CHARACTERIZING THE BRIGHTEST GAMMA-RAY FLARES OF FLAT SPECTRUM RADIO QUASARS

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ON BEHALF OF THE FERMI-LAT COLLABORATION
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FLAT SPECTRUM RADIO QUASARS AS GAMMA-RAY EMITTERS
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- Bright $\gamma$-ray emitters with extreme flares, 1/3 of Fermi observed AGNs [3LAC, Ackermann+ 2015]

- Variability on time scales of minutes observed above 100 MeV (100 GeV) for 2 (1) sources [e.g., Aleksic+ 2012, Ackermann+ 2015, Shukla+ 2018, and talks this session]

- Location and mechanism of $\gamma$-ray emission still unclear: lepto-hadronic / synchrotron self Compton / external Compton [e.g., Finke 2016 and references therein]

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SOURCE SELECTION AND ANALYSIS

• Goal: select brightest flares to guarantee high S/N spectra and ability to search for variability within one Fermi-LAT orbit

• Requirement: daily flux $> 10^{-5}$ ph cm$^{-2}$ s$^{-1}$ within $1\sigma$ uncertainty in weekly monitored light curves

• Perform Fermi-LAT analysis above 100MeV with 9.5 years of Pass 8 data

https://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl_lc/
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WEEKLY LIGHT CURVES
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BAYESIAN BLOCKS TO DETECT SIGNIFICANT VARIATIONS [SCARGLE+ 2012]
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IMPLEMENTATION OF HOP ALGORITHM / HILL CLIMBING [EISENSTEIN & HUT 1998] TO GROUP BAYESIAN BLOCKS
**WEEKLY LIGHT CURVES**

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[SCARGLE+ 2012]

**IMPLEMENTATION OF HOP ALGORITHM / HILL CLIMBING**

[EISENSTEIN & HUT 1998] TO GROUP BAYESIAN BLOCKS

**SELECT BRIGHT HOP GROUPS TO ZOOM IN ON SHORTER TIME SCALES (DAYS, ORBITS)**
Adaptive binning used so that flux uncertainty is ~ constant and 20% \cite{Lott et al. 2012}.

If Bayesian blocks indicate significant flux change within one orbit, perform $\chi^2$ test for constant flux to minimize trials.
SUB-ORBITAL LIGHT CURVES: SEARCH FOR VARIABILITY ON MINUTE TIME SCALES

PRELIMINARY
SUB-ORBITAL LIGHT CURVES: SEARCH FOR VARIABILITY ON MINUTE TIME SCALES

<table>
<thead>
<tr>
<th>$t_0$ [MJD]</th>
<th>$\Delta t$ [mins]</th>
<th>$\chi^2$/d.o.f.</th>
<th>$p$-value (post trial)</th>
<th>$p$-value (min($t_{var}$))</th>
<th>min($t_{var}$) [mins]</th>
</tr>
</thead>
<tbody>
<tr>
<td>57189.07</td>
<td>30.72</td>
<td>1.93</td>
<td>0.051 (1.95$\sigma$)</td>
<td>0.188 (1.32$\sigma$)</td>
<td>5.6</td>
</tr>
<tr>
<td>57189.14</td>
<td>35.13</td>
<td>1.68</td>
<td>0.071 (1.81$\sigma$)</td>
<td>0.254 (1.14$\sigma$)</td>
<td>3.6</td>
</tr>
<tr>
<td>57189.47</td>
<td>53.08</td>
<td>1.94</td>
<td>0.015 (2.42$\sigma$)</td>
<td>0.060 (1.88$\sigma$)</td>
<td>3.7</td>
</tr>
<tr>
<td>55854.07</td>
<td>50.80</td>
<td>2.01</td>
<td>0.091 (1.69$\sigma$)</td>
<td>0.173 (1.36$\sigma$)</td>
<td>7.9</td>
</tr>
</tbody>
</table>

3C279

PKS1510-089

55520.25    | 25.83             | 1.96            | 0.048 (1.98$\sigma$)  | 0.216 (1.24$\sigma$)     | 3.2                    |
SEARCH FOR ABSORPTION FEATURES IN SPECTRA

- Stratified BLR model with flattened geometry: emission lines emitted from rings perpendicular to jet [Finke 2016]

- Ring radii and line luminosities from reverberation mapping [Liu+ 2006; Torrealba+ 2012]

- Only free parameter: distance of γ-ray emission region to BH
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\[ t_{\text{cool}} \propto \frac{1}{u} \]

\[ \text{BLR/dust torus} \propto r^2 \]

BLR photons: \( \sim 10 \text{ mins} \); dust torus: \( \sim 10 \text{ hours} \) assuming jet properties from VLBI observations [Jorstad+ 2017]
CORRELATION ANALYSIS BETWEEN GAMMA-RAY AND RADIO LIGHT CURVES

- Search for time lags with local cross correlation function [Max-Moerbeck+ 2014]

- Radio observations:
  - SMA (1.3 mm / 230 GHz)
  - ALMA Band 3 (~3 mm / 100 GHz)
  - OVRO (15 GHz)
RESULTS FOR CROSS CORRELATION STUDY

- Correlations with significance > 2σ found for 3C273 (OVRO, SMA), CTA102 (ALMA), and 3C454.3 (OVRO, ALMA, SMA)
- γ-ray leads radio emission
- Distance between γ-ray and radio emitting zones:
  \[ d_{\gamma,r} = \frac{\Gamma \delta \beta c t_{\text{peak}}}{1 + z} \]
  [jet parameters from Jorstad+ 2017]
- Core position from VLBI observations [Lister+ 2016 and following Fuhrmann+ 2014]
- For 3C454.3 and CTA102: γ-ray emission consistent with mm emission produced at distances \( \gtrsim \) pc, however would drastically increase cooling time!

68%, 95%, 99% ENVELOPES FROM 5000 PAIRS OF SIMULATED LIGHT CURVES
CONCLUSIONS

• Carried out systematic study of brightest γ-ray emitting FSRQs with 9.5 years of LAT data

• Flaring episodes determined using Bayesian blocks and implementation of HOP algorithm

• Sources show complex flaring behaviour and flicker noise on longer time scales

• Evidence for variability on minute time scales found for 4 sources

• Absence of spectral BLR absorption features places γ-ray emitting region close to Lyα emitting BLR ring [see other talks this session]

• Evidence for correlation between γ-ray and radio emission found for 3 sources, consistent with co-spatial production of γ rays and mm emission, however, might conflict with short cooling times
BACK UP
WEEKLY, DAILY, ORBITAL LIGHT CURVES
WEEKLY, DAILY, ORBITAL LIGHT CURVES

Preliminary

Flux (E > 100 MeV) [10^{-15} erg cm^{-2} s^{-1}]
WEEKLY, DAILY, ORBITAL LIGHT CURVES

Preliminary

\[ F \times 10^{-6} \text{ cm}^{-2} \text{s}^{-1} \]
WEEKLY, DAILY, ORBITAL LIGHT CURVES

Preliminary

$F = \times 10^{-6} \text{cm}^{-2} \text{s}^{-1}$

$t-t_0$ [days]

$P_{\text{KS1222+216}}$

Bayesian blocks, $N_{\text{blocks}} = 79$

Average flux

$P_{\text{KS1510-089}}$

Bayesian blocks, $N_{\text{blocks}} = 71$

Average flux

$P_{\text{Cen A}}$

Bayesian blocks, $N_{\text{blocks}} = 118$

Average flux

$P_{\text{CTA102}}$

Bayesian blocks, $N_{\text{blocks}} = 119$

Average flux

$P_{\text{3C654.3}}$

Bayesian blocks, $N_{\text{blocks}} = 156$

Average flux
WEEKLY, DAILY, ORBITAL LIGHT CURVES
DETERMINING THE POWER SPECTRUM

- Best-fit periodogram derived from simulated light curves [following method of Max-Moerbeck+ 2014 and Emmanoulopoulos+ 2013]

- Best-fit power spectral density with power law with index ~ 1, flicker noise
FIT TO ORBITAL LIGHT CURVES

\[ F_0 \times \left[ \exp \left( \frac{t - t_0}{\tau_{\text{rise}}} \right) + \exp \left( \frac{t_0 - t}{\tau_{\text{decay}}} \right) \right]^{-1} \]
FIT TO ORBITAL LIGHT CURVES

- PKSB1222+216, $t_g = 2.0$ hrs
- 3C273, $t_g = 2.3$ hrs
- 3C279, $t_g = 0.5$ hrs
- PKS1510-089, $t_g = 0.4$ hrs
- CTA102, $t_g = 2.3$ hrs
- 3C454.3, $t_g = 1.9$ hrs
All sources show rise and decay times shorter than horizon crossing time (in observer’s frame)
FIT TO ORBITAL LIGHT CURVES: ASYMMETRY

- $A < 0$: fast rise exponential decay (FRED), could indicate particle injection and cooling
- $A \sim 0$: symmetric flares, could indicate beam sweeping through line of sight, or superposition of flares
- $A > 0$: exponential rise fast decay (ERFD)

$$A = \frac{\tau_{\text{rise}} - \tau_{\text{decay}}}{\tau_{\text{rise}} + \tau_{\text{decay}}}$$
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GAMMA-RAY OPACITY DUE PAIR PRODUCTION WITH BLR PHOTONS

\[ \tau_{\gamma\gamma}(\epsilon_1) = \int_{r}^{\infty} d\ell \int_{0}^{2\pi} d\phi \int_{-1}^{1} d\mu \]
\[ \times (1 - \cos \psi) \int_{0}^{\infty} d\epsilon \frac{u(\epsilon, \Omega; \ell)}{\epsilon m_e c^2} \]
\[ \times \sigma_{\gamma\gamma} \left[ \frac{\epsilon \epsilon_1 (1 + z)}{2} \right] (1 - \cos \psi) \]

[Model adapted from Finke 2016]
ENERGY DEPENDENT ORBITAL LIGHT CURVES

- Light curves only shown if at least 2 bayesian blocks per energy bin detected
- Time delay searched with ZDCF method [Alexander 1997, 2013]
- Positive and negative time lags are found, peak width of ZDCF consistent with zero lag
## RESULTS FOR SEARCH FOR GAMMA-RAY RADIO CORRELATION

<table>
<thead>
<tr>
<th>Source</th>
<th>$\hat{\beta}$</th>
<th>$p_\beta$</th>
<th>$\tau_{\text{peak}}$ [days]</th>
<th>$p_\tau$</th>
<th>$d_{\gamma,r}$ [pc]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>OVRO</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>PKSB1222+216</td>
<td>$1.92^{+0.39}_{-0.59}$</td>
<td>0.59</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3C273</td>
<td>$2.38^{+0.30}_{-0.97}$</td>
<td>0.94</td>
<td>$-416.5^{+217.0}_{-140.0}$</td>
<td>0.0068</td>
<td>10.96 [5.2, 14.6] ± 4.4</td>
</tr>
<tr>
<td>3C279</td>
<td>$2.29^{+0.32}_{-0.94}$</td>
<td>0.71</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PKS1510-089</td>
<td>$1.89^{+0.45}_{-0.84}$</td>
<td>0.34</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTA102</td>
<td>$2.23^{+0.26}_{-0.92}$</td>
<td>0.84</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3C454.3</td>
<td>$2.20^{+0.36}_{-2.20}$</td>
<td>0.40</td>
<td>$-101.5^{+49.0}_{-112.0}$</td>
<td>0.0156</td>
<td>15.39 [8.0, 32.4] ± 2.8</td>
</tr>
<tr>
<td><strong>ALMA Band 3</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3C273</td>
<td>$2.12^{+0.40}_{-2.12}$</td>
<td>0.73</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3C279</td>
<td>$1.82^{+0.35}_{-0.45}$</td>
<td>0.89</td>
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<tr>
<td>CTA102</td>
<td>$1.94^{+0.42}_{-1.33}$</td>
<td>0.45</td>
<td>$-216.0^{+209.0}_{-110.0}$</td>
<td>0.0092</td>
<td>58.85 [1.9, 61.8] ± 7.3</td>
</tr>
<tr>
<td>3C454.3</td>
<td>$1.73^{+0.36}_{-0.30}$</td>
<td>0.25</td>
<td>$-27.0^{+30.0}_{-30.0}$</td>
<td>0.0164</td>
<td>4.09 [−0.5, 8.6] ± 0.7</td>
</tr>
<tr>
<td><strong>SMA 1.3mm</strong></td>
<td></td>
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<tr>
<td>3C273</td>
<td>$1.48^{+0.40}_{-0.33}$</td>
<td>0.17</td>
<td>$-122.5^{+84.0}_{-7.0}$</td>
<td>0.0088</td>
<td>3.22 [1.0, 3.4] ± 1.3</td>
</tr>
<tr>
<td>3C279</td>
<td>$1.61^{+0.16}_{-0.28}$</td>
<td>0.97</td>
<td></td>
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<tr>
<td>3C454.3</td>
<td>$1.64^{+0.31}_{-1.64}$</td>
<td>0.21</td>
<td>$10.5^{+21.0}_{-28.0}$</td>
<td>0.0002</td>
<td>−1.59 [−4.8, 2.7] ± 0.3</td>
</tr>
</tbody>
</table>
CALCULATING THE COOLING TIME FOR EXTERNAL COMPTON SCATTERING

\[ t_{\text{cool, BLR}}/dt = \frac{1 + z}{\delta_D} \frac{3m_e c^2}{4c\sigma_T u'_{\text{BLR}}/dt} \gamma'_{\text{BLR}}/dt \]

\[ u'_{\text{BLR}}/dt,\text{ring} = \frac{\xi_\text{li} L_{\text{disk}}}{4\pi c (R_{\text{li}}^2 + r^2)} \]

\[ u_{\text{BLR}}/dt,\text{ring} = \frac{4}{3} \Gamma^2 u_{\text{BLR}}/dt,\text{ring} \]

\[ \gamma'_{\text{BLR}}/dt = \frac{1}{\delta_D} \sqrt{\frac{\epsilon_\text{s}^{\text{obs}} (1 + z)}{2\epsilon_{\text{BLR}}/dt,0}} \]

[E.g., Dermer & Schlickeiser 2002; Dermer & Menon 2009; Finke 2016]
SEARCH FOR ABSORPTION

PRELIMINARY
## Results for Search for Absorption

<table>
<thead>
<tr>
<th>$t_0$</th>
<th>$\Delta t$</th>
<th>$r_{\text{lim}}$</th>
<th>$r_{\text{lim}}$</th>
<th>$r_{\text{lim}}$</th>
<th>$E_{\text{HEP}}$</th>
<th>$E_{\gamma\gamma=1}$</th>
<th>$t_{\text{cool, BLR}}$</th>
<th>$t_{\text{cool, dt}}$</th>
<th>$\tau_{\text{decay}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[MJD]</td>
<td>[days]</td>
<td>[10^{17} cm]</td>
<td>[R_{Ly\alpha}]</td>
<td>[r_g]</td>
<td>[GeV]</td>
<td>[GeV]</td>
<td>[mins]</td>
<td>[hours]</td>
<td>[hours]</td>
</tr>
<tr>
<td>PKSB1222+216</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>8.2</td>
<td>26.8</td>
<td>47.4 ± 8.3</td>
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<tr>
<td>55364.68</td>
<td>3.42</td>
<td>1.33</td>
<td>1.40</td>
<td>609</td>
<td>75.39</td>
<td>69.69</td>
<td></td>
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<tr>
<td>3C279</td>
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<td></td>
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<td>2.7</td>
<td>19.0</td>
<td>0.5 ± 0.9</td>
</tr>
<tr>
<td>57188.07</td>
<td>1.87</td>
<td>0.49</td>
<td>0.64</td>
<td>867</td>
<td>56.03</td>
<td>42.91</td>
<td>9.0</td>
<td>19.0</td>
<td>8.2 ± 6.3</td>
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<tr>
<td>58133.34</td>
<td>5.32</td>
<td>1.45</td>
<td>1.91</td>
<td>2580</td>
<td>92.56</td>
<td>107.91</td>
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<tr>
<td>PKS1510-089</td>
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<td></td>
<td>0.6</td>
<td>4.5</td>
<td>0.4 ± 0.3</td>
</tr>
<tr>
<td>57114.16</td>
<td>1.42</td>
<td>0.51</td>
<td>0.66</td>
<td>1088</td>
<td>66.54</td>
<td>54.99</td>
<td>0.8</td>
<td>4.5</td>
<td>44.4 ± 9.4</td>
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<td>1591</td>
<td>75.93</td>
<td>65.39</td>
<td></td>
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<tr>
<td>CTA102</td>
<td></td>
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<td>1.0</td>
<td>6.4</td>
<td>0.3 ± 0.5</td>
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<tr>
<td>57737.41</td>
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<td>0.86</td>
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<td>6.4</td>
<td>8.7 ± 1.2</td>
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<tr>
<td>57749.10</td>
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<td>3.20</td>
<td>1.95</td>
<td>1275</td>
<td>73.80</td>
<td>37.94</td>
<td>2.2</td>
<td>6.4</td>
<td>24.6 ± 2.3</td>
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<tr>
<td>57757.55</td>
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<td>2.76</td>
<td>1.67</td>
<td>1096</td>
<td>39.19</td>
<td>32.38</td>
<td>1.4</td>
<td>6.4</td>
<td>1.2 ± 0.7</td>
</tr>
<tr>
<td>57861.71</td>
<td>2.42</td>
<td>1.95</td>
<td>1.18</td>
<td>776</td>
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