The connection between radio and gamma-ray emission in relativistic jets in the Fermi era and beyond

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Relativistic Jets: Creation, Dynamics, and Internal Physics
Krakow, 23 Apr 2015
• *Fermi* & gamma-ray emission

• radio-gamma connection with MeV/GeV data

• radio-gamma connection with E>10 GeV data

• future

• references at the end
Fermi catalogues

- four main catalogues: 0FGL (3 months of data, 205 sources), 1FGL (11 months, 1451 src), 2FGL (2yr, 1873 src), 3FGL (4yr, 3033 src)
  - each one accompanied by a dedicated AGN catalogue (LBAS, 1LAC, 2LAC, 3LAC, talk by Lott)
Gamma-ray AGN demographics

- EGRET: 66 blazar (+27 low conf., FSRQ:BLL=4.7)
- LBAS: 106 AGN (FSRQ:BLL=1.4)
- 1LAC: 709 AGN (FSRQ:BLL=1.0)
- 2LAC: 1017 AGN (FSRQ:BLL=0.8)
- 3LAC: 1591 AGN (FSRQ:BLL=0.7)
- Only a few unidentified sources remain at high fluxes
- Gamma-ray sources continue to be associated to radio loud objects
  - Vast majority (97.3%) of Fermi high-b associated sources are blazars
  - Non blazar sources are typically misaligned blazars (MAGN, Abdo et al. 2010c), or very blazar-like sources (RL NLS1, Abdo et al. 2009b)
  - Only truly non blazar sources are Cen A lobes and a handful of starbursts
Radio and gamma-ray emission in blazars: Spectral Energy Distribution

3c279 Ra=194.04653 deg Dec=-5.78931 deg (NH=2.0E20 cm^-2)

Low, Intermediate, High synchrotron peaked blazars
Radio and gamma-ray emission in blazars

• synchrotron radio emission originates from relativistic e\(^-\) that can upscatter photons to high energy
  – leptonic models naturally predict some connection between radio and gamma-ray emission
  – all EGRET AGNs were radio loud, differently from most X-ray QSOs

• the blazar sequence was originally devised on the basis of the radio luminosity

• evidence or not of flux-flux, Lum-Lum correlations is a debated issue
  – Stecker et al. (1993), Mücke et al. (1997), Bloom (2008), etc.
  – bias, variability, number of sources, etc.
• Big questions
  – is there a correlation between radio and gamma-ray emission in AGNs?
  – is it also significant?
  – does it depend on simultaneity?
  – does it depend on blazar type?
  – does it depend on energy band?

• See also works from Kovalev et al. (2009), Ghirlanda et al. (2010, 2011), Mahony et al. (2010)

• We base our work on
  – 0.2” angular resolution archival 8.4 GHz for all 599 AGNs
  – 15 GHz single dish simultaneous data for 199 AGNs
  – 1LAC data in 5 energy sub-bands between 0.1-100 GeV
Main novelties

1. Include ALL gamma-ray AGNs
   – faintest ones (typically, BL Lacs) are not included in most other works
2. Use both archival and simultaneous radio data
3. Assess statistical significance with dedicated tools
   – Pavlidou et al. (2012)
Results

- All 599 1LAC clean sources
- black: with redshift
- magenta: without redshift
- correlation coefficient: $r=0.47$

NB no unassociated sources have gamma-ray flux larger than $4 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ (green dashed line)

how many times can we get such $r$ from random datasets, with the same flux density and luminosity dynamic ranges?

– well, less than once in ten million cases!

• probability of chance correlation: $P<1e^{-7}$
Timing

- Considering the subset of sources regularly monitored by OVRO, the correlation coefficient and the significance improve when considering simultaneous vs archival data

  - gamma-ray vs 15 GHz **non concurrent** data:
    - Spearman’s rho=0.36, Pearson’s r=0.42, significance=$1.9\times10^{-6}$

  - gamma-ray vs 15 GHZ **concurrent** data:
    - Spearman’s rho=0.39, Pearson’s r=0.46, significance=$9\times10^{-8}$

- number of sources considered: 160
Additional tests: 2 - blazar types

- **Comments:**
  - BL Lacs show a moderately stronger correlation than FSRQs
  - Each sub-class (FSRQ and BLL) independently still shows very high significance of a correlation (chance prob. < 1e-7)
  - HSP blazars have the stronger correlation among the various SED-based classification

<table>
<thead>
<tr>
<th>source type</th>
<th>corr. coeff.</th>
<th># sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>All sources</td>
<td>0.43</td>
<td>599</td>
</tr>
<tr>
<td>FSRQ</td>
<td>0.39</td>
<td>248</td>
</tr>
<tr>
<td>BL Lacs</td>
<td>0.46</td>
<td>275</td>
</tr>
<tr>
<td>LSP</td>
<td>0.4</td>
<td>242</td>
</tr>
<tr>
<td>ISP</td>
<td>0.33</td>
<td>60</td>
</tr>
<tr>
<td>HSP</td>
<td>0.55</td>
<td>129</td>
</tr>
</tbody>
</table>
Additional tests: 3 - energy bands

- not all LAT energy bands correlate with radio with the same strength...
  - for the whole 1LAC, the strongest correlation is found using Band 2 (0.3-1 GeV)
- in every band, HSP blazars are the subclass with the largest correlation coefficient
  - except for Band 1 (0.1-0.3 GeV), where there’s very few of them
Discussion #1

- Correlation is highly significant, but scatter is large
  - connected but different physical processes
    - leptonic contribution generally present
  - connected but different time domains (and emitting regions)
    - study of light curves, SEDs, and jet structure evolution remains very valuable for single sources (Hovatta, Lister, Jorstad talks)
    - concurrent data do correlate better
  - gamma-ray flux/luminosity can not be predicted on the basis of the radio flux density/luminosity
    - caveat for gamma-ray background studies
    - and many (moderately) bright FSRQs are still undetected in 1LAC/2LAC/3LAC
Discussion #2

- We studied flux-flux correlations to avoid square-distance effects common for luminosity.
  - Luminosities remain of great interest both at high and low values.
- Great discovery space at low luminosity ($L_r \sim 10^{39-41}$ erg s$^{-1}$) for intrinsically weak and/or misaligned blazars.
• We studied flux-flux correlations to avoid square-distance effects common for luminosity
  – luminosities remain of great interest both at high and low values

  • great discovery space at low luminosity ($L_r \sim 10^{39-41}$ erg s$^{-1}$) for intrinsically weak and/or misaligned blazars
• Physical implications of these results:
  – there must be some connection between radio and gamma-ray processes and emission regions
  – leptonic processes contribute to gamma-ray emission
    • synchrotron self-Compton processes are favoured in BL Lacs and particularly in HSP blazars (stronger correlation)
    • additional effects play a role in FSRQs (external Compton? evolution?)
  – gamma rays and main radio emitting regions are within <1pc
Conclusions, part 1

• Big *questions* answers:
  – is there a correlation between radio and gamma-ray flux in AGNs?
    • YES
  – is it also significant?
    • YES
  – does it depend on simultaneity?
    • YES
  – does it depend on blazar type?
    • ~yes
  – does it depend on energy band?
    • ~yes
Very High Energy (VHE) gamma rays and lack of radio-VHE connection

- observations above ~100 GeV based on detection of Cherenkov atmospheric radiation (IACT)
- limited field of view, limited observing time, limited (integrated) sensitivity
  - census: 47 AGNs over 151 detection (with 25 UNID and many galactic sources); mostly HSP-blazars
  - bias: plenty of! no systematic survey, observations in flaring state, ...

- physical issues
  - anti-correlation between SED peak and source power (blazar sequence)
  - extragalactic background light (EBL) attenuation
  - complex framework!
• **1FHL**: first *Fermi* catalog of high energy sources (E>10 GeV, Ackermann et al. 2013)
• three years of survey data, as uniform and unbiased as possible
• 514 sources, 76% of which are AGN, 13% unassociated
  – AGN fraction larger than in 2FGL, census leaning towards extreme spectral type blazars (HSP, 41%)
  – still significant fraction of unidentified sources
    • remarkable, given generally smaller positional ellipses
1FHL vs radio flux density

- 375 associated AGNs
  - radio data from NVSS/SUMSS
    - ($<\alpha>$=0)

- $r=0.32$
- chance probability <1e-6
1FHL vs VLBI flux density

- mas resolution data from radio fundamental catalogue (RFC)
  - VLBI @8GHz
  - 340 sources

- $r=0.29$
- chance probability $<1e^{-6}$
radio-gamma correlation at E>10 GeV

- correlation is
  - scattered
  - weaker than for lower energy gamma rays
    - $r=0.66$ using NVSS+3FGL data for the same population
    - but still very highly significant
- even at E>10 GHz, radio and gamma-ray regions “know” about each other
- large scale and VLBI data give similar results
- yet, VLBI important to associate sources
VLBI observations

- goal: complete the VLBI observations for entire 1FHL
  - and address the bias against weak and unassociated sources
- EVN & VLBA observations of ~70 sources
  - 1.6 GHz e-EVN
  - 5 GHz VLBA
- phase reference, no known position
  - found offsets as large as 6” from NVSS centroid
- detection rate
  - 83% overall
    - **100%** for blazar candidates
    - **70%** for unassociated sources
Radio flux densities

- Sources are generally weak (VLBI brightness distribution peaks ~10mJy)
- A fair amount of resolved flux is present ($S_{\text{vlbi}}/S_{\text{nvss}} \sim 0.1$)
- 1FHL AGNs and UNID behave similarly

- UNID sources classified as blazar candidates (D’Abrusco et al. 2013, Massaro et al. 2014) are confirmed as compact radio sources
1. radio-MeV/GeV connection very strong but very scattered
   – work needed to constrain blazar physics

2. radio-VHE connection not as strong, but still there
   – pc scale radio cores are confirmed
   – towards a complete dataset of VLBI images for VHE blazars
     (Lister talk, Piner poster)

3. *Fermi* operation continues, CTA will become operational soon, SKA pathfinders/precursors are active
   – let’s use them all!
References

- Ghirlanda, G. et al. 2011, MNRAS 413, 852