Study of the extreme flaring activity of Mrk 501: Multi-wavelength observations in 2012

Gareth Hughes, Amit Shukla, David Paneque, Francesco Borracci, Luis Reyes
on behalf of the MAGIC, VERITAS, FACT, Fermi-LAT collaborations, as well as GASP-WEBT, F-GAMMA

ICRC 2015
Outline

- Multi-wavelength Campaign 2012
  March to July
  (organized by David Paneque)

- Including: MAGIC, VERITAS, Fermi-LAT collaborations, as well as GASP-WEBT, F-GAMMA

- Here we present:
  - MWL data from Radio to VHE
  - Variability and Correlation studies
  - Comparison between MAGIC and FACT
  - TeV and X-ray Spectra
  - SED Modeling
Mrk 501 and MWL Campaigns

- Since 2009 campaigns have been organized in advance
- Source observed regardless of state
- Something unexpected/surprising is often observed

- Mrk 501:
  - nearby $z = 0.034$
  - First seen at VHE by Whipple (Quinn et al '96)
  - Quiescent state $<$ Crab nebula flux
  - Often shows large flaring events

- **Excellent laboratory** to study AGN
Light Curve

- Excellent coverage from Radio - TeV
- Over 25 instruments (not all shown)
Light Curve

- Excellent coverage from Radio -TeV
  Over 25 instruments (not all shown)

- Flare: 9th June
  Swift-XRT, MAGIC and FACT
  >10 CU above 1 TeV
Light Curve

- Excellent coverage from Radio - TeV
  Over 25 instruments (not all shown)

- Flare: 9th June
  Swift-XRT, MAGIC and FACT
  >10 CU above 1 TeV

- Swift-XRT sees a larger flare later: no observation by TeV instruments

- Shows the benefits of monitoring
Fractional Variability

- Highest variability at higher energies

- **Different to Mrk 421** where the maximum variability in the X-ray

- Measured X-ray emission of Swift relates mostly to the rising segment of the Synchrotron peak

- in Mrk 421 is the falling segment of the Sync peak

\[
F_{\text{var}} = \sqrt{\frac{S^2 - \langle O^2 \rangle}{\langle F^2 \rangle}}
\]

Fractional Variability

- Highest variability at higher energies

- **Different to Mrk 421** where the maximum variability in the X-ray

- Measured X-ray emission of *Swift* relates mostly to the rising segment of the Synchrotron peak

- in Mrk 421 is the falling segment of the Sync peak

\[
F_{\text{var}} = \sqrt{\frac{S^2 - \langle O^2 \rangle}{\langle F^2 \rangle}}
\]

*Vaughan S. et al MNRAS 345 (2003)*
X-ray TeV Correlation

- Compare X-ray and TeV Flux
- Swift-XRT 3-10 keV vs TeV data
- Data taken < 6 hours apart
- No correlation seen except the flare
MAGIC and FACT Light Curves

Excellent Agreement
TeV Spectra

MAGIC analysis:
Francesco Borracci

VERITAS analysis:
Luis Reyes

VERITAS

EBL Corrected
Spectra always hard

MAGIC
Spectral Fits

- TeV spectral index (de-absorbed) is **hard throughout the whole period**
- Does not follow Hardness-Brightness rule
- This is an extreme behavior
Modeling

- Modeling is being done by Amit Shukla
- Given the very hard X-ray spectra and TeV spectra makes modeling difficult/interesting

- Take every TeV spectra that is within 12 hrs of an X-ray spectra
- Fit using XSpec, Krawczynski SSC model and $\chi^2$ fitting
  

- Fit the X-ray and TeV data only
- Assuming that the optical/UV is dominated by a different component
  Very low variability detected, and in 2012 we see one of the lowest optical fluxes
- Applied both one and two zone models
Largest observed shift in IC peak
SED Modeling: Two Zone

Largest observed shift in IC peak
## SED Parameters

### One zone

<table>
<thead>
<tr>
<th>MJD</th>
<th>R [10^16 cm]</th>
<th>B [G]</th>
<th>Doppler [σ]</th>
<th>$\gamma_{\text{min}}$</th>
<th>$\gamma_{\text{max}}$</th>
<th>$\gamma_{\text{brk}}$</th>
<th>p1</th>
<th>p2</th>
<th>$U_r$ [10^3 erg/cm^3]</th>
<th>$y_{r/u_B}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>56009 V (2.50)</td>
<td>2.65</td>
<td>0.019</td>
<td>10</td>
<td>3.17</td>
<td>7.96</td>
<td>0.96</td>
<td>1.9</td>
<td>3.1</td>
<td>12.0</td>
<td>817</td>
</tr>
<tr>
<td>56015 V (2.30)</td>
<td>2.65</td>
<td>0.024</td>
<td>10</td>
<td>3.17</td>
<td>7.96</td>
<td>1.14</td>
<td>2.0</td>
<td>3.0</td>
<td>10.5</td>
<td>460</td>
</tr>
<tr>
<td>56032 M (1.60)</td>
<td>2.65</td>
<td>0.055</td>
<td>10</td>
<td>3.17</td>
<td>7.96</td>
<td>0.85</td>
<td>2.0</td>
<td>3.7</td>
<td>5.7</td>
<td>114</td>
</tr>
<tr>
<td>56036 M (1.80)</td>
<td>2.65</td>
<td>0.022</td>
<td>10</td>
<td>3.17</td>
<td>7.96</td>
<td>1.30</td>
<td>2.0</td>
<td>3.7</td>
<td>10.7</td>
<td>531</td>
</tr>
<tr>
<td>56038 V (1.90)</td>
<td>2.65</td>
<td>0.035</td>
<td>10</td>
<td>3.17</td>
<td>7.96</td>
<td>0.67</td>
<td>2.0</td>
<td>3.1</td>
<td>4.7</td>
<td>96</td>
</tr>
<tr>
<td>56040 M (1.04)</td>
<td>2.65</td>
<td>0.031</td>
<td>10</td>
<td>3.17</td>
<td>7.96</td>
<td>0.77</td>
<td>2.0</td>
<td>3.7</td>
<td>6.6</td>
<td>169</td>
</tr>
<tr>
<td>56046 V (1.40)</td>
<td>2.65</td>
<td>0.037</td>
<td>10</td>
<td>3.17</td>
<td>7.96</td>
<td>0.63</td>
<td>2.0</td>
<td>3.1</td>
<td>4.7</td>
<td>84</td>
</tr>
<tr>
<td>56061 V (2.00)</td>
<td>2.65</td>
<td>0.037</td>
<td>10</td>
<td>3.17</td>
<td>7.96</td>
<td>0.69</td>
<td>2.0</td>
<td>3.2</td>
<td>4.8</td>
<td>90</td>
</tr>
<tr>
<td>56066 V (2.50)</td>
<td>2.65</td>
<td>0.044</td>
<td>10</td>
<td>3.17</td>
<td>7.96</td>
<td>0.71</td>
<td>2.0</td>
<td>3.6</td>
<td>5.6</td>
<td>73</td>
</tr>
<tr>
<td>56073 V (1.10)</td>
<td>2.65</td>
<td>0.023</td>
<td>10</td>
<td>3.17</td>
<td>7.96</td>
<td>1.24</td>
<td>2.0</td>
<td>3.0</td>
<td>11.7</td>
<td>575</td>
</tr>
</tbody>
</table>

### Two zone

<table>
<thead>
<tr>
<th>MJD</th>
<th>R [10^16 cm]</th>
<th>B [G]</th>
<th>Doppler [σ]</th>
<th>$\gamma_{\text{min}}$</th>
<th>$\gamma_{\text{max}}$</th>
<th>$\gamma_{\text{brk}}$</th>
<th>p1</th>
<th>p2</th>
<th>$U_r$ [10^3 erg/cm^3]</th>
<th>$y_{r/u_B}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>56087 M (4.30)</td>
<td>2.65</td>
<td>0.017</td>
<td>10</td>
<td>3.17</td>
<td>7.96</td>
<td>1.41</td>
<td>1.9</td>
<td>3.0</td>
<td>20.7</td>
<td>1762</td>
</tr>
<tr>
<td>56090 V (3.20)</td>
<td>2.65</td>
<td>0.029</td>
<td>10</td>
<td>3.17</td>
<td>7.96</td>
<td>1.41</td>
<td>2.0</td>
<td>3.6</td>
<td>9.4</td>
<td>290</td>
</tr>
<tr>
<td>56094 M (0.63)</td>
<td>2.65</td>
<td>0.048</td>
<td>10</td>
<td>3.17</td>
<td>7.96</td>
<td>1.41</td>
<td>2.4</td>
<td>3.6</td>
<td>10.7</td>
<td>116</td>
</tr>
</tbody>
</table>

### Quiescent state

<table>
<thead>
<tr>
<th>MJD</th>
<th>R [10^16 cm]</th>
<th>B [G]</th>
<th>Doppler [σ]</th>
<th>$\gamma_{\text{min}}$</th>
<th>$\gamma_{\text{max}}$</th>
<th>$\gamma_{\text{brk}}$</th>
<th>p1</th>
<th>p2</th>
<th>$U_r$ [10^3 erg/cm^3]</th>
<th>$y_{r/u_B}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>56009 V (3.00)</td>
<td>0.33</td>
<td>0.093</td>
<td>10</td>
<td>8.93</td>
<td>7.96</td>
<td>1.00</td>
<td>2.0</td>
<td>3.7</td>
<td>19.27</td>
<td>556</td>
</tr>
<tr>
<td>56015 V (3.70)</td>
<td>0.33</td>
<td>0.123</td>
<td>10</td>
<td>8.93</td>
<td>7.96</td>
<td>1.00</td>
<td>2.0</td>
<td>3.7</td>
<td>14.65</td>
<td>243</td>
</tr>
<tr>
<td>56032 M (2.47)</td>
<td>0.33</td>
<td>0.185</td>
<td>10</td>
<td>8.93</td>
<td>7.96</td>
<td>0.63</td>
<td>2.0</td>
<td>3.6</td>
<td>6.41</td>
<td>47</td>
</tr>
<tr>
<td>56036 M (3.20)</td>
<td>0.33</td>
<td>0.094</td>
<td>10</td>
<td>8.93</td>
<td>7.96</td>
<td>1.00</td>
<td>2.0</td>
<td>3.7</td>
<td>16.20</td>
<td>458</td>
</tr>
<tr>
<td>56038 V (2.50)</td>
<td>0.33</td>
<td>0.128</td>
<td>10</td>
<td>8.93</td>
<td>7.96</td>
<td>0.89</td>
<td>2.0</td>
<td>3.7</td>
<td>8.50</td>
<td>93</td>
</tr>
<tr>
<td>56040 M (1.52)</td>
<td>0.33</td>
<td>0.132</td>
<td>10</td>
<td>8.93</td>
<td>7.96</td>
<td>0.63</td>
<td>2.0</td>
<td>3.7</td>
<td>8.34</td>
<td>120</td>
</tr>
<tr>
<td>56046 V (1.98)</td>
<td>0.33</td>
<td>0.160</td>
<td>10</td>
<td>8.93</td>
<td>7.96</td>
<td>0.91</td>
<td>2.0</td>
<td>3.6</td>
<td>5.55</td>
<td>54</td>
</tr>
<tr>
<td>56061 V (2.29)</td>
<td>0.33</td>
<td>0.160</td>
<td>10</td>
<td>8.93</td>
<td>7.96</td>
<td>0.79</td>
<td>2.0</td>
<td>3.7</td>
<td>5.80</td>
<td>56</td>
</tr>
<tr>
<td>56066 V (3.49)</td>
<td>0.33</td>
<td>0.320</td>
<td>10</td>
<td>8.93</td>
<td>7.96</td>
<td>1.00</td>
<td>2.3</td>
<td>3.7</td>
<td>5.70</td>
<td>14</td>
</tr>
<tr>
<td>56073 V (2.58)</td>
<td>0.33</td>
<td>0.099</td>
<td>10</td>
<td>8.93</td>
<td>7.96</td>
<td>1.12</td>
<td>2.0</td>
<td>3.1</td>
<td>19.00</td>
<td>480</td>
</tr>
<tr>
<td>56087 M (3.25)</td>
<td>0.33</td>
<td>0.092</td>
<td>10</td>
<td>8.93</td>
<td>7.96</td>
<td>1.12</td>
<td>1.8</td>
<td>3.7</td>
<td>35.40</td>
<td>1033</td>
</tr>
<tr>
<td>56090 V (4.35)</td>
<td>0.33</td>
<td>0.131</td>
<td>10</td>
<td>8.93</td>
<td>7.96</td>
<td>1.12</td>
<td>1.9</td>
<td>3.7</td>
<td>15.10</td>
<td>222</td>
</tr>
<tr>
<td>56094 M (1.18)</td>
<td>0.33</td>
<td>0.078</td>
<td>10</td>
<td>8.93</td>
<td>7.96</td>
<td>1.12</td>
<td>2.0</td>
<td>3.7</td>
<td>12.20</td>
<td>500</td>
</tr>
</tbody>
</table>
Summary

- Mrk 501 2012 MWL campaign collected an excellent dataset
- First MWL Paper with **FACT** (GAPD) data

- Fvar different to that of Mrk 421
- **No correlation** between X-ray and TeV

- 9th June caught an extraordinary **10 cu** (>1 TeV) flare
- IC Spectra **Peaks in the TeV**
  Largest IC peak shift seen
- **Index does not change** - throughout the time spectrum is always hard
- We do a good job of fitting the SEDs

- In 2012 Mrk 501 was an **extreme** BL Lac (Sync Peak >> 1 keV)