*Fermi meets Jansky – AGN in Radio and Gamma-Rays*
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# The radio gamma-ray connection in AGNs in the era of Fermi/LAT

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**Abstract.** Radio and gamma-ray emission from active galactic nuclei (AGN) are thought to share a common origin, related to the ejection phenomena in the vicinity of supermassive black holes. Thanks to its sensitivity, surveying capability, and broad energy range, the Large Area Telescope (LAT) onboard the *Fermi* Gamma-ray Space Telescope has permitted us to discover and characterize several hundreds extragalactic gamma-ray sources. These sources are typically associated with blazars, characterized by significant radio emission and flat spectrum. The radio luminosity distribution is extended over 7 orders of magnitudes, with flat spectrum radio quasars clustered at higher powers and BL Lacs more scattered. We present here a comparison of the gamma-ray and radio emission properties during year 1 of the Fermi-LAT observations, using both archival and simultaneous radio observations. We remark the need to consider different case studies (dividing by source class, origin of radio data, gamma-ray energy band) and to discuss the statistical significance of the results with the use of Monte Carlo simulations.

## 1. Introduction

Around 10% of active galactic nuclei (AGN) are strong sources of radio emission. This includes radio galaxies, radio quasars (flat or steep spectrum), and BL Lac type objects. All these sources are generally referred to as radio loud (RL) AGN, whereas flat spectrum radio quasars (FSRQ) and BL Lac objects are collectively known as *blazars*. Interestingly, the vast majority of identified extragalactic sources in the third EGRET catalog (3EG, Hartman et al., 1999) belong to the blazar class.

RL AGN, and blazars in particular, are by far the most numerous and most luminous class of extragalactic gamma-ray sources. Since these sources are bright in both gamma-ray and radio, it is natural to expect a connection between the emission processes in the two energy bands. Radio emission from blazars (and RL AGN in general) is generally accepted to be synchrotron radiation emitted by relativistic electrons, while the physical processes responsible for the $\gamma$-ray emission are much less well constrained. The presence of non-thermal synchrotron emission implies the existence of a population of relativistic electrons. In the presence of low energy seed photons and relativistic beaming, Inverse Compton (IC) up-scattering of the photons is frequently invoked to explain the $\gamma$-ray emission.

Indeed, in the well known *blazar sequence* (Fossati et al., 1998; Ghisellini et al., 1998; Donato et al., 2001), it is proposed that the synchrotron and inverse Compton mechanisms give rise to a connection between the radio luminosity and the peak frequencies and relative intensities of the characteristic two-humped spectral energy distribution (SED) of blazars. On the other hand, evidence for a direct correlation between radio and $\gamma$-ray flux density or luminosity with EGRET data has been widely debated (e.g., Stecker et al., 1993; Salamon & Stecker, 1994; Taylor et al., 2007; Bloom, 2008) but not conclusively demonstrated, when all the relevant biases and selection effects are considered (e.g., Mücke et al., 1997).

The Large Area Telescope (LAT) onboard the *Fermi Gamma-ray Space Telescope*, with its large field of view and unprecedented sensitivity, is now putting us in the condition of a better understanding of the extragalactic $\gamma$-ray source population. In anticipation of the launch of *Fermi*, large projects in the radio band have been undertaken (e.g., Healey et al., 2007; Fuhrmann et al., 2007; Richards et al., 2009; Lister et al., 2009). The results of these projects can now be exploited to gain insights into the radio properties of this population (see also Max-Moerbeck et al., 2009) and into the relation between radio and gamma-ray properties. Indeed, a number of papers (e.g., Abdo et al., 2009b; Kovalev et al., 2009) have appeared discussing this topic as soon as the first list of bright sources was announced (Abdo et al., 2009c); a few more (Giroletti et al., 2010; Mahony et al., 2010; Ghirlanda et al., 2010) have then addressed the same issue considering the sources in the 1 year *Fermi*/LAT catalog (1FGL, Abdo et al., 2010b).

We report in Sect. 2 the main results obtained after three months of sky-survey operation (LAT Bright AGN

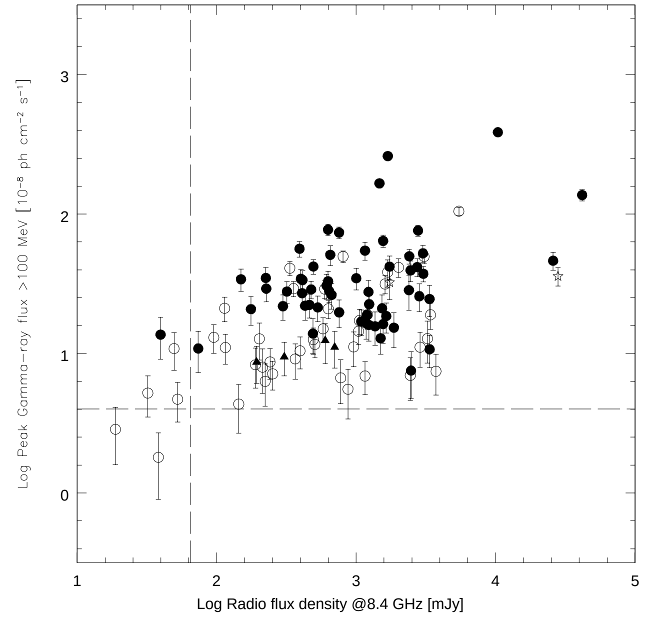

**Fig. 1.** Peak gamma-ray flux vs. radio flux density at 8.4 GHz for LBAS sources; the dashed lines show the CRATES flux density limit and the typical LAT detection threshold in three months. Filled circles: FSRQs; open circles: BL Lacs; triangles: blazars of unknown type; stars: radio galaxies.

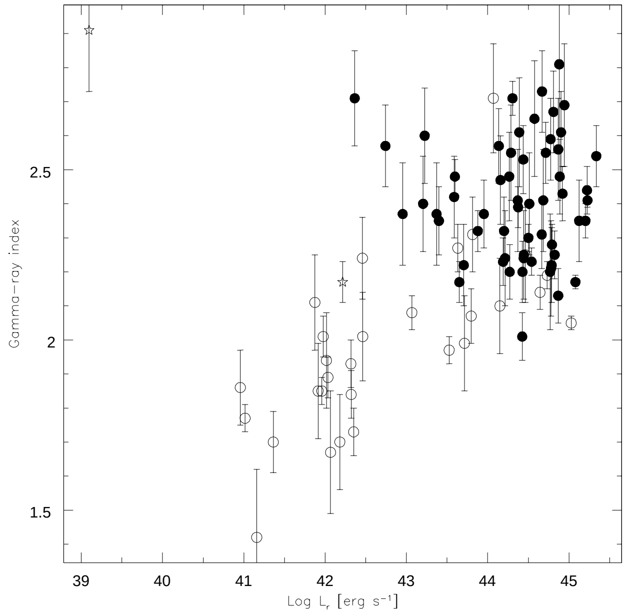

**Fig. 2.** Gamma-ray photon index vs. radio luminosity for LBAS sources. Symbols as in Fig. 1. The object in the top left corner is the gamma-ray source associated to Cen A.

Sample, LBAS, Abdo et al., 2009b). Some analysis performed on the 1 year catalog sources is presented in Sect. 3. A discussion and the conclusions so far are given in Sect. 4, along with our future plans. We use a ΛCDM cosmology with $h = 0.71$, $\Omega_{\rm m} = 0.27$ and $\Omega_\Lambda = 0.73$, where the Hubble constant $H_0 = 100h$ km s$^{-1}$ Mpc$^{-1}$ and define radio spectral indices $\alpha$ such that the flux density $S(\nu) \propto \nu^{-\alpha}$.

## 2. Radio/gamma-ray connection in the LBAS

In its first three months of sky-survey operation, the LAT has revealed 125 non-pulsar bright sources at $|b| > 10^\circ$ with test statistic greater than 100 ($TS > 100$, corresponding to a detection significance of $\sim 10\sigma$); 106 of these sources have high-confidence associations with known AGN, 10 have lower-confidence associations, and only 9 remain un-associated. Therefore, the fraction of high-latitude bright $\gamma$-ray sources associated with radio loud AGN turns out to be as high as 93%! Of the 106 LBAS sources, 104 are blazars, consisting of 58 FSRQs (including one narrow-line Seyfert 1, J0948+0022, Abdo et al., 2009a); 42 BL Lacs; four blazars with unknown classification; and two radio galaxies (Centaurus A and NGC 1275).

By combining data in the radio archives and the LAT measurements, the properties of the LBAS sources at low and high energy were compared. The basic radio properties were obtained from the radio catalogs used for the associations, i.e., CRATES (Healey et al., 2007) and BZCat (Massaro et al., 2009). CRATES provides 8.4 GHz VLA data for sources brighter than $S_{4.8\,\rm GHz} = 65$ mJy, typically with sub-arcsecond resolution. BZCat is a multi-frequency catalog giving low frequency radio data, typically from the NVSS.

Using these data, we show the peak $\gamma$-ray flux vs. the radio flux density in Fig. 1 and the radio luminosity vs. $\gamma$-ray spectral index plane in Fig. 2. These plots are also discussed in detail in Abdo et al. (2009b). The calculation of a simple Spearman's rank correlation coefficient $\rho$ for the distribution in the flux-flux plane (Fig. 1) of the 106 objects yields $\rho = 0.42$. When FSRQs and BL Lacs are considered separately, however, quite different results are obtained ($\rho_{\rm FSRQ} = 0.19$, $\rho_{\rm BL\,Lac} = 0.49$). The other relevant plot for the comparison of radio and $\gamma$-ray properties is the radio luminosity vs. $\gamma$-ray spectral index plane (see Fig. 2). The broad LAT energy range permits to readily reveal the separation between BL Lacs and FSRQs, with FSRQs at largest $L_r$ and softer indices and BL Lacs at lower $L_r$ and harder indices. As far as the two radio galaxies are concerned, NGC 1275 is similar to BL Lacs, while Cen A is well displaced, having a much softer $\gamma$-ray spectral index than other low-power radio sources.

## 3. Radio/gamma-ray connection in the 1LAC

After more than 1 year of scanning the gamma-ray sky, the LAT First Year catalog[1] (Abdo et al., 2010b), including more than 1400 sources, has been made public. About half of these sources belong to the AGN class (1LAC, Abdo et al., 2010a) with most of them identified via radio catalogs

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[1] `http://fermi.gsfc.nasa.gov/ssc/data/access/lat/1yr_catalog/`

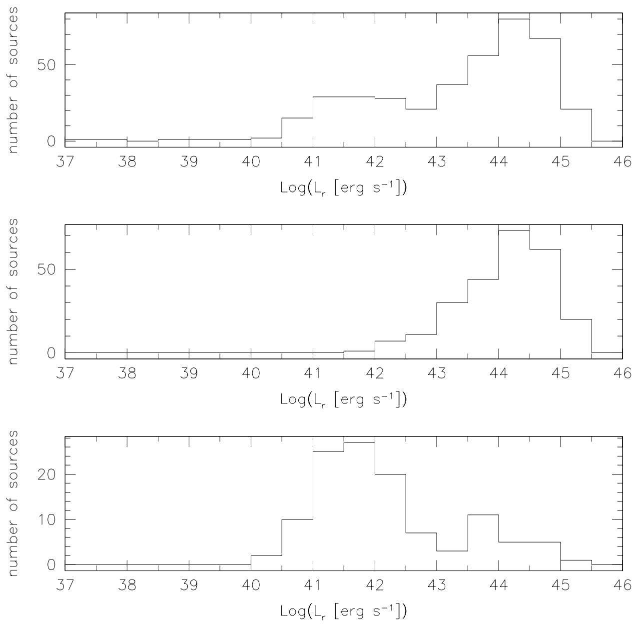

**Fig. 3.** Histogram of radio luminosity distribution for sources in the 1LAC catalog. Top panel: all sources; middle: FSRQs; bottom: BL Lacs.

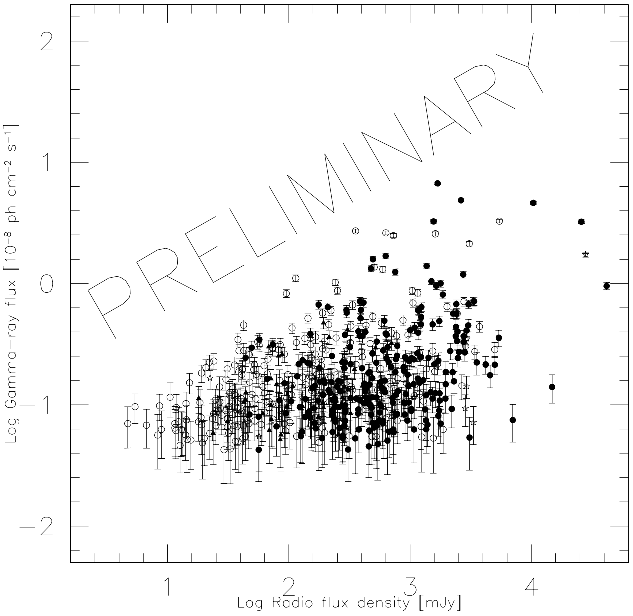

**Fig. 4.** Preliminary distribution of 1-yr LAT sources in the gamma-ray photon flux at $E > 1\,\mathrm{GeV}$ vs. 8 GHz radio flux density plane. Symbols as in Fig. 1.

as for the LBAS. In particular, 599 high latitude 1FGL sources have a single high confidence association with an AGN, including 248 FSRQs and 275 BL Lacs. In the following, we consider this set of sources (also known as the *1LAC clean sample*) for our analysis.

Whereas the LBAS results were based on sources with $TS > 100$ in three months of survey, the 1LAC clean sample considered here is selected with $TS > 25$ (significance about $5\sigma$). As a consequence, the explored space of parameters becomes significantly larger: thanks to the *great sensitivity* and *broad energy range* of the LAT, *Fermi* has already been successful in revealing faint $\gamma$-ray sources and in the characterization of their diverse photon indices.

However, although several gamma-ray sources are associated to blazars as weak as a few tens mJy, the radio properties of the 1LAC sources remain overall similar to those found for the LBAS sources. For example, the different distributions for the radio luminosity of FSRQs and BL Lacs are confirmed, with $\log L_{\mathrm{r,\,FSRQ}}$ $[\mathrm{erg\,s^{-1}}] = 44.2 \pm 0.7$ and $\log L_{\mathrm{r,\,BL\,Lac}}$ $[\mathrm{erg\,s^{-1}}] = 42.2 \pm 1.2$, respectively (see Fig. 3). In particular, the BL Lacs remain spread over a wider interval of radio luminosities, reaching as low luminosities as $L_r = 10^{40}$ erg s$^{-1}$.

As far as the radio spectral properties are concerned, the vast majority of sources have a flat spectrum ($\langle\alpha\rangle = 0.06 \pm 0.23$), including sources as weak as a few tens of mJy. However, a small but significant tail of steeper spectrum sources is also present, which are described in more detail in dedicated works, such as the one on misaligned AGNs by Abdo et al. (2010c).

Finally, the radio flux density vs. mean $\gamma$-ray flux plane becomes more populated, as shown in Fig. 4. The Spearman's rank correlation coefficient for the full sample changes to $\rho = 0.39$. Of course, the remarks noted above still apply: different source classes sample different regions of the plane, data are not simultaneous, and observational biases could be present. For these reasons, we have considered both archival and simultaneous radio data. The simultaneous radio data are available from the Owens Valley Radio Observatory (OVRO) monitoring program (Richards et al., 2009) for 199 sources, while the archival radio data are from CRATES (Healey et al., 2007) or CRATES-like programs, such as CLASS (Myers et al., 2003).

For each of the two samples, we have also compared the radio flux density to the 1-yr gamma-ray photon flux in various energy bands, considering only the sources that are significant in a given one. Moreover, we tested the two populations of FSRQs and BL Lacs separately, since they have different spectral properties and showed different behaviors in the preliminary analysis (Abdo et al., 2009b; Giroletti et al., 2010).

Indeed, FSRQs and BL Lacs continue to reveal different behaviors, with BL Lacs displaying larger values of $\rho$ than FSRQs. For example, in the $E > 1\,\mathrm{GeV}$ energy band. we find $\rho = 0.49$ for BL Lacs and $\rho = 0.34$ for FSRQs, which bracket the value obtained considering all the 599 sources ($\rho = 0.39$). Moreover, in FSRQs the correlation coefficient increases with the energy range, while BL Lacs behave on the contrary.

## 4. Discussion and an outlook

The correlation coefficients reported in the previous section provide information about its apparent strength, but a quantitative evaluation of its statistical significance can only be obtained with Monte-Carlo tests. Pavlidou et al. (2010) have devised a method to investigate how frequently a sample of objects with intrinsically uncorrelated gamma/radio flux densities will yield an apparent correlation as strong as the one seen in the data, when subjected to the same distance effects as the sample actually under consideration.

While, we defer to other papers the details of the method and its applications to the 1LAC sample (Pavlidou et al., 2010; Abdo et al., 2010d), we just highlight one result that shows the relevance of the effect of the redshift range on the probability distribution of $\rho$ for the uncorrelated cases. Since BL Lacs have a much more limited redshift range than FSRQs, FSRQs exhibit the effect of an induced correlation by the $d_L^2$ factor in a much more pronounced way in our statistical tests. As a consequence, and not simply because $\rho_{\rm FSRQ}$ is actually lower, it is harder to demonstrate a statistically robust correlation for FSRQs. On the other hand, several BL Lacs lack a measured redshift and including them in the statistical test requires assumptions that have to be carefully pondered.

All in all, thanks to its unique capabilities, *Fermi* has revealed that the bright gamma-ray extragalactic sky is dominated by radio loud AGN, and blazars in particular, even more than it could be probed during the EGRET era. The presence of a correlation between the observed radio and gamma-ray flux density for the *Fermi* sources seems to hold, as also discussed by Kovalev et al. (2009), Mahony et al. (2010), and Ghirlanda et al. (2010). However, a statistically sound assessment of its significance – as well as an understanding of its possible physical implications – can only be explored with Monte-Carlo simulations (Pavlidou et al., 2010; Abdo et al., 2010d).

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## References

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009a, ApJ, 699, 976

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009b, ApJ, 700, 597

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009c, ApJS, 183, 46

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010a, ApJ, 715, 429

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010b, ApJS, 188, 405

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010c, ApJ submitted (misaligned AGNs)

Abdo, A. A., et al. 2010d, in preparation

Bloom, S. D. 2008, AJ, 136, 1533

Donato, D., Ghisellini, G., Tagliaferri, G., & Fossati, G. 2001, A&A, 375, 739

Fossati, G., Maraschi, L., Celotti, A., et al. 1998, MNRAS, 299, 433

Fuhrmann, L., Zensus, J. A., Krichbaum, T. P., et al. 2007, AIPC, 921, 249

Ghirlanda, G., Ghisellini, G., Tavecchio, F., & Foschini, L. 2010, submitted to MNRAS, `arXiv:1003.5163`

Ghisellini, G., Celotti, A., Fossati, G., et al. 1998, MNRAS, 301, 451

Giroletti, M., Reimer, A., Fuhrmann, L., Pavlidou, V., & Richards, J. L. 2010, in 2009 Fermi Symposium, eConf Proceedings C091122, `arXiv:1001.5123`

Hartman, R. C., Bertsch, D. L., Bloom, S. D., et al. 1999, ApJS, 123, 79

Healey, S. E., Romani, R. W., Taylor, G. B., et al. 2007, ApJS, 171, 61

Kovalev, Y. Y., Aller, H. D., Aller, M. F., et al. 2009, ApJ, 696, L17

Lister, M. L., Aller, H. D., Aller, M. F., et al. 2009, AJ, 137, 3718

Mahony, E. K., Sadler, E. M., Murphy, T., Ekers, R. D., Edwards, P. G., & Massardi, M. 2010, submitted to ApJ, `arXiv:1003.4580`

Massaro, E., Giommi, P., Leto, C., et al. 2009, A&A, 495, 691

Max-Moerbeck, W., et al. 2009, in 2009 Fermi Symposium, eConf Proceedings C091122 `arXiv:0912.3817`

Mücke, A., Pohl, M., Reich, P., et al. 1997, A&A, 320, 33

Myers, S. T., Jackson, N. J., Browne, I. W. A., et al. 2003, MNRAS, 341, 1

Pavlidou, V., Richards, J. L., Max-Moerbeck, W., et al. 2010, ApJ submitted

Richards, J. L., Max-Moerbeck, W., Pavlidou, V., et al. 2009, in 2009 Fermi Symposium, eConf Proceedings C091122 `arXiv:0912.3780`

Stecker, F. W., Salamon, M. H., & Malkan, M. A. 1993, ApJ, 410, L71

Salamon, M. H., & Stecker, F. W. 1994, ApJ, 430, L21

Taylor, G. B., Healey, S. E., Helmboldt, J. F., et al. 2007, ApJ, 671, 1355