Photohadronic modelling of the 2010 gamma-ray flare from Markarian 421

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Motivations

Gamma-ray blazar samples and neutrino correlation studies:
- TANAMI BLAZAR SAMPLE + HESE (Krauß et al. 2014 & 2015);
- FERMI-LAT (70 months 2FGL catalogue) + HESE (track events) (Brown et al. 2015);
- FERMI-LAT (2FHL VHE sources E>50 GeV & 3LAC catalogue E>100 MeV) + HESE (Padovani et al. 2016); etc...

Possible neutrino sources associated with IceCube events:
- TXS 0506+056 and IC-170922A (Aartsen et al. 2018);
- 3HSP J095507.9+355101 & IceCube200107A (Giommi et al. 2020);
- PKS B1424-418 (FSRQ) and HESE IC35 (Kadler et al. 2016).

Hadronic emission as a possible explanation of observed gamma-ray spectral hardening at TeV energies
- 1ES 1101-232 and H 2356-309 (Aharonian et al. 2006);
- 1ES 0229+200 (Tavecchio et al. 2009);
- W Comae, 3C 66A (Böttcher et al. 2013).

Past and ongoing SED modelling for flaring blazars, including orphan TeV flares
- Markarian 501 Mücke & Protheroe (2001); 3C 279 Diltz & Böttcher (2016); TXS 0506+056 by numerous authors, etc...
a case study: Markarian 421

Mrk 421: prominent blazar (BL Lac)
RA=66.114°, Dec = 38.209°, z=0.031
near bright gamma-ray source (TeV),
highly active, constant monitoring (MWL campaign 2010)

2010 Flaring activity:
14-days in March 2010 (MJD 55264–55277)
remarkable flux variability at the VHE band (E > 100 GeV)

Let’s assume:
One-zone leptonic model (electron-synchrotron + SSC) + Hadronic ($p\gamma \rightarrow \Delta^+$-resonance approx)

Model output: PH contribution

$\sigma_{\text{peak}} \approx 500 \, \mu\text{barn}$, which is $5 \times 10^{-28} \, \text{cm}^2$, being this the dominant decay channel (~5x the direct channel)
Akaike Information Criterion

Akaike (1974)

Is a test used to compare and select a model from a set of models. Seeks the preferred model based on:

\[ AIC_s = -2 \ln(L_s) + 2k_f \]

1) goodness of the fit:
How close it is to the true values
\[ L_s = \text{Likelihood of a model } s \]

2) simplicity of the model:
\[ k_f = \text{Number of free parameters} \]

As a rule of thumb: Any model comparison with an AIC difference
\[ \Delta AIC_{p,q} = AIC_p - AIC_q \]

\[ p\gamma \text{ vs one-zone SSC (Aleksić et al., 2015)} \]
\[ p\gamma \text{ vs two-zone SSC (Aleksić et al., 2015)} \]

\[ \Delta_i \text{ Level of Empirical Support of Model } i \]

<table>
<thead>
<tr>
<th>( \Delta_i )</th>
<th>Level of Empirical Support of Model ( i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2</td>
<td>Substantial</td>
</tr>
<tr>
<td>4-7</td>
<td>Considerably less</td>
</tr>
<tr>
<td>&gt; 10</td>
<td>Essentially none.</td>
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Burnham and Anderson (2002).
Likelihood is assessed using a $\chi^2$ statistic.

Number of free parameters:

- $p_Y = 4$
- one-zone SSC = 5
- two-zone SSC = 4

## Results

<table>
<thead>
<tr>
<th>Time MJD</th>
<th>$A_\gamma$</th>
<th>$\alpha$</th>
<th>Preferred Model</th>
<th>$\Delta \text{AIC}_{\text{SSC, } \gamma \gamma}$</th>
<th>$\Delta \text{AIC}_{\text{two zone, SSC, } \gamma \gamma}$</th>
</tr>
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<tbody>
<tr>
<td>55266</td>
<td>5.02 ± 2.74</td>
<td>3.12 ± 0.07</td>
<td>two-zone SSC</td>
<td>25.45</td>
<td>−48.78</td>
</tr>
<tr>
<td>55267</td>
<td>27.24 ± 12.79</td>
<td>3.41 ± 0.09</td>
<td>$\gamma \gamma$</td>
<td>6.11</td>
<td>9.10</td>
</tr>
<tr>
<td>55274</td>
<td>0.19 ± 0.01</td>
<td>2.31 ± 0.03</td>
<td>inconclusive</td>
<td>2.54</td>
<td>0.73</td>
</tr>
<tr>
<td>55276</td>
<td>0.10 ± 0.02</td>
<td>2.17 ± 0.03</td>
<td>$\gamma \gamma$</td>
<td>26.40</td>
<td>2.04</td>
</tr>
<tr>
<td>55277</td>
<td>0.18 ± 0.02</td>
<td>2.32 ± 0.03</td>
<td>$\gamma \gamma$</td>
<td>5.92</td>
<td>2.90</td>
</tr>
</tbody>
</table>

- In most of cases the $\gamma \gamma$ model was favoured as a better fit description, and always with a respect to the one-zone leptonic model from Aleksic et al. (2015)

- The high frequency of the seed photons considered lowers the energy threshold for the protons: $40 \text{ GeV} < E_p < 2.45 \text{ TeV}$ (comoving reference frame)

- Above TeV energies is where the models differ the most, this can be tested further with the upcoming CTA.

- Neutrinos Expected? For IC-59, during the 14 days we calculated an upper limit of $N_{\text{events}} < 0.14$
Conclusions & Outlook

- Results show the potential of $p\gamma$ contributions within a lepto-hadronic origin of VHE gamma-rays and neutrinos

Advantages:
- Proton energy required for $p\gamma$ interactions
- Balance: goodness of the fit & simplicity

Caveats:
- Extension to lower energies?
- Data in the MeV energy range would enable a better description

- A hadronic component could be dominant at VHE, followed by a dominant SSC leptonic component. If the proton injection occurs randomly, there is no preferred time for hadronic dominance during the flare.

- To explore the neutrino/gamma-ray connection in the upcoming years, the next generation of gamma-ray and neutrino observatories, such as CTA, SWGO, AMEGO, IceCube-Gen2, Trinity, will play a crucial role.

- Future gamma-ray observations above tens of TeV (CTA) and below 100 MeV in energy (AMEGO) will be crucial to test and discriminate between models.
THANKS FOR YOUR ATTENTION

Durham University

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