Parsec-Scale Radio Properties of Gamma-ray Emitting Blazars

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FERMI AND JANSKY - OUR EVOLVING UNDERSTANDING OF AGN
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The Tools: Fermi & VLBI

- The Fermi Gamma-ray Space Telescope
  - Large Area Telescope (LAT)
  - Wide-field
  - Covers ~20 MeV to 300 GeV

- VLBI
  
  NASA

  NRAO/AUI & NASA/GSFC

  Paul Boven & NASA

  Tasso Tzioumis, ATNF
Our Sample

LAT-detected

- 244 sources from 1LAC catalog
  - 102 VIPS sources (90 observed in 2 epochs)
  - 7 MOJAVE sources
  - 135 sources not in VIPS or MOJAVE

- VIPS observations made prior to and during 2006
- New observations made between Nov. 2009 and July 2010

Non-LAT

- VIPS: VLBA Imaging and Polarimetry Survey (Helmboldt et al. 2007)
- 1018 non-LAT sources
- 5 GHz (6 cm)
Lister et al. (2011) used the ratio of $\gamma$-ray to radio luminosity as a measure of $\gamma$-ray loudness

All of our LAT sources are $\gamma$-ray loud
Flux-Flux Correlation

- **BL Lacs**
  - Rho = 0.467
  - P = 2x10\(^{-6}\)
  - Correlation

- **FSRQs**
  - Rho = 0.510
  - P = 2x10\(^{-8}\)
  - Correlation

- **AGN/Other**
  - Rho = 0.443
  - P = 0.014
  - Tentative correlation

- **Radio and γ-ray emission are probably related**

LAT fluxes: 100 MeV – 100 GeV
Flux Densities

LAT FSRQs have higher core and total 5 GHz flux densities than non-LAT FSRQs

LAT FSRQs appear to be extreme sources
The percentage of sources found to be polarized is higher for LAT blazars than for non-LAT blazars.

Strong, uniform magnetic fields in the cores are tied to γ-ray emission.

VIPS: data taken prior to or during 2006
VIPS+: Follow-up on 90 VIPS/LAT sources plus 7 MOJAVE/LAT sources, 2009-2010
VIPS++: 135 LAT sources not in VIPS or MOJAVE, 2010
Core Polarization

- LAT sources are more likely to be polarized.
  - LAT: 176/232 (75.9%)
  - Non-LAT: 270/1018 (26.5%)

- Fractional polarization is slightly less for LAT sources.
  - LAT median: 3.3%
  - Non-LAT median: 4.4%
  - This is different from other studies (e.g. Hovatta et al. 2010)

- FSRQ core fractional polarization may be different for LAT and non-LAT
  - K-S test: 0.4% probability that they are drawn from same parent population

LAT sources are polarized more often, but do not appear to be more strongly polarized
48 of 90 sources showed higher core fractional polarization during LAT detection

15 sources had no detectable core polarization in both epochs

Only 3 sources went from polarized in archival data to unpolarized in new data
K-S tests indicate that the FSRQs are very different, but BL Lac objects are similar.

Median core $T_B$ s for FSRQS:
- LAT: $6.4 \times 10^{10}$ K
- Non-LAT: $2.5 \times 10^{10}$ K

LAT FSRQs are extreme sources
Core Brightness Temperature Correlations

- We found a significant correlation between core $T_B$ and $\gamma$-ray loudness
  - 1FGL: $\rho=-0.3$, $p=2\times10^{-6}$
  - 2FGL: $\rho=-0.3$, $p=8\times10^{-5}$

- We also found a correlation between core $T_B$ and peak synchrotron frequency, but only for BL Lacs
  - $\rho=-0.4$, $p=10^{-4}$
Jet Opening Angle

- Only had opening angle measurements for 49 LAT sources.
- There is evidence that LAT sources have larger opening angles, especially FSRQs.
- K-S test done on combined BL Lac-FSRQ samples showed 0.4% chance that LAT and non-LAT distributions are related.
Lister et al. (2011) reported a non-linear relation between jet opening angle and γ-ray loudness.

We also found a hint of a correlation, but only for FSRQs and only in the 2FGL data:
- 1FGL: $\rho=0.2, p=0.34$
- 2FGL: $\rho=0.6, p=0.009$
Jet bending ($\Delta PA$) and jet length distributions are very similar for LAT and non-LAT sources.

LAT FSRQs appear to have higher jet brightness temperatures than non-LAT FSRQs (K-S test: $10^{-5}$)

FSRQ jet brightness temperatures
Our LAT BL Lac sample is almost 4 times the size of our non-LAT sample
- Possibly a selection effect – could there be a population of dim BL Lacs that do not produce γ-rays?

3 small differences between LAT and non-LAT BL Lac populations:
- LAT BL Lacs have core polarization more often (70% LAT vs. 42% non-LAT)
- LAT BL Lacs are more often “long-jet” morphology
- LAT BL Lacs may have larger opening angles

It seems likely that all BL Lacs are producing γ-rays, but some are just below the LAT threshold
FSRQs

- LAT FSRQs appear to be very different from the non-LAT FSRQs
  - Higher radio flux densities
  - Higher core and jet brightness temperatures
  - More often polarized (90% LAT, 33% non-LAT)
  - May have larger opening angles

- 28 of 44 LAT FSRQs with observations in 2 epochs showed an increase in core polarization during LAT detection
FSRQs

- It seems that the LAT FSRQs are extreme sources.
- The LAT FSRQs can be explained with Doppler boosting, but they require a substantially higher Doppler factor than the LAT BL Lacs.
- Lister et al. (2009) reported that the median jet speeds for LAT FSRQs were more than a factor of 2 faster than for the LAT BL Lacs.
Correlation between radio flux density and LAT flux implies synchrotron and inverse Compton emission are related
- $\gamma$-rays should be coming from jets

Most of the differences between LAT and non-LAT samples are related to the cores
- $\gamma$-rays should be coming from the BASE of the jets

It is possible that BL Lacs and FSRQs have different $\gamma$-ray production mechanisms
- BL Lacs may be synchrotron self-Compton (SSC)
- FSRQs may be external inverse Compton (EC) – seed photons may come from broad-line region (BLR)
Conclusions

- BL Lacs are probably all producing gamma-rays, but we don’t detect some because of low Doppler factors and/or variability.
- Gamma-ray loud FSRQs are extreme sources with high radio flux densities and high brightness temps.
- There is a hint that LAT blazars have larger jet opening angles than non-LAT blazars.
- Strong, uniform magnetic fields in the cores/at the base of the jets play a role in γ-ray emission.
- The γ-rays are probably coming from the base of the jets.
Backup slides
Inverse Compton scattering

2 possibilities

- Synchrotron Self-Compton (SSC) – seed photons are from the electrons’ own synchrotron emission
- External Inverse Compton (EC) – seed photons are from some external source

Diagrams from venables.asu.edu
No Strong Redshift Correlations

BL Lacs

LAT-z: $\rho = 0.08$, $P = 54\%$

$S_5$-z: $\rho = 0.31$, $P = 2.1\%$

FSRQs

LAT-z: $\rho = 0.02$, $P = 87\%$

$S_5$-z: $\rho = 0.11$, $P = 26\%$

$\gamma$-ray flux is in units of $10^{-9}$ ph cm$^{-2}$ s$^{-1}$
Core Brightness Temperatures (New vs. old)

Nearly all of the sources had new core $T_B$ measurements within 5% of the old measurement, or showed an increase in core $T_B$. 
# Source Morphology

<table>
<thead>
<tr>
<th>LAT/ non-LAT</th>
<th>Opt Type</th>
<th>LJET (&gt;6mas)</th>
<th>SJET (&lt;6mas)</th>
<th>PS</th>
<th>CPLX</th>
<th>CSO</th>
<th>N/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BL Lac</td>
<td></td>
<td>55 (58%)</td>
<td>25 (26%)</td>
<td>12 (13%)</td>
<td>5 (3%)</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>FSRQ</td>
<td></td>
<td>54 (50%)</td>
<td>30 (28%)</td>
<td>21 (20%)</td>
<td>2 (1%)</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td>21 (70%)</td>
<td>5 (17%)</td>
<td>4 (13%)</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Non-LAT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BL Lac</td>
<td></td>
<td>11 (46%)</td>
<td>7 (29%)</td>
<td>6 (25%)</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>FSRQ</td>
<td></td>
<td>188 (39%)</td>
<td>121 (25%)</td>
<td>136 (28%)</td>
<td>2 (~1%)</td>
<td>30 (6%)</td>
<td>2 (~1%)</td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td>214 (42%)</td>
<td>98 (19%)</td>
<td>111 (21%)</td>
<td>11 (2%)</td>
<td>71 (14%)</td>
<td>10 (2%)</td>
</tr>
</tbody>
</table>
The major difference between the LAT and non-LAT AGN/Others is that 43% of the LAT sources have polarization in their cores, compared to only about 20% for the non-LAT AGN/Others.

Note: we used the optical classification system from the 1LAC (Abdo et al. 2010). There is controversy about the classification of several of the objects we call AGN/Other.
Stawarz et al. (2008) predicted there should be many CSOs among LAT detections due to inverse Compton scattering of ultrarelativistic electrons in their lobes.

However, there are no compact symmetric object candidates among the LAT sources in our sample or any other survey, to date.