HIGH-RESOLUTION MONITORING OF PC-SCALE JETS IN THE FERMI ERA

November 10th, 2011
Fermi and Jansky Meeting, St. Michaels, MD, USA
Eduardo Ros (Univ. Valencia & MPIfR)
Gamma and radio sky

Collage: M. Kadler (images by MOJAVE & NASA)
Fermi/LAT catalogs

- Since EGRET we know that the gamma-sky is dominated by the Galactic Plane, PSR, and Blazars
- The 1st Fermi-LAT catalog (Abdo+’10) contains 1400 sources, from which ½ are AGN
- 2nd Fermi-LAT catalog (2LAC, submi.) contains 1749 sou.*
  - 950 are AGN
    - 360 FSRQ
    - 420 BL Lac (60% have z)
    - 160 unknown
    - 20 other AGN

* Numbers from Lott’s talk at CTA meeting
The gamma sky is extragalactic

- *Fermi*/LAT shows that BL Lacs are the most common γ-emitters, over flat spectrum radio quasars
- Big biases are present, both in γ and radio:
  - Doppler beaming: orientation bias
  - Luminosity grows with redshift: Malmquist bias
  - Spectral Energy Distribution (jet contribution, directly probed by radio)
VLBI capabilities

- VLBI shows beamed sources:
  - Superluminal speeds
  - One-sided core-jet structure
  - Compact core emission (high $T_b$)
  - Rapid variability in jets
Blazar Characteristics

- Powerful jets oriented towards the observer
- High $T_b$ (VLBI targets)
- Smaller apparent speeds than QSOs, especially for TeV sources (smaller viewing angles?)
- Predominantly high-synchrotron-peaked (HSP) sources

Note:
HSP $\Rightarrow \nu_p > 10^{15}$ Hz;
ISP $\Rightarrow 10^{14}$ Hz $< \nu_p < 10^{15}$ Hz;
LSP $\Rightarrow \nu_p < 10^{14}$ Hz
Blazars in radio and gamma-rays

- **Major open questions:**
  - What makes a particular blazar gamma-ray loud?
  - Where in the jet do gamma-rays originate?
  - What is the gamma-ray production mechanism?
Observing

- Blazars are being detected and observed by
  - Fermi/LAT
  - AGILE
  - VHE telescopes (VERITAS, MAGIC, HESS)
- Radio-γ-connection
- Blazars are imaged and monitored by VLBI arrays
  - Ideally: multi-wavelength, multi-epoch, polarization
Properties probed by VLBI

- Multifrequency/phase-referencing ➔ core-shift ➔ magnetic field, pressure gradients, etc.
- $T_b$ (usually of $\approx 10^{12}$ in core, dropping to $\approx 10^{10}$ or lower in jet)
- Shocks and/or instabilities (components/features)
- Linear and circular polarization ➔ magnetic field orientation
- Structural changes ➔ helical jets, binary BH hypothesis
- Ejection times for traveling components, related to core flux density outbursts
- Interaction from moving with standing shocks
VLBI today

- **Astronomy:**
  - Antennas worldwide
    - Predominantly at the Northern Hemisphere
    - Hardly present in South Africa or South America
  - Frequencies from 330 MHz ($\lambda$90cm) to 86 GHz ($\lambda$3.6mm)
  - Australian, European, North American and East Asian arrays

- Trend towards telescopes connected by optical fibre (eVLBI)

- **Geodesy:**
  - Sparse network in all continents, operation at 2.3/8.4 GHz
    - Preliminary plans for a continuous 1-14 GHz receiver system
VLBI Arrays

VLBA

EVN

LBA

HSA

GMVA

VERA

Geodetic Array
The quest for resolution

Resolution = Observing wavelength / Telescope diameter

<table>
<thead>
<tr>
<th>Angular Resolution</th>
<th>Optical (5000Å)</th>
<th>Radio (4cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Diameter</td>
<td>Instrument</td>
</tr>
<tr>
<td>1’</td>
<td>2mm</td>
<td>Eye</td>
</tr>
<tr>
<td>1&quot;</td>
<td>10cm</td>
<td>Amateur Telescope</td>
</tr>
<tr>
<td>0.”05</td>
<td>2m</td>
<td>HST</td>
</tr>
<tr>
<td>0.”001</td>
<td>100m</td>
<td>Interferometer</td>
</tr>
</tbody>
</table>

Atmosphere gives 1" limit without corrections which are easiest in radio

Jupiter and Io as seen from Earth

1 arcmin 1 arcsec 0.05 arcsec 0.001 arcsec
Parsec-scale properties

- Directly measured:
  - Apparent speed $\beta_{app}$
  - Comp. flux density $S$
  - Brightness temperature $T_b$
  - Apparent opening angle $\psi$
  - Luminosity $L_R$
  - P.A. misalignment with kpc $\Delta \phi$
  - Spectral index $\alpha$
  - Lin. polarisation angle $\chi$
  - Lin. polarisation level $m$

- Indirectly:
  - Viewing angle $\theta$
  - Lorentz factor $\Gamma$
  - Doppler factor $\delta$
  - Component ej. epoch $t_0$

**y-properties**

- Direct properties:
  - Detection (yes/not)
  - Flaring activity
  - Flux $S_{\gamma}$
  - Luminosity $L_{\gamma}$
  - Photon index $\Gamma$

- SED properties:
  - Gamma-radio loudness $G_r$
  - High-energy peak frequency vIC factor $\nu_{IC}$

**Det** | **Histograms**, selecting by opt. class ad HBL/IBL/…

<table>
<thead>
<tr>
<th>Det</th>
<th>Fl.</th>
<th>$S_\gamma$</th>
<th>$L_\gamma$</th>
<th>$\Gamma$</th>
<th>$G_r$</th>
<th>$\nu$</th>
</tr>
</thead>
</table>

CORRELATION PLOTS
Basic relations

- Lorentz factor and apparent speed
  \[ \Gamma = \frac{1}{\sqrt{1 - \beta^2}} \quad \beta_{\text{app}} = \frac{\beta \sin \theta}{1 - \beta \cos \theta} \]
  \[ \beta_{\text{app,max}} = \beta \Gamma \quad \cos \theta_{\text{max}} = \beta \]

- Doppler factor
  \[ \delta = \frac{1}{\Gamma \sqrt{1 - \beta^2} \cos \theta} \]

- Intrinsic and apparent opening angles \( \psi \)
  \[ \psi_{\text{int}} = \psi_{\text{app}} \sin \theta \]

- Intrinsic and observed Tb and luminosity
  \[ L_{\text{obs}} = L_{\text{int}} \times \delta^{n+\alpha} \quad (n = 2, 3) \]
  \[ T_{b,\text{obs}} = T_{b,\text{int}} \times \delta \]
Basic relations (ii)

- Variability Doppler factor from flux density variations:

  \[ \tau_{\text{obs}} = \frac{dt}{d(\ln S)} \]

  \[ T_{b,\text{obs(var)}} = 5.87 \times 10^{21} h^{-2} \frac{\lambda^2 S_{\text{max}}}{\tau_{\text{obs}}} \left(\sqrt{1 + z} - 1\right)^2 \]

  \[ \delta_{\text{var}} = 3 \left( \frac{T_{b,\text{obs(var)}}}{T_{b,\text{int}}} \right) \quad \text{(} T_{b,\text{int}} = 5 \times 10^{10} K) \]

- \( \beta_{\text{app}} \) & \( \delta_{\text{var}} \) provide viewing angle \( \theta \) and bulk Lorentz factor \( \Gamma \):

  \[ \theta = \arctan \frac{2 \beta_{\text{app}}}{\beta_{\text{app}}^2 + \delta_{\text{var}}^2 - 1} \]

  \[ \Gamma = \frac{\beta_{\text{app}}^2 + \delta_{\text{var}}^2 + 1}{2 \delta_{\text{var}}} \]

Hovatta et al. 2009 A&A 494 527
Surveys: an overview

\[ N_{\text{epochs}} \]

\[ \sqrt{N_{\text{sources}}} \]

**\( \lambda \)**
- 13cm
- 6cm
- 3.6cm
- 2cm
- 13mm
- 7mm

**CJF**
- 3e, 293s

**MOJAVE**
- \( \sim 30 \text{ e. } 300 \text{ s} \)

**TANAMI**
- 3.6cm
- \( \sim 5 \text{ e. } 80 \text{ s} \)

**Boston Univ.**
- \( \sim 50 \text{ e. } 35 \text{ s} \)

**VIPS Extension**
- 2e., 100 s

**VIPS**
- 1e. 1100 s

**Bologna low-z**
- 2 e. 42 s

**TeV Sample**
- \( \sim 5 \text{ e. } 7 \text{ s} \)
Main survey programs (tabulated)

<table>
<thead>
<tr>
<th>Program</th>
<th>$\lambda$</th>
<th>$N_{\text{sources}}$</th>
<th>$N_{\text{epochs}}$ &amp; Obs.</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boston Univ.</td>
<td>7mm</td>
<td>35</td>
<td>50 (2007-now)</td>
<td>Marscher, Jorstad +</td>
</tr>
<tr>
<td>TeV Sample</td>
<td>7mm (+1.3/3.6cm)</td>
<td>7</td>
<td>5 (2006-now)</td>
<td>Piner+ 2010 ApJ 723 1150</td>
</tr>
<tr>
<td>MOJAVE</td>
<td>2cm</td>
<td>300</td>
<td>20 (1994-now)</td>
<td>Lister+ 2009 AJ 138 1874</td>
</tr>
<tr>
<td>Bologna low-z</td>
<td>2/3.6cm</td>
<td>42</td>
<td>2 (2010-now)</td>
<td>Giroletti+’11</td>
</tr>
<tr>
<td>TANAMI</td>
<td>1.3/3.6cm</td>
<td>80</td>
<td>5 (2008-now)</td>
<td>Ojha+’10, Kadler+’11</td>
</tr>
<tr>
<td>VIPS</td>
<td>6cm</td>
<td>1127</td>
<td>1 (2007)</td>
<td>Hemboldt+’07</td>
</tr>
<tr>
<td>VIPS subsample</td>
<td>6cm</td>
<td>100</td>
<td>2 (20010-now)</td>
<td>Linford+’11</td>
</tr>
<tr>
<td>CJF</td>
<td>6cm</td>
<td>293</td>
<td>3 (1990s)</td>
<td>Taylor+’96, Pearson+’98</td>
</tr>
<tr>
<td>VCS &amp; Co.</td>
<td>3.6/13cm</td>
<td>$10^2$</td>
<td>$10^{0-3}$ (1990s-now)</td>
<td>Kovalev+’09 &amp; Co.</td>
</tr>
</tbody>
</table>

Selection criteria: usually flux and spectrum based
Survey goals
(e.g. MOJAVE)

- Overall distribution of superluminal speeds and intrinsic velocities in jets?
- Location of acceleration and collimation area
- Trajectories of components within jets?
  - Same speeds?
  - Curved or straight?
  - Accelerations or deccelerations present?
- Velocity relation to nature of host galaxy?
- Differences between bulk flow and pattern velocity?
- Nature of material responsible of polarization alterations?
- Mechanism of production of circular polarization?
- Gamma ray emission and jet activity correlation?

Adapted from http://www.physics.purdue.edu/astro/MOJAVE/project.html
VLBI Imaging and Polarimetry Survey (VIPS)

- 1127 sources at 5 GHz
- One epoch, pre-Fermi era
- Polarisation included
- Followed by VLBA observations of 100 blazars (at least two epochs) – P.I. G.B. Taylor

See Linford’s Talk
VIPS Extension

- Median value in core fractional polarization is 3.5% for $\gamma$-detected and 4.4% for non-$\gamma$

- Brightness temperature of $\gamma$-bright higher than non-$\gamma$

LAT sources have unusually large opening angles

10 sources with opening angles larger than 30deg
TeV Blazars VLBA Monitoring

- VLBA images of TeV Blazars including polarimetry
- Mostly at 43 GHz
- Sampled sources:
  - Mrk 421, Mrk 501, H 1426+428, 1ES 1959+650, PKS 2155−304, 1ES 2344+514
- New, recent additions (AAS#218 #327.05):
  - 1ES 1101−232, Mrk 180, 1ES 1218+304, PG 1553+113, H 2356−309
- All new detected components have $\beta_{\text{app}} < 2c$

Fig. 8 in Piner, Pant & Edwards 2010 ApJ 723 1150

Note: several of these sources are being also observed by Giroletti et al. with the EVN

10nov11
MOJAVE
The Brightest Radio Galaxies in the Northern Sky
MOJAVE:

- 28% overlap in samples of bright $\gamma$-rays and radio-selected AGN

1FM:
- 118 sources bright at $\gamma$-rays

1FM-matching sample
- 105 left ($S_{\text{VLBA}} \geq 1.5$ Jy)
MOJAVE program

- Milliarcsecond-resolution, full Stokes images
- Currently ~300 sources monitored
- Continuous long-term monitoring, good sensitivity, source-specific observing cadences ➔ High-quality jet motions
- Large, well-defined sample ➔ Statistics, properties of the parent population
- Calibrated data are made public

https://www.physics.purdue.edu/astro/mojave/
MOJAVE results on jet kinematics

Accurate kinematics of 526 features in 127 jets over 12 years:

*Image of the jet:*

*Trajectory of the moving feature:*

Lister et al. 2009, AJ 138, 1874
MOJAVE results on jet kinematics

- Dispersion of $\beta_{\text{app}}$ within individual jet is >3 times smaller than the overall dispersion among all jets
  - characteristic speed describing each jet, reflected by obs. proper motions
- $\text{Max}(\beta_{\text{app}})$ distribution peaks at ~10c and ranges up to 50c
  - Lorentz factors >10 are common
  - maximum Lorentz factor of the parent population is ~50
MOJAVE results on jet kinematics

Over 1/3 of the bright features show acceleration:

- Parallel accelerations are generally larger than perpendicular accelerations → changes in intrinsic speed are common – not only changes in jet direction.
- Prevalent positive acceleration (speeding up) close to the core (within 15 pc) → jets are still becoming organized in parsec scales. ➔ see jet launching models.

MOJAVE – Viewing angle

- γ-ray bright sources have a narrower viewing angle than γ-quiet
- (LBAS: 3-months AGN list)

Savolainen et al. A&A 2010 512 A24

See Lister’s Talk
MOJAVE pc-scale properties

- AGN with wide apparent opening angles tend to have high γ-ray loudness values
- HSP BL Lac objects have low core $T_b$
- No trend between radio core polarization degree or vector offset and γ-loudness

![Graph](image)

All highest opening angle jets >40º are γ-bright

Similar result obtained by the TANAMI team (Ojha et al. 2010 A&A 519 A45) and by the VIPS γ-sample (Linford et al. 2011 ApJ 726 16)
MOJAVE-Fermi results

- LAT-detected AGN have higher apparent speeds
BU Blazar Monitoring

- Study of 35 blazars at 43 GHz, observed monthly by the VLBA
- High spatial and time resolution, with polarimetry
- (Lack of) opacity: closer view the core region and the birth of new features traveling downstream
- Several studies presented individually in publications
- Calibrated data are made public

http://www.bu.edu/blazars/
BU Blazar Monitoring

- High levels of $\gamma$-ray activity coincide with the production of superluminal knots and their passage through stationary features in the jet
- Outburst in $\gamma$-rays occur parsecs downstream of the central engine

See Jorstad & Marscher Talks
TANAMI Project
Tracking AGN with Austral Milliarcsecond Interferometry

- Monitoring of ~80 Southern Sources at 8.4 GHz and 22 GHz
- Addition of antennas in Chile and Antarctica provide unprecedented austral resolution at 8.4 GHz
- Observations since November 2007, 2-month cadence

http://pulsar.sternwarte.uni-erlangen.de/tanami/
TANAMI results

- Several ‘terra incoginta’ sources
- SPIX images are being produced
- In data collection phase, first proper motions coming
- Individual source studies being processed
Individual Source Studies
M 87

- eEVN observations by M. Giroletti after a TeV flare (09feb2010, ATel2431)

Giroletti et al. EVN Symp 2010 (PoS 047)

- Role of HST1 is unclear (see Cheung et al. 2007 and Chang et al. 2010)
3C84

- At the Perseus cluster, $z=0.017559$
- VERA observations report a jet component ($\beta_{\text{app}} \sim 0.23c$) getting brighter during a $\gamma$-flare
IC310

- Close galaxy at the Perseus cluster (z=0.0189)
- VHE source detected by MAGIC, also detected by Fermi LAT
- 1\textsuperscript{st} VLBI obs ever on May 2011, discovered the blazar-like parsec-scale, one-sided structure

BL Lac

- 3 major γ-flares reported (25jan10, ATel2402; 16feb11, ATel3171; 22may11, ATel3368)
- Present in major surveys
  - MOJAVE $\beta_{\text{app}} \sim 10.6c$
- Frequent ejection of jet features

SPIX map from VLBA data: for $\delta \sim 7.3$, $B < 3G$

OJ 287

- Change in jet direction since 2005
- Flares A and B happen at the same time components pass through C1 (quasi-stationary shock?)

4C +21.35 (1222+216)

- Jorstad et al. 2011 eConf C110509 arXiv: 1111.0110 report a superluminal component K1 with 14c crossing a stationary jet simultaneously to the \( \gamma \)-high state
3C273

- Relationship between VLBI core and gamma-ray flare (delay implies location distance of 4-11 pc)

Also studied by the BU program, see below

Lisakov & Kovalev (Fermi Symp. 2011)
3C 345

- QSO $z = 0.593$, $\beta_{\text{app}} \approx 20$, $\delta \approx 8$, $\theta = (2.6-6)^\circ$, $\psi_{\text{app}} \approx 12.9^\circ$

- Radio flares in the jet have a $\gamma$-counterpart, 40pc away from core

- SSC should produce $\gamma$-emission
RL-NSL1: PMN J0948+0022

- Radio-loud narrow-line Seyfert 1 Galaxy (RL NLS1) detected in gamma
- eEVN observations, 3 epochs so far
- $3.4 \times 10^{11}$ K
- Similar to flat-spectrum radio quasar

Giroletti et al. (2011, A&A 528, L11)
Other sources

- **3C 454.3**
  - Intensively studied in VLBI

- **Centaurus A**
  - Only source with $\gamma$-emission beyond pc-scales
  - TANAMI results reported by Abdo et al. 2010 719 1433 and Müller et al. 2011 A&A 530 L11

- **Mrk 421**
  - Monitored by 2cmSurvey/MOJAVE (0.04-0.3c) and by Giroletti et al. at several frequencies

- **PKS 1510−089**
  - Huge change in $\chi$ during a major $\gamma$-flare
Other sources (ii)

- **3C 273**
  - 4 new components since Fermi/LAT, with $\beta_{\text{app}} \sim 4-7$ (0.7 knots/yr)
  - Fastest coincides with $\gamma$-flare

- **3C 279**
  - 2 new knots, $\beta_{\text{app}} \sim 16-19$, also related with $\gamma$-activity

- **AO 0235+164**
  - Claim of 70c component related to $\gamma$-flare
LSI+61°303 – a precessing microblazar

- Strong and variable γ-ray source (Fermi/LAT, MAGIC, VERITAS)
- Re-analysis of 2006 VLBA data (Massi, Ros & Zimmermann, A&A subm.):
  - Radio emission with double structure
  - Peaks of the image trace a defined ellipse in (27-30)d: precession period
- Model for emission processes in blazars?

See Massi’s Poster
Filling the table of γ--radio-pc-scale properties

| Det       | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ | ☑ | ✔ | ✔ | ✔ |
| Flaring   | ✔ | ✔ | ✔ |  ✔ |  ✔ |  ✔ |  ✔ |  ✔ |  ✔ |  ✔ |
| Sγ        | ✔ | ✔ | ✗ |  ✔ |  ✔ |  ✔ |  ✔ |  ✔ |  ✔ |  ✔ |
| Lγ        | ✔ | ✔ | ✗ |  ✔ |  ✔ |  ✔ |  ✔ |  ✔ |  ✔ |  ✔ |
| Γ         | ✗ | ✔ | ✗ |  ✔ |  ✔ |  ✔ |  ✔ |  ✔ |  ✔ |  ✔ |
| Gr        | ✔ | inv | ✔ |  ✔ |  ✔ |  ✔ |  ✔ |  ✔ |  ✔ |  ✔ |
| V_{IC,SED} | ✔ | ✔ | ✔ |  ✔ |  ✔ |  ✔ |  ✔ |  ✔ |  ✔ |  ✔ |

MOJAVE
VIPS
BU
TANAMI

TeV: transverse changes

PERMANENTLY UNDER CONSTRUCTION
Some evidences

- Changes in pc-scale emission are related to $\gamma$-activity
- $\gamma$-activity related to changes in polarization
- $\delta$ seems to be higher at $\gamma$-active stages
- Warning: $\gamma$-samples are very biased, and the radio samples are usually flux-density selected
- No source with low $L_\gamma$ has high $\beta_{\text{app}}$
Answering some questions

1. Do the gamma-ray flares originate in relativistic shocks? *Probably.*

2. At what distance from the central engine is the main energy dissipation site? *It depends on who you are asking.*

3. What is the dominant emission mechanism? *Synchrotron in the radio, wait for talks and discussion*

4. What determines the ratio of gamma-ray luminosity to the synchrotron luminosity? *A conspiracy of facts (modulated by Doppler!)*
What remains

- Collecting VLBI data at low and high frequencies at both hemispheres
- Intensive campaigns on selected sources
- Important connection to single-dish flux density monitoring results (not covered in this talk)
- Need for frequent mm-wavelength images, to address the core neighbourhood