The connection between radio and gamma-ray emission in AGN

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Pre-Fermi Background

- synchrotron radio emission originates from relativistic electrons that can upscatter photons to high energy
  - some connection between radio and γ-ray properties is expected!
  - observationally, all EGRET AGNs are 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.
- is there a correlation? do radio and γ-ray fluxes in BL Lacs and FSRQs behave in the same way?
LAT Bright AGN Sample

- 125 non-pulsar sources at $|b|>10^\circ$
  - 106 high-confidence (P>90%) associations with AGNs: (LBAS)
  - 10 lower-confidence associations
  - 9 unassociated (3EG: 96/181 at $|b|>10^\circ$)

- High-confidence associations:
  - FSRQs: 58
  - BL Lacs: 42 (including 7 HBLs)
  - Uncertain class: 4
  - Radiogalaxies: Cen A, NGC1275

- LBAS sources are associated to CRATES/BZ Cat sources:
  - CRATES: Healey et al. (2007, 8.4 GHz VLA data)
  - BZCAT: Massaro et al. (2009, multifrequency catalog)

- Radio properties typical of compact self-absorbed components
  - relatively bright: 98/106 (92%) have $S_{8.4}>100$ mJy
  - flat spectral index: $\alpha=0.02\pm0.27$, with $S(\nu)\sim\nu^{-\alpha}$
Low vs high radio frequency: luminosity plane

- Caveat: distance dependence stretches distribution
- All cores more luminous than expected for RG of same $P_{\text{low}}$
  - Doppler boost!
  - even more if one could subtract core from truly extended emission
  - indeed, extended radio emission of LBAS sources could be as low as $10^{23}$ W Hz$^{-1}$
  - CenA well behaved: fair amount of extended radio emission
- Radio luminosity $L_r = \nu L(\nu)$ span a broad range $10^{39.1} < L_r < 10^{45.3}$ erg s$^{-1}$, ($\nu = 8.4$ GHz)
- BL Lacs and FSRQ follow different distributions:
  - FSRQ: Log$L_r = 44.4 \pm 0.6$ [erg s$^{-1}$]
  - BL Lacs: Log$L_r = 42.8 \pm 1.1$ [erg s$^{-1}$]
Radio vs gamma-ray flux

- Radio: CRATES/NED flux density at 8.4 GHz
- Gamma-ray: Fermi-LAT peak flux at E>100 Mev in 3 months
- Spearman’s rank correlation coefficient: r=0.42, for 106 elements, but...
  - do few data points drive correlation?
  - BL Lacs and FSRQ sample rather different regions
    - FSRQ: 57 sources, r=0.19,
    - BL Lacs: 42 sources, r=0.49
  - total without the most extreme data points goes down to r=0.24 (12% of the sample)
- Significance difficult to claim. Issues:
  - variability, extended radio emission
  - selection effects?
• Only sources with known redshift
  – K-corrected

• FSRQs
  – largest $L_r$, softer indices

• BL Lacs
  – lower $L_r$, harder indices

• Radio galaxies
  – 3C84 BL Lac-like, Cen A well displaced

Abdo et al. (2009)
Beyond the LBAS: 1FGL and 1LAC

• LBAS results were restricted to
  – 3 months of \( \gamma \)-ray data
  – TS>100 (highest confidence \( \gamma \)-ray sources)
• Fermi has continued its operation in survey mode with unique characteristics:
  – Sensitivity: include the weakest \( \gamma \)-ray (and radio?) sources
  – Field of view: gather data from as large sky area as possible
  – Spectral range: collect and discuss soft (radio bright?) and hard (radio weak?) sources
• Milestones after 11 months of data collection
  – the 1FGL (first Fermi-LAT catalog), which contains and characterizes 1451 sources (Abdo et al. 2010b)
  – the 1LAC (first catalog of Fermi-LAT detected AGNs), which includes 671 \( \gamma \)-ray sources statistically associated to high latitude AGNs (Abdo et al. 2010a)
Radio luminosity

- $L_r = \nu L(\nu)$, $\nu = 8.4$ GHz
- Radio luminosity $L_r$ is typically $10^{41}-10^{45}$ erg s$^{-1}$
  - but it can be as low as $10^{37}$ erg s$^{-1}$
- FSRQ are clustered at higher luminosities
  - $\log L_{r,\text{FSRQ}} = 44.1 \pm 0.7$ [erg s$^{-1}$]
- BL Lacs follow a broader distribution down to $10^{40}$ erg s$^{-1}$
  - $\log L_{r,\text{BLLacs}} = 42.2 \pm 1.1$ [erg s$^{-1}$]
- Unknown type blazars and some BL Lacs lack redshift so actual distribution may be a little different!

(Abdo et al. 2010a)
Radio spectral index

- Sources with radio data at
  - 1.4 GHz from NVSS: extended, optically thin radio emission
  - 8.4 GHz from CRATES/NED: nuclear, self-absorbed emission
- Most sources with typical flat spectrum ($\langle \alpha \rangle = 0.06 \pm 0.23$)
- However, a small but non negligible fraction has $\alpha > 0.5$
  - see T. Cheung’s talk on Wed
Radio vs gamma-ray fluxes

Gamma-ray data from 1FGL
Radio data from CRATES (or Crates-like): interferometric, 8 GHz
Correlation coefficient by source type and energy

<table>
<thead>
<tr>
<th>Energy Band</th>
<th>&gt;1 GeV</th>
<th>100-300 MeV</th>
<th>300 MeV-1 GeV</th>
<th>1-3 GeV</th>
<th>3-10 GeV</th>
<th>10-100 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>All sources</td>
<td>0.39</td>
<td>0.43</td>
<td>0.43</td>
<td>0.38</td>
<td>0.32</td>
<td>0.3</td>
</tr>
<tr>
<td>FSRQs</td>
<td>0.34</td>
<td>0.29</td>
<td>0.37</td>
<td>0.32</td>
<td>0.39</td>
<td>0.42</td>
</tr>
<tr>
<td>BL Lacs</td>
<td>0.49</td>
<td>0.63</td>
<td>0.49</td>
<td>0.45</td>
<td>0.41</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Numbers give correlation coefficients, symbol size is proportional to number of sources.

Energy band
Main findings - summary

- Correlation coefficient for all sources, E>1 GeV is \( r=0.39 \)
- \( R>0 \) for all 18 source type/energy band combinations
- \( r_{\text{BLL}}>r_{\text{FSRQ}} \), except for highest energy band
- \( r_{\text{BLL}} \) decreases with increasing energy band (0.65->0.31)
- \( r_{\text{FSRQ}} \) is more stable, slightly increasing (0.29->0.42)

- Owens Valley Radio Observatory provides also simultaneous radio data for a sub-sample of radio bright sources (see Max-Moerbeck talk)

See also next talk (Mahony, AT20G), Ghirlanda et al. (2010, AT20G), Kovalev et al. (2009, LBAS), Pushkarev et al. (2010, Mojave)
What about significance?

• Strong apparent correlation ≠ significant intrinsic correlation
• Need to simulate MANY samples with intrinsically uncorrelated flux densities and see how often we can get as high a ‘r’ as the observed one
  – with the same distance and dynamic range of our sample
  – spectroscopic information is very important!
• Preliminary results:
  – \( \text{Prob}(\text{FSRQ, E}>1 \text{ GeV}) \sim 2 \times 10^{-3} \)
  – \( \text{Prob}(\text{BLL, E}>1 \text{ GeV}) < 1 \times 10^{-7} \)
  – distance range does make a big difference – and so will the assumption on \( d_L \) for the sources without \( z \)
    • only BL Lacs with measured \( z \) considered so far
1. The bright gamma-ray extragalactic sky remains dominated by radio loud AGN
   - mostly blazars but also some steep spectrum radio sources are there
2. Radio and gamma-ray fluxes appear to correlate over 4 magnitudes
   - with some possible difference between FSRQs and BL Lacs
3. Monte-Carlo simulations provide an estimate of the correlation significance
   - significance is high but sensitive to source distance distribution and other assumptions
References

- Abdo, A. A. et al. 2010b, ApJS 188, 405 (1FGL)
EXTRA SLIDES
Radio and Gamma-ray Luminosity

Gamma-ray data from 1FGL
Radio data from CRATES (or Crates-like):
interferometric, 8 GHz

FSRQ
BL Lacs
Other AGNs

a potential discovery space?
Low vs high radio frequency:
flux-flux

- not subject to distance bias
  - Low frequency from NVSS (1.4 GHz) or SUMSS (0.8 GHz)
  - High frequency typically from CRATES (8.4 GHz, or NED)
- another representation of the spectral index flatness
- little to none extended radio emission
  - except Cen A!

![Chart showing radio flux-flux relationship](chart.png)
Radio luminosity according to type

- $L_r = \nu L(\nu)$, $\nu = 8.4$ GHz
- range $10^{39.1} < L_r < 10^{45.3}$ erg s$^{-1}$
- BL Lacs and FSRQ follow different distributions:
  - FSRQ: $\log L_r = 44.4 \pm 0.6$ [erg s$^{-1}$]
  - BL Lacs: $\log L_r = 42.8 \pm 1.1$ [erg s$^{-1}$]
- 2 RGs:
  - NGC1275 similar to BL Lacs: $L_r = 10^{42.2}$ erg s$^{-1}$
  - CenA lies at the very lower end of the radio power distribution, with $L_r = 10^{39.1}$ erg s$^{-1}$.
Radio vs gamma-ray fluxes

with more sources than in the LBAS, $r=0.60$