Following the flare of PKS 1502+106 with mm-VLBI imaging and light curve modelling

Vassilis Karamanavis

Max Planck Institute for Radio Astronomy

Why PKS 1502+106?

- FSRQ with $M_\bullet \approx 10^9 M_\odot$
at $z = 1.839$

- Motivation:
  In 2008 *Fermi/LAT* discovered a bright high-energy flare from PKS 1502+106

- followed by delayed radio emission

Fuhrmann et al. 2014
Why PKS 1502+106?

- FSRQ with $M_* \approx 10^9 M_\odot$ at $z = 1.839$

- Motivation:
  In 2008 Fermi/LAT discovered a bright high-energy flare from PKS 1502+106

- followed by delayed radio emission

Opportunity:
Jet physics (esp. $\gamma$-ray emission mechanism) of a distant blazar after a prominent $\gamma$-ray flare
What is addressed here and how?

1. Spatial localization of the γ-ray emission region
What is addressed here and how?

1. Spatial localization of the γ-ray emission region

2. Constraining the seed photon field for EC
   - Accretion disk
   - BLR photons
   - IR torus
   - other
What is addressed here and how?

1. Spatial localization of the $\gamma$-ray emission region

2. Constraining the seed photon field for EC
   - Accretion disk
   - BLR photons
   - IR torus
   - other ...

By combining VLBI and single-dish data at multiple frequencies
PKS 1502+106 in its finest detail

- **15 GHz**
  - 19 observing epochs between 2002–2011
  - VLBA
  - MOJAVE program
    (Lister et al. 2009)

- **43 GHz**
  - 6 epochs (2009–2012)
  - VLBA

- **86 GHz**
  - 6 epochs (2009–2012)
  - GMVA (VLBA + European stations)
  - Simultaneous with 43 GHz
PKS 1502+106 in its finest detail

- **15 GHz**
  - 19 observing epochs between 2002–2011
  - VLBA
  - MOJAVE program (Lister et al. 2009)

- **43 GHz**
  - 6 epochs (2009–2012)
  - VLBA

- **86 GHz**
  - 6 epochs (2009–2012)
  - GMVA (VLBA + European stations)
  - Simultaneous with 43 GHz

1 mas = 8.5 pc

**15 GHz**: (0.15%–19.2%) x 2.8 Jy/b

**43 GHz**: (0.1%–12.8%) x 3.5 Jy/b

**86 GHz**: (0.15%–19.2%) x 2.2 Jy/b
PKS 1502+106 in its finest detail

- One-sided core–jet morphology
- Bent jet at pc-scales

1 mas = 8.5 pc

15 GHz: (0.15%–19.2%) x 2.8 Jy/b
43 GHz: (0.1%–12.8%) x 3.5 Jy/b
86 GHz: (0.15%–19.2%) x 2.2 Jy/b
PKS 1502+106 in its finest detail

- One-sided core–jet morphology
- Bent jet at pc-scales
- 3 knots cross-identified travelling in different parts of the jet
  - With C3 seen only at 43 and 86 GHz

1 mas = 8.5 pc

15 GHz: (0.15%–19.2%) x 2.8 Jy/b
43 GHz: (0.1%–12.8%) x 3.5 Jy/b
86 GHz: (0.15%–19.2%) x 2.2 Jy/b
PKS 1502+106 in its finest detail

\[ \beta_{\text{app}} \& \ t_{\text{ej}} \]

C1 (22c, 2002)

C2 (9c, 2006)

C3 (7c, 2008.3)

Karamanavis et al. 2016a

1 mas = 8.5 pc
PKS 1502+106 in its finest detail

\[ \beta_{\text{app}} \quad \text{&} \quad t_{\text{ej}} \]

- C1 (22c, 2002)
- C2 (9c, 2006)
- C3 (7c, 2008.3)

Karamanavis et al. 2016a

\[ l \text{mas} = 8.5 \text{ pc} \]

\[ \delta \]

(i) Kinematics, (ii) Variability (Jorstad et al. 2005), and
(iii) Magnetic field from SSA (Marscher 1983) and Equipartition (e.g. Bach et al. 2005)

- C1 (22c, 2002, \( \delta = 22–50 \))
- C3 (7c, 2008.3, \( \delta = 7–13 \))
What only mm-VLBI can do!

Flux density evolution of jet features

Gray area: Full flare duration
Red line: Ejection time of C3 ± uncertainty
What only mm-VLBI can do!

Flux density evolution of jet features

Core and C3 drive the flare (C3 in decaying phase)

Gray area: Full flare duration
Red line: Ejection time of C3 ± uncertainty
What only mm-VLBI can do!

Gray area: Full flare duration
Red line: Ejection time of C3 ± uncertainty

Core and C3 drive the flare (C3 in decaying phase)
What only mm-VLBI can do!

- Core and C3 drive the flare (C3 in decaying phase)
- C3’s ejection time coincides with the onset of γ-ray activity and
- Only C3 can be associated with the flare

Gray area: Full flare duration
Red line: Ejection time of C3 ± uncertainty
Single-dish add-ons
\[ \gamma - \text{rays } > 100\text{MeV} \]

**F-GAMMA program**

(Fuhrmann et al. 2016)
Extraction of parameters:

- Flare amplitude,
- Flare time scales, and
- Time delays of flare maxima at different frequencies (cross-band delays)

\[ \gamma\text{-rays} > 100\text{MeV} \]
2.64 GHz
4.85 GHz
8.35 GHz
10.45 GHz
14.60 GHz
23.05 GHz
32.00 GHz
43.00 GHz
86.24 GHz
142.33 GHz
345.00 GHz

γ-rays > 100 MeV

Gaussian process regression

DCCF
10.45/15.00 GHz
Various methods used for light curve fitting:

- Exponential flares
- Gaussian fits
- Other…
Various methods used for light curve fitting:

- Exponential flares
- Gaussian fits
- Other…

**BUT**

parametric models; i.e. all assume a $f(x)$
Gaussian processes & regression

Various methods used for light curve fitting:

- Exponential flares
- Gaussian fits
- Other…

BUT

Parametric models; i.e. all assume a $f(x)$

GPs are generalized Gaussian distributions over functions;

i.e. collection of functions characterized by a mean and a st. dev.

See Rasmusen & Williams 2006
Gaussian processes & regression

Various methods used for light curve fitting:
• Exponential flares
• Gaussian fits
• Other…

BUT
parametric models;
i.e. all assume a $f(x)$

GPs are generalized Gaussian distributions over functions;
i.e. collection of functions characterized by a mean and a st. dev.

See Rasmussen & Williams 2006
Gaussian processes & regression

Various methods used for light curve fitting:
- Exponential flares
- Gaussian fits
- Other…

BUT
parametric models;
i.e. all assume a $f(x)$

GPs are generalized Gaussian distributions over functions;
i.e. collection of functions characterized by a mean and a st. dev.

The only assumption going into them is the covariance kernel that generates them:

$$k(x_i, x_j) = \sigma_f^2 \exp \left[ -\frac{(x_i - x_j)^2}{2l^2} \right]$$

Defines the covariance between two $f$ values at $x_i$ and $x_j$

Maps our prior beliefs for the underlying process

See Rasmusen & Williams 2006
Gaussian processes & regression

Prior distribution
We optimize, i.e. select the functions that pass through all observations.
Gaussian processes & regression

Prior distribution

Posterior distribution

Training on data

We optimize, i.e. select the functions that pass through all observations.

Roberts et al. 2011
Gaussian processes & regression

Prior distribution

Posterior distribution

We optimize, i.e. select the functions that pass through all observations.

Posterior mean and confidence interval
Gaussian processes & regression

Prior distribution

Posterior distribution

Training on data

We optimize, i.e. select the functions that pass through all observations.

Posterior mean and confidence interval
Gaussian processes & regression

Prior distribution

Training on data

Posterior distribution

We optimize, i.e. select the functions that pass through all observations.

Posterior mean and confidence interval
Gaussian processes & regression

- J1504+1029, PKS1502+106
- Flux Density (Jy)
- MJD

**4.85 GHz**
- Posterior mean
- 95% confidence interval
- Observations at 4.85 GHz

**14.6 GHz**
- Posterior mean
- 95% confidence interval
- Observations at 14.6 GHz

**23 GHz**
- Posterior mean
- 95% confidence interval
- Observations at 23 GHz

**86 GHz**
- Posterior mean
- 95% confidence interval
- Observations at 86 GHz
GPs offer:

- An elegant alternative to parametric fitting
- Results generally free of biases
- Very good error estimation
- Vast domain of application (not only blazars!)
Jet nuclear opacity & the HE emission

- Flare maxima show time delays wrt highest frequency

\[ \alpha \nu^{-1/k_r} \]

GP : \( k_r = 1.4 \pm 0.1 \)

DCCF: \( k_r = 1.8 \pm 0.2 \)
Jet nuclear opacity & the HE emission

- Flare maxima show time delays wrt highest frequency
- Due to optical depth; i.e. synchrotron opacity (Lobanov 1998, Hirotani 2005)
Jet nuclear opacity & the HE emission

• Flare maxima show time delays wrt highest frequency

• Due to optical depth; i.e. synchrotron opacity (Lobanov 1998, Hirotani 2005)

• Tomography of the jet in terms of nuclear opacity (VLBI-free core shifts)
  (e.g. Kudryavtseva et al. 2011, Kutkin et al. 2013)

<table>
<thead>
<tr>
<th>$\nu$ (GHz)</th>
<th>$r_{\text{core}}$ (pc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.64</td>
<td>10.2 ± 1.2</td>
</tr>
<tr>
<td>4.85</td>
<td>7.1 ± 1.0</td>
</tr>
<tr>
<td>8.35</td>
<td>5.3 ± 0.8</td>
</tr>
<tr>
<td>10.45</td>
<td>4.8 ± 0.8</td>
</tr>
<tr>
<td>14.60</td>
<td>4.0 ± 0.7</td>
</tr>
<tr>
<td>15.00</td>
<td>3.8 ± 0.7</td>
</tr>
<tr>
<td>23.05</td>
<td>2.6 ± 0.6</td>
</tr>
<tr>
<td>32.00</td>
<td>2.9 ± 1.0</td>
</tr>
<tr>
<td>43.05</td>
<td>3.4 ± 0.8</td>
</tr>
<tr>
<td>86.24</td>
<td>4.0 ± 1.1</td>
</tr>
</tbody>
</table>

Karamanavis et al. 2016b
Jet nuclear opacity & the HE emission

- Flare maxima show time delays wrt highest frequency
- Due to optical depth; i.e. synchrotron opacity (Lobanov 1998, Hirotani 2005)
- Tomography of the jet in terms of nuclear opacity (VLBI-free core shifts)
  (e.g. Kudryavtseva et al. 2011, Kutkin et al. 2013)

\[
\alpha \nu^{-1} / k_r
\]

<table>
<thead>
<tr>
<th>$\nu$ (GHz)</th>
<th>$r_{core}$ (pc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.64</td>
<td>10.2 ± 1.2</td>
</tr>
<tr>
<td>4.85</td>
<td>7.1 ± 1.0</td>
</tr>
<tr>
<td>8.35</td>
<td>5.3 ± 0.8</td>
</tr>
<tr>
<td>10.45</td>
<td>4.8 ± 0.8</td>
</tr>
<tr>
<td>14.60</td>
<td>4.0 ± 0.7</td>
</tr>
<tr>
<td>15.00</td>
<td>3.8 ± 0.7</td>
</tr>
<tr>
<td>23.05</td>
<td>2.6 ± 0.6</td>
</tr>
<tr>
<td>32.00</td>
<td>2.9 ± 1.0</td>
</tr>
<tr>
<td>43.05</td>
<td>3.4 ± 0.8</td>
</tr>
<tr>
<td>86.24</td>
<td>4.0 ± 1.1</td>
</tr>
</tbody>
</table>

Karamanavis et al. 2016b
Jet nuclear opacity & the HE emission

- Flare maxima show time delays wrt highest frequency
- Due to optical depth; i.e. synchrotron opacity (Lobanov 1998, Hirotani 2005)
- Tomography of the jet in terms of nuclear opacity (VLBI-free core shifts) (e.g. Kudryavtseva et al. 2011, Kutkin et al. 2013)
- **Relative distance between the 3mm core and HE site** (Fuhrmann et al. 2014)

Karamanavis et al. 2016b
Jet nuclear opacity & the HE emission

• Flare maxima show time delays wrt highest frequency

• Due to optical depth; i.e. synchrotron opacity (Lobanov 1998, Hirotani 2005)

• Tomography of the jet in terms of nuclear opacity (VLBI-free core shifts) (e.g. Kudryavtseva et al. 2011, Kutkin et al. 2013)

• Relative distance between the 3mm core and HE site (Fuhrmann et al. 2014)

• With our absolute distance of the 3mm core from the jet base (~4 pc)
Jet nuclear opacity & the HE emission

- Flare maxima show time delays wrt highest frequency
- Due to optical depth; i.e. synchrotron opacity (Lobanov 1998, Hirotani 2005)
- Tomography of the jet in terms of nuclear opacity (VLBI-free core shifts) (e.g. Kudryavtseva et al. 2011, Kutkin et al. 2013)
- **Relative distance** between the 3mm core and HE site (Fuhrmann et al. 2014)
- With our **absolute distance of the 3mm core from the jet base** (~4 pc)
- Managed to constrain the site of HE emission to **about 2 pc from the base**

Karamanavis et al. 2016b
Jet nuclear opacity & the HE emission

- Flare maxima show time delays wrt highest frequency
- Due to optical depth; i.e. synchrotron opacity (Lobanov 1998, Hirotani 2005)
- Tomography of the jet in terms of nuclear opacity (VLBI-free core shifts) (e.g. Kudryavtseva et al. 2011, Kutkin et al. 2013)

- **Relative distance** between the 3mm core and HE site (Fuhrmann et al. 2014)
- With our **absolute distance** of the 3mm core from the jet base (~4 pc)
- Managed to constrain the site of HE emission to **about 2 pc** from the base

  - **Important:** BLR radius for PKS 1502+106 = 0.1 pc (Abdo et al. 2010)
  
  - BLR photon field too dilute [ $n(R) \propto 1/R$; Poutanen & Stern (2010) ]

Karamanavis et al. 2016b
Conclusions

1. mm-VLBI allowed us to pinpoint the component connected with the intense gamma-ray flare from PKS 1502+106 (C3)
Conclusions

1. mm-VLBI allowed us to pinpoint the component connected with the intense gamma-ray flare from PKS 1502+106 (C3)

2. High-energy emission originates from a region ~2 pc away from the jet base.
Conclusions

1. mm-VLBI allowed us to pinpoint the component connected with the intense gamma-ray flare from PKS 1502+106 (C3)

2. High-energy emission originates from a region ~2 pc away from the jet base.

3. We can readily exclude accretion disk and Broad-Line Region (BLR) photons as targets for External Compton (ERC)
Conclusions

1. mm-VLBI allowed us to pinpoint the component connected with the intense gamma-ray flare from PKS 1502+106

2. High-energy emission originates from a region $\sim$2 pc away from the jet base.

3. We can readily exclude accretion disk and Broad-Line Region (BLR) photons as targets for External Compton (ERC)

4. Photon field of the IR torus could play a role here
   – In addition to the Synchrotron Self-Compton (SSC) mechanism
Thank you!
Lots of hidden slides
Doppler and Lorentz factors

1. Kinematics
   \[ \gamma_{\text{min}} = \sqrt{\beta_{\text{app}}^2 + 1} \] (e.g. Urry & Padovani 1995)
   1. C1: \( \delta_{\text{min}} \approx \gamma_{\text{min}} \approx 22 \)
   2. C2: \( \delta_{\text{min}} \approx \gamma_{\text{min}} \approx 9 \)
   3. C3: \( \delta_{\text{min}} \approx \gamma_{\text{min}} \approx 7 \)

2. Variability of components (causality arguments and size of the emitting region) (Jorstad et al. 2005)
   1. C1: \( \delta_{\text{var}} \leq 52 \) and \( \gamma_{\text{var}} \leq 31 \) (15 GHz)
   2. C3: \( \delta_{\text{var}} \leq 12–15 \) and \( \gamma_{\text{var}} \leq 7–9 \) (43 & 86 GHz)

3. Magnetic field from SSA (Marscher 1983) and Equipartition (e.g. Bach et al. 2005)
   \[ \frac{B_{\text{eq}}}{B_{\text{SSA}}} = \delta_{\text{eq}}^{2/7}\alpha. \]
   - C1: \( \delta_{\text{eq}} \approx 50 \)
Intrinsic jet properties

Components C1 and C3 travel in two distinct regions within the jet:

- C1 at >1 mas and C3 < 0.5 mas

  **C1:**  $20 < \gamma < 30$
  $0.8^\circ \leq \theta \leq 2.5^\circ$

  **C3:**  $7 < \gamma < 10$
  $4^\circ \leq \theta \leq 8^\circ$

  (with conservative error estimates)

Karamanavis et al. 2016a
Intrinsic jet properties

- The Doppler factor difference (~40) cannot be ascribed only to differential Doppler boosting; i.e. jet bending towards us.

- Acceleration must also be taking place within the first mas = 8.5 pc. At least, from $\gamma = 10$ to 22.

$C1: 22 \leq \delta \leq 50$ and $\beta_{\text{app}} \approx 22$

$C3: 7 \leq \delta \leq 12–13$ and $\beta_{\text{app}} \approx 3–8$

(with conservative error estimates)
Flux density evolution of jet features

Gray area: Full flare duration
Red line: Ejection time of C3 ± uncertainty
Jet nuclear opacity structure & B-field

<table>
<thead>
<tr>
<th>( \nu ) (GHz)</th>
<th>( \tau ) (d)</th>
<th>( r_{\text{core}} ) (pc)</th>
<th>( B_{1\text{pc}} )</th>
<th>( B_{1\text{pc min}}, B_{1\text{pc max}} )</th>
<th>( B_{\text{core}} )</th>
<th>( B_{\text{core min}}, B_{\text{core max}} ) (mG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.64</td>
<td>196.1 ± 11.1</td>
<td>9.91 ± 0.01</td>
<td>169</td>
<td>[93, 314]</td>
<td>17</td>
<td>[9, 32]</td>
</tr>
<tr>
<td>4.85</td>
<td>140.9 ± 12.1</td>
<td>7.43 ± 0.02</td>
<td>189</td>
<td>[101, 363]</td>
<td>25</td>
<td>[14, 49]</td>
</tr>
<tr>
<td>8.35</td>
<td>106.2 ± 13.8</td>
<td>5.93 ± 0.05</td>
<td>217</td>
<td>[109, 440]</td>
<td>37</td>
<td>[18, 74]</td>
</tr>
<tr>
<td>10.45</td>
<td>95.8 ± 15.2</td>
<td>5.52 ± 0.06</td>
<td>235</td>
<td>[114, 495]</td>
<td>43</td>
<td>[21, 90]</td>
</tr>
<tr>
<td>14.60</td>
<td>75.2 ± 8.8</td>
<td>4.59 ± 0.08</td>
<td>243</td>
<td>[122, 493]</td>
<td>53</td>
<td>[27, 107]</td>
</tr>
<tr>
<td>15.00</td>
<td>61.1 ± 3.1</td>
<td>3.75 ± 0.08</td>
<td>194</td>
<td>[106, 365]</td>
<td>52</td>
<td>[28, 97]</td>
</tr>
<tr>
<td>23.05</td>
<td>38.4 ± 4.6</td>
<td>2.62 ± 0.13</td>
<td>174</td>
<td>[91, 340]</td>
<td>66</td>
<td>[35, 130]</td>
</tr>
<tr>
<td>32.00</td>
<td>30.8 ± 2.2</td>
<td>2.35 ± 0.17</td>
<td>196</td>
<td>[105, 373]</td>
<td>83</td>
<td>[45, 159]</td>
</tr>
<tr>
<td>43.05</td>
<td>36.4 ± 1.4</td>
<td>3.20 ± 0.22</td>
<td>354</td>
<td>[180, 712]</td>
<td>112</td>
<td>[56, 222]</td>
</tr>
<tr>
<td>86.24</td>
<td>23.9 ± 0.9</td>
<td>4.12 ± 0.41</td>
<td>807</td>
<td>[370, 1799]</td>
<td>196</td>
<td>[90, 437]</td>
</tr>
</tbody>
</table>

Diagram:

- GP: \( k_{\tau} = 1.4 \pm 0.1 \)
- DCCF: \( k_{\tau} = 1.8 \pm 0.2 \)

Equation: \( \alpha \nu^{-1/k_{\tau}} \)
The HE emission site

- From the time-lag core shifts the position of the 86 GHz core can be decisively constrained to $\sim 4.0$ pc

- So can the $\gamma$-ray emitting region:

\[
\begin{align*}
\Phi_{\text{int}} & \quad \text{Time lag 3mm core,} \\
86 \text{ GHz} & \quad \tau = 1 \\
d_{\text{core}} & = 4.0 \pm 1.1 \text{ pc}
\end{align*}
\]

Karamanavis et al. 2016b
The shock origin of component C3

- Different variability mechanisms predict different signatures in the time domain,

- The flare origin can be explored through the comparison of the frequency dependence of light curve parameters:
  - amplitude, time scales, cross-band delays

- …with expectations of the shock-in-jet model (Marscher & Gear 1985)
The shock origin of component C3

Frequency dependence of light curve parameters in agreement with expectations from a shock propagating downstream the jet

Flare amplitude

Flare rise & decay time scales

Cross-band delays

\(d = -0.3\)

\(d = 0\)

\(d = 0.3\)

(Fromm et al. 2014)
For the SE kernel, the vector of hyperparameters is \( \mathbf{\theta} = \{l, \sigma^2\} \) and the probability (or evidence) of the training data \( y \), given the hyperparameters vector \( \mathbf{\theta} \), is \( p(y \mid x, \mathbf{\theta}) \). The log marginal likelihood is given by

\[
\mathcal{L} = \log p(y \mid x, \mathbf{\theta}) = -\frac{1}{2} y^T k_n^{-1} y - \frac{1}{2} \log |k_n| - \frac{n}{2} \log 2\pi. \tag{3}
\]

More generally, in the case of a hyperparameter vector \( \mathbf{\theta} = \{\theta_j \mid j = 1, \ldots, n\} \), the derivatives of the log marginal likelihood with respect to each \( \theta_j \) are

\[
\frac{\partial \mathcal{L}}{\partial \theta_j} = \frac{1}{2} y^T \frac{\partial k_n}{\partial \theta_j} \left( k_n^{-1} y - \frac{1}{2} \text{Trace} \left( k_n^{-1} \frac{\partial k_n}{\partial \theta_j} \right) \right). \tag{4}
\]

By means of numerical gradient optimization algorithms one can maximize the log marginal likelihood using Eq. 4 and obtain the best set of hyperparameters (for an outline of the algorithm see [19]).