th $\rightarrow$ Highest VHE activity $\rightarrow$ July 9th

**Flaring and Flickering** (see talk S. Wagner on Monday)
2.2- Intra-night flux variations \((E > 150 \text{ GeV})\)

June 30th ⇐ Highest VHE activity ⇒ July 9th

Assumption: Flux variation (flare) on the top of a stable emission

\[
F(t) = a + \frac{b}{2^{-\frac{t-t_0}{c}} + 2^{\frac{t-t_0}{d}}}
\]

\(a\): pedestal (not fit)

\(b\): amplitude of flux variation

\(t_0\): ~ peak position (not fit)

\(c, d\): flux-doubling times
2.2- Intra-night flux variations \((E > 150 \text{ GeV})\)

**Assumption:** Flux variation (flare) on the top of a stable emission

<table>
<thead>
<tr>
<th></th>
<th>(b)</th>
<th>(c)</th>
<th>(d)</th>
<th>(\chi^2/\text{NDF})</th>
<th>(P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\frac{10^{-10} , \text{ph}}{\text{cm}^2 \cdot \text{s}})</td>
<td>(13.2 \pm 4.7)</td>
<td>(81 \pm 41)</td>
<td>(50 \pm 23)</td>
<td>(20.0/15)</td>
<td>(17.3^f)</td>
</tr>
<tr>
<td></td>
<td>(20.3 \pm 3.3)</td>
<td>(95 \pm 24)</td>
<td>(185 \pm 40)</td>
<td>(4.2/7)</td>
<td>(75.8)</td>
</tr>
</tbody>
</table>

\(a\): pedestal (not fit)

\(b\): amplitude of flux variation

\(t_0\): \(~\) peak position (not fit)

\(c, d\): flux-doubling times
LCs for different energy ranges (4 min bins)

Active night: June 30

Flare is NOT seen in all energies

All energies are compatible with a constant flux emission, except for the range 250-600 GeV, where a constant emission is highly improbable.
LCs for different energy ranges (4 min bins)

Active night: July 9
Flare is seen in all energy ranges
LCs for different energy ranges (4 min bins)

Active night: July 9

Flare is seen in all energy ranges

Time delay of $4 \pm 1$ minute between highest and lowest energy ranges

First time in VHE !!
LCs for different energy ranges (4 min bins)

Active night: July 9

Flare is seen in all energy ranges

Time delay of $4 \pm 1$ minute between highest and lowest energy ranges

First time in VHE !!

If photons at different energies were emitted simultaneously

$$\Delta T = 4 \pm 1 \text{ min}; \Delta E \sim 1 \text{ TeV}$$

$$E_{QG} = \frac{L \cdot \Delta E}{c \cdot \Delta t} = (0.6 \pm 0.2) \cdot 10^{17} \text{ GeV}$$
LCs for different energy ranges (4 min bins)

Active night: July 9

Flare is seen in all energy ranges

Time delay of $4 \pm 1$ minute between highest and lowest energy ranges

First time in VHE !!

Flux variations are larger at the largest energies

First time in VHE !!
2.3 - Flux variability vs Energy

Quantification following prescription given in Vaughan et al. 2003

\[ F_{\text{var}} = \sqrt{S^2 - \langle \sigma^2_{\text{err}} \rangle} \]

\[ < F_\gamma >^2 \]

All the observing nights (low and high state) included

\[ F_{\text{var}}^{Mrk501} (VHE) \text{ increases with energy} \]

\[ F_{\text{var}}^{Mrk501} \text{ increases with energy also at X-rays (see Gliozzi et al. 2006)} \]

\[ F_{\text{var}}^{Mrk501} (VHE) > F_{\text{var}}^{Mrk501} (X-rays) \]

The highest \( F_{\text{var}}^{Mrk501} (X-rays) \) is \( \sim 0.6 \) (in 1998). In 1997, year with very high activity, the highest \( F_{\text{var}}^{Mrk501} (X-rays) \) was \( \sim 0.4 \). Perhaps flux variability is highest when source is in low state
2.4 - Correlation spectral index - gamma flux (E>150 GeV)

All 24 nights included
Flare nights split into 2 ("pre-flare" and "flare")

Spectra hardens with increasing flux

Constant fit gives Chi2/NDF = 76.6/25  (Prob 4 e-7)

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2.5 - Spectra for the 2 nights with the highest VHE activity

Curved spectra is favoured over simple power law

Power law

Log-Parabolic func.

<table>
<thead>
<tr>
<th>Date</th>
<th>$K_0$ ($10^{-10}$ $\text{ph cm}^{-2} \text{s}^{-1} \text{TeV}^{-1}$)</th>
<th>$\alpha$</th>
<th>$\chi^2 / \text{NDF}$</th>
<th>$P$ (%)</th>
<th>$K_0$ ($10^{-10}$ $\text{ph cm}^{-2} \text{s}^{-1} \text{TeV}^{-1}$)</th>
<th>$a$</th>
<th>$b$</th>
<th>$\chi^2 / \text{NDF}$</th>
<th>$P$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 30</td>
<td>17.4±0.05</td>
<td>2.09±0.03</td>
<td>26.1/11</td>
<td>0.6</td>
<td>18.6±0.06</td>
<td>1.89±0.06</td>
<td>0.35±0.09</td>
<td>6.1/10</td>
<td>80.1</td>
</tr>
<tr>
<td>July 9</td>
<td>14.3±0.06</td>
<td>2.20±0.04</td>
<td>22.5/11</td>
<td>2.1</td>
<td>15.5±0.07</td>
<td>2.06±0.07</td>
<td>0.36±0.16</td>
<td>15.2/10</td>
<td>12.5</td>
</tr>
</tbody>
</table>

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2.6 - Position of spectral peak before and after EBL correction

Model used: ‘low’ EBL from Kneiske et al 2004

EBL correction moves the spectral peak to higher energies

During the nights of low activity, the flare is not seen at E > 100 GeV

Peak location seems to depend on the source luminosity
2.7 - Overall SED during these observations

Very dynamic spectra in VHE:
3 flux levels + 2 active nights =
= 5 different spectra

Unluckily, we do not have
simultaneous broad band X-rays:
big intra-model degeneracy

It is important to organize
multiwavelength campaigns

<table>
<thead>
<tr>
<th>spectrum</th>
<th>$\gamma_{min}$</th>
<th>$\gamma_{br}$</th>
<th>$\gamma_{max}$</th>
<th>n1</th>
<th>n2</th>
<th>B</th>
<th>K</th>
<th>R</th>
<th>Doppler factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 30</td>
<td>1</td>
<td>$10^6$</td>
<td>$10^7$</td>
<td>2</td>
<td>3.5</td>
<td>0.52</td>
<td>$2.5 \cdot 10^4$</td>
<td>$10^{15}$</td>
<td>25</td>
</tr>
<tr>
<td>June 30 (bis)</td>
<td>1</td>
<td>$5 \cdot 10^5$</td>
<td>$10^7$</td>
<td>2</td>
<td>3.5</td>
<td>0.115</td>
<td>$2.5 \cdot 10^4$</td>
<td>$10^{15}$</td>
<td>50</td>
</tr>
<tr>
<td>Low flux</td>
<td>1</td>
<td>$10^5$</td>
<td>$5 \cdot 10^6$</td>
<td>2</td>
<td>3.2</td>
<td>0.55</td>
<td>$1.6 \cdot 10^4$</td>
<td>$10^{15}$</td>
<td>25</td>
</tr>
</tbody>
</table>

SED fit with one zone SSC model (Tavecchio et al. 2001)
CONCLUSIONS

Observations of Mrk 501 with MAGIC allowed us to study flux and spectra variations down to 100 GeV on a night by night basis.

1 - Changes in flux and spectra on several timescales: 
   months, days, and few minutes

2 - Intra-day variations with flux-doubling times ~2 minutes
   Much shorter than previous Mrk 501 and Mrk 421 observations

3 - Flux variability increases with energy

4 - Time delay of ~4 minutes between flare location at
   E <0.25 TeV and E > 1.2 TeV

5 - Spectra hardens with flux

6 - Detection of the IC peak in the SED for the most active nights

New IACTs increased our capability to study blazars (low/high)
GLAST will increase it further next year

Good times for gamma-ray astronomy !!