The Connection between Radio and Gamma-ray Emission in Active Galactic Nuclei

Marcello Giroletti  
*INAF Istituto di Radioastronomia, Bologna, Italy*

Anita Reimer  
*Leopold-Franzens-Universität Innsbruck, Austria*

Lars Fuhrmann  
*Max-Planck-Institut für Radioastronomie, Bonn, Germany*

Vasiliki Pavlidou and Joseph L. Richards  
*California Institute of Technology, Owens Valley Radio Observatory*

on behalf of the Fermi-LAT collaboration

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 a huge number of extragalactic γ-ray sources. Similarly to what was found by EGRET, 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; the average spectral index is consistent with $\alpha = 0$, although a few remarkable sources have $\alpha > 0.5$ ($S(\nu) \propto \nu^{-\alpha}$). A comparison of the radio flux density and the gamma-ray photon flux is presented, although claims on its significance require a detailed discussion and Monte Carlo simulations which will be presented in a future paper.

I. 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, 16] belong to the blazar class.

RL AGN, and blazars in particular, are the most numerous and most luminous class of extragalactic gamma-ray sources. That these sources are bright in both gamma-ray and radio suggests 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 γ-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 γ-ray emission.

Indeed, in the well known blazar sequence [10, 12, 14], 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 γ-ray flux density or luminosity has been widely debated since the EGRET era [e.g. 7, 13, 26–28] but not conclusively demonstrated, when all the relevant biases and selection effects are considered [e.g. 23].

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 γ-ray source population. In anticipation of the launch of Fermi, large projects in the radio band have been undertaken [e.g. 13, 17, 20, 23]. The results of these projects can now be exploited to gain insights into the radio properties of this population [see also 22] and into the relation between radio and gamma-ray properties.

In the present paper, we report in §II the main results obtained after three months of sky-survey operation [LAT Bright AGN Sample, LBAS, 1] and in §III some analysis of an expanded source set based on a preliminary version of the 1 year catalog. Conclusions and future plans are given in §IV. We use a ΛCDM cosmology with $h = 0.71$, $\Omega_m = 0.27$ and $\Omega_\Lambda = 0.73$, where the Hubble constant $H_0 = 100h$ km s$^{-1}$ Mpc$^{-1}$. 

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2009 Fermi Symposium, Washington, D.C., Nov. 2-5

arXiv:1001.5123v1 [astro-ph.CO] 28 Jan 2010
FIG. 1: High vs. low frequency radio flux density for LBAS sources; the dashed line corresponds to $S_{\text{low}} = S_{\text{high}}$.

and define radio spectral indices $\alpha$ such that the flux density $S(\nu) \propto \nu^{-\alpha}$.

II. RADIO/GAMMA-RAY CONNECTION IN THE LBAS

In the 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 unassociated. Therefore, considering both high- and lower-confidence associations, the fraction of high-latitude bright $\gamma$-ray sources associated with radio loud AGN is as high as 93%. While EGRET results suggested that RL AGN would dominate this population, this degree of dominance is nonetheless amazing. More than 50% (96/181) of the high-latitude ($|b| > 10^\circ$) sources in the 3EG catalog were unassociated and it seems that the overwhelming majority of those were RL AGN!

Of the 106 LBAS sources, 104 are blazars, consisting of 58 FSRQs [including one narrow-line Seyfert 1, J0948+0022, 2]; 42 BL Lacs; four blazars with unknown classification; and two radio galaxies (Centaurus A and NGC 1275). The basic radio properties can be obtained from the radio catalogs used for the associations, i.e. CRATES [17] and BZCat [21]. CRATES provides 8.4 GHz VLA data for sources brighter than $S_{4.8 \text{ GHz}} = 65\,\text{mJy}$, typically with subarcsecond resolution. BZCat is a multi-frequency catalog giving low frequency radio data, typically from the NVSS. Not surprisingly, given the flux and spectral selection criteria of the samples, the LBAS sources are relatively bright (98/106 $\sim 92%$ have $S_{8.4} > 100\,\text{mJy}$) and have flat spectral index ($\langle \alpha \rangle = 0.02 \pm 0.27$), which are typical signatures of compact self-absorbed components.

A. Low/high radio frequency comparison

In Fig. 1 and Fig. 2 we show the comparison between the low and high frequency radio flux density and luminosity for the LBAS sources. The flux density plane (Fig. 1) clearly reflects the flatness of the spectral index, with all the points (but one) close to the $S_{\text{low}} = S_{\text{high}}$ line; the outlying point represents Cen A, the only source with a significant amount of extended radio emission dominating the low frequency flux density. In the luminosity plot (Fig. 2), the common dependence on the square of the distance stretches the distribution even more. Here, the interesting result is the relative distribution of the LBAS sources with respect to a complete sample of radio galaxies [dashed line, from [15]: except Cen A (which lies near the radio galaxy region), all cores of LBAS sources are more luminous when compared to radio galaxies of the same extended luminosity, which can be accounted for by a large Doppler factor for the radio cores of $\gamma$-ray sources. Moreover, the low frequency
luminosity (generally taken as a measure of the extended, optically thin emission) is contaminated by the nuclear emission for LBAS sources, so that the actual extended emission luminosity would be lower than the observed $P_{\text{low}}$ (corresponding to a shift of the points in the direction of the parallel arrows in Fig. 2). The two main consequences are as follows: (1) the Doppler beaming effect can actually be larger than apparent from the figure and (2) $\gamma$-ray sources can be found even in blazars with extended emission as low as $\sim 10^{22}$ W Hz$^{-1}$.

B. Radio luminosity

In terms of the radio luminosity $L_r = \nu L(\nu)$ (calculated at $\nu = 8.4$ GHz), the sources in the present sample with a measured redshift span the range $10^{39.1}$ erg s$^{-1} < L_r < 10^{45.3}$ erg s$^{-1}$. BL Lacs and FSRQs are not uniformly distributed in this interval: the former span a broad range of radio luminosities ($\log L_{r,\text{BL Lac}}$ [erg s$^{-1}$] = 42.8 ± 1.2) while the latter are more clustered at high radio luminosity ($\log L_{r,\text{FSRQ}}$ [erg s$^{-1}$] = 44.4 ± 0.6). Blazars of unknown type have low-S/N optical spectra, so a redshift is generally not available and their radio luminosities are not determined. Of the two radio galaxies associated with objects in the LBAS, NGC 1275 is similar to the BL Lacs ($L_r = 10^{42.2}$ erg s$^{-1}$), while Cen A lies at the very low end of the radio power distribution ($L_r = 10^{39.1}$ erg s$^{-1}$).

C. Gamma-ray vs radio plane

By combining data in the radio archives and the LAT measurements, it is possible to compare the properties of the LBAS sources at low and high energy. The relevant plots are shown in Fig. 3 and Fig. 4 and concern the peak $\gamma$-ray flux vs. the radio flux density and the radio luminosity vs. $\gamma$-ray spectral index planes, respectively. These plots are also discussed in detail in Abdo et al. [1].

FIG. 3: 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.

The calculation of a simple Spearman’s rank correlation coefficient $\rho$ for the distribution in the flux-flux plane (Fig. 3) of the 106 objects yields $\rho = 0.42$. However, the actual significance of this result can not be assessed without Monte Carlo simulations, since biases and/or selection effects modify the distribution of $\rho$ from the ideal case. Moreover, when FSRQs and BL Lacs are considered separately, quite different results are obtained ($\rho_{\text{FSRQ}} = 0.19$, $\rho_{\text{BL Lac}} = 0.49$), so that it is not possible to claim significant correlations at this stage. Furthermore, the radio and $\gamma$-ray data are not simultaneous. The importance of this effect needs to be taken into account, and the only method to address its impact is to apply similar tests to a simultaneous sample, such as the one provided from the F-GAMMA (OVRO 15 GHz, Effelsberg & IRAM 30 m 2-230 GHz) monitoring programs. First results using these data indicate significant correlations [24, Fuhrmann et al., Richards et al., in prep.].

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. 4). 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.

III. RADIO/GAMMA-RAY CONNECTION WITH EXPANDED SOURCE SET

With the continuation of the LAT operation in sky-survey mode, the number of detected blazars is bound to increase. In the 1-year catalog under development from the LAT team [29], more than 1000 sources have been detected and characterized [6]. In particular, the large field of view of the LAT has allowed us to reach weak gamma-ray sources all over the sky and the search for their possible radio counterparts has required a huge amount of work [see e.g. 18]. Indeed, while the LBAS results were based on sources with
TS > 100 in three months of survey, the 1-year preliminary results presented here are based on sources with TS > 25 (significance about 5σ). As long as there is a significant overlap with the LBAS, the total number of sources available for analysis becomes several times as large, and the explored space of parameters is also larger. Thanks to the great sensitivity and broad energy range of the LAT, Fermi has already been successful in revealing faint γ-ray sources and in the characterization of their diverse photon indices.

It is therefore interesting to have a preliminary look at the topics discussed in the previous section using the 1-year database. The total radio luminosity range of the associated sources spans seven orders of magnitude; the overall distribution remains similar to that found for the LBAS sources. Also the different distributions of FSRQs and BL Lacs are confirmed, with log \( L_r,\text{FSRQ} [\text{erg s}^{-1}] = 44.2 \pm 0.7 \) and log \( L_r,\text{BL Lac} [\text{erg s}^{-1}] = 42.2 \pm 1.2 \) (Fig. 5). In particular, the BL Lacs remain spread over a wider interval of radio luminosities, even with a hint of bimodality (note however that the counts are smaller for the BL Lacs since their redshift is generally more difficult to determine).

As far as the spectral properties are concerned, we show in Fig. 6 the distribution of the associations in the high vs. low frequency radio flux density and in Fig. 7 the corresponding histogram of the spectral index distribution. It is readily apparent from both plots that 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 M87 [3, 11] and Cen A [9], as well as in the review by Cavazzuti et al. [8].

Finally, the radio flux density vs. mean γ-ray flux plane becomes more populated, as shown in Fig. 8. The Spearman’s rank correlation coefficient for the full sample changes to \( \rho = 0.57 \). 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. A more rigorous analysis is therefore necessary to claim the significance and to discuss the physical implication of the observed distribution. This will be the subject of a dedicated paper [Abdo et al., in preparation].

IV. CONCLUSIONS AND OUTLOOK

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. Therefore, the γ-ray data from the LAT, as well as the radio data from large ongoing projects, represent a great resource to constrain the physical processes related to ejection phenomena in AGN. The preliminary analysis presented in this work certainly needs a more detailed follow-up, although the fraction...
and type of associated sources, the ranges of their core and extended radio luminosity, and the distribution of the sources in the various radio–γ-ray planes look already quite interesting.

In particular, the discussion of variability and the use of simultaneous data, the comparison to radio data at higher frequencies \[5\] and/or resolution \[25\], and a deeper analysis with Monte Carlo simulations are necessary before significant claims can be made. Finally, it is worthwhile to remind that as we discover weaker γ-ray sources, we will need to broaden our constraints on possible counterparts, including radio-faint BL Lacs (HBLs), steep spectrum radio sources, and Seyfert galaxies.

**Acknowledgments**

The authors would like to thank E. Angelakis, W. Max-Moerbeck, and A. Readhead for useful discussions and comments on the presentation and manuscript. The Fermi LAT Collaboration acknowledges support from a number of agencies and institutes for both development and the operation of the LAT as well as scientific data analysis. These include NASA and DOE in the United States, CEA/Irfu and IN2P3/CNRS in France, ASI and INFN in Italy, MEXT, KEK, and JAXA in Japan, and the K. A. Wallenberg Foundation, the Swedish Research Council and the National Space Board in Sweden. Additional support from INAF in Italy and CNES in France for science analysis during the operations phase is also gratefully acknowledged. AR acknowledges support from a Marie Curie International Reintegration Grant within the 7th European Commu-
nity Framework Programme. VP acknowledges support provided by NASA through Einstein Postdoctoral Fellowship grant number PF8-90060 awarded by the Chandra X-ray Center, which is operated by the Smithsonian Astrophysical Observatory for NASA under contract NAS8-03060.

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