IL NUOVO CIMENTO Vol. 34 C, N. 3 Maggio-Giugno 2011
DOI 10.1393/ncc/i2011-10856-3

Colloquia: Scineghe2010

Misaligned AGN with *Fermi*-LAT: A different perspective on relativistic jets

G. Migliori on behalf of the Fermi-LAT Collaboration
SISSA/ISAS - Via Bonomea 265, I-34136 Trieste, Italy

(ricevuto il 25 Febbraio 2011; pubblicato online il 28 Aprile 2011)

Summary. — We review the latest results on misaligned AGNs (MAGNs), *i.e.* radio sources with the jet pointed away from the observer, detected by the Large Area Telescope (LAT) on board the *Fermi* satellite. We have analyzed the spectral properties in the γ-ray band of a sample of eleven radio sources, associated with the 3CR, 3CRR and Molonglo 4 Jy catalogues. The location of the γ-ray emission, the radiative processes responsible for it and the emerging jet structure are discussed in the framework of unification schemes for radio-loud AGNs. The results of a dedicated study on the nuclear spectral energy distribution (SED) of the radio galaxy NGC6251, one of the MAGNs of the LAT sample, are also presented.

PACS 95.85.Pw – Astronomical observations: γ-ray.
PACS 98.54.Cm – Active and peculiar galaxies and related systems (including BL Lacertae objects, blazars, Seyfert galaxies, Markarian galaxies, and active galactic nuclei).

1. – Introduction

The detection of GeV-TeV emission associated with radio galaxies, first with the EGRET telescope (on board the Compton Gamma-ray Observatory) and then with ground-based Cherenkov observatories, was an unexpected discovery. In AGN unified schemes [1], an increase of the inclination angle of the jet axis with respect to the line of sight corresponds to a de-amplification of the observed flux and a general shift of the emission to lower energies. In the framework of simple one-zone synchrotron self-Compton (SSC) models this should make misaligned sources unlikely γ-ray candidates. Therefore, γ-ray detected MAGNs provide a deep insight into the structure of the region where the most energetic radiation is produced and a test for the unification view.

Now, with *Fermi*-LAT we can proceed further into the study of this interesting class of sources. Its combination of unprecedented flux sensitivity and spatial resolution in the γ-ray band [2] allows us to increase the number of MAGN detections and for the first time to perform spatially resolved studies for a limited number of giant sources [3]. In the following we summarize the main results on the MAGN class for the first 15 months of *Fermi*-LAT activity presented in [4].

TABLE I. – *The Fermi-LAT sample of misaligned sources.*

Object/ 1FGL name	Redshift	Class Radio/Optical	TS([a])	Γ_γ	Flux([b]) (> 100 MeV)	logLum([c]) (0.1–10 GeV)
3C 78(NGC 1218)/ 1FGLJ0308.3+0403	0.029	FR I/G	35	1.95±0.14	4.7±1.8	42.84
3C 84(NGC 1275)/ 1FGLJ0319.7+4130	0.018	FR I/G	4802	2.13±0.02	222±8	44.00
3C 111/ 1FGLJ0419.0+3811	0.049	FR II/BLRG	34	2.54±0.19	40±8	44.00
3C 120	0.033	FR I/BLRG	32	2.71±0.35	29±17	43.43
PKS 0625-354/ 1FGLJ0627.3-3530	0.055	FR I/G	97	2.06±0.16	4.8±1.1	43.7
3C 207 1FGLJ0840.8+1310	0.681	FR II/SSRQ	79	2.42±0.10	24±4	46.44
PKS 0943-76 1FGLJ0940.2-7605	0.27	FR II/G	65	2.83±0.16	55±12	45.71
M87(3C 274)/ 1FGLJ1230.8+1223	0.004	FR I/G	194	2.21±0.14	24±6	41.67
CENA 1FGLJ1325.6-4300	0.0009	FR I/G	1010	2.75±0.04	214±12	41.13
NGC 6251 1FGLJ1635.4+8228	0.024	FR I/G	143	2.52±0.12	36±8	43.30
3C 380 1FGLJ1829.8+4845	0.692	FR II/SSRG	95	2.51±0.30	31±18	46.57

(a) Source statistical significance.
(b) $\times 10^{-9}$ photon $cm^{-2}\,s^{-1}$.
(c) erg s^{-1}.

2. – Misaligned AGNs with *Fermi*-LAT: results and open issues

In order to search for misaligned sources, the eleven-month LAT list of AGN candidates has been cross-correlated with the 3CR catalog [5, 6], the revised 3CRR catalog [7] and the Molonglo Southern 4 Jy sample [8, 9]. There are three main reasons for this choice: i) the low frequency (178 MHz, 408 MHz) selection criteria of these catalogs favor radio sources primarily on the relatively steep spectrum synchrotron emission of the extended lobes, ii) they represent a good coverage of the northern and southern sky, iii) morphological radio (FRI/FRII) and optical (Radio Galaxy/Quasar) classification are given for the majority of the sources. The list of the sources with an association is reported in table I, together with the test statistic (TS) significance and the spectral parameters of the fitting technique, namely the power law spectral slope Γ_γ, the integrated flux above 100 MeV and the K-corrected luminosity between 100 MeV and 10 GeV (see [4] for all the analysis details). The sample is formed by 7 FRI and 4 FRII sources, two of them classified as Steep Spectrum Radio Quasars (SSRQs). All the associations were already reported in the first-year LAT AGN Catalog paper (1LAC, [10]) with the exception of 3C120, whose γ-ray detection has been reported for the first time in [4]. Dedicated studies have been devoted to NGC1275 [11, 12], M87 [13], and Centaurus A [3, 14].

The misaligned AGNs of the LAT sample are generally faint and soft sources. Their 100 MeV–10 GeV spectrum can be well described by a simple power law with an average spectral index $\langle\Gamma_\gamma\rangle = 2.4$ and the integrated flux above 100 MeV is of the order of $\approx 10^{-8}$ photon $cm^{-2}\,s^{-1}$. A more complex spectral shape is displayed by NGC1275, which is also the only source characterized by flux and spectral variability [11, 12]. No variability in the γ-ray band has been detected for the other sources on month timescales. It is not clear if this reflects the real situation or is rather due to the low statistics, which could hamper the detection of flux changes of factor of 2.

2˙1. *Broad Line Radio Galaxies.* – Two of the LAT MAGNs, 3C120 and 3C111, are Broad Line Radio Galaxies (BLRG). The nuclear X-ray (2–10 keV band) flux of these objects is likely the combination of thermal, related to the accretion flow, and non-thermal, from the base of the jet, emission. The γ-ray information could be useful to disentangle the jet from the disk emission, as the latter is expected to rapidly drop in this band [15].

2˙2. *Location of the γ-ray emission in MAGNs.* – The location of the region of the γ-ray emission is a crucial and delicate point. In variable sources, correlated radio and γ-ray observations seem to indicate the bright radio core as the favorite candidate of the γ-ray emission origin (but see also [16, 17]).

LAT observations have revealed more complexity for the class of MAGNs. High-energy emission can be certainly produced on nuclear scales. Support to this scenario comes from: i) the variability observed in NGC1275 [11,12]; ii) the fast ($\Delta t \sim 1$ day) TeV flares accompanied by an increase of the VLBI core flux in M87 [18], which place the site of high-energy photon production at 30–60 Schwarzschild radii. Beyond this, LAT has detected for the first time γ-ray emission associated to the extended lobes of a radio galaxy, namely CenA [3]. The extended γ-ray emission is explained as up-scattered radiation from the cosmic microwave background photons by the ultra-relativistic electrons in the lobes, with additional contribution at higher energies from the infrared to optical extragalactic background. In CenA, the nuclear and extended γ-ray luminosities [3,14] are comparable. Thus, core and lobes may be competing contributions. This factor should be carefully considered in those misaligned sources whose extended structures cannot be resolved out with the LAT point spread function.

2˙3. *Hints on the jet structure.* – In the unification scenario for radio-loud AGNs [1], radio galaxies are the misaligned counterparts of blazars: FRI and FRII radio galaxies are the parent populations of BL Lac sources and Flat Spectrum Radio Quasars (FSRQ), respectively. In fig. 1 (left panel) Γ_γ is plotted against the apparent isotropic γ-ray (100 MeV–10 GeV band) luminosity L_γ for all the misaligned sources of the sample, along with the FSRQs and BL Lac objects of the 1LAC with known redshifts. Misaligned sources generally occupy a separate region in the L_γ-Γ_γ plane, with lower γ-ray luminosities and softer spectral indexes than their parent populations as predicted by unification models. However, when a simple one-zone synchrotron/SSC model is assumed, the SEDs of the radio galaxies require bulk Lorentz factors (Γ) smaller than the aligned sources. Furthermore, the X-ray to γ-ray luminosities of the FRI sources are lower but still larger than expected by debeaming the radiation of a typical BL-Lac [19]. A complex jet structure, with a velocity gradient either axial (spine-layer models [20, 21]) or radial (decelerating jet [22]) is a viable solution to reconcile observations and unified scheme. In case of a multi-layer jet the larger FRI inclination angles would favor the observation of external jet regions usually swamped by the much brighter fast component responsible for the blazar emission. The FRI sources of the LAT sample are ideal candidates to investigate the jet structure. Detailed studies of NGC1275, M87 and CenA have con-

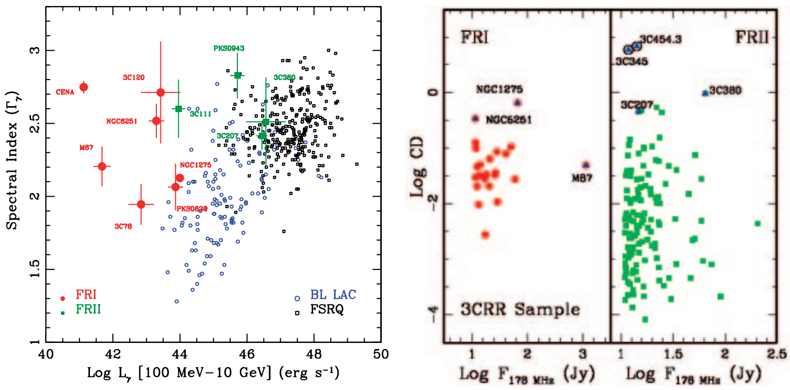

Fig. 1. – (Color online) Left panel: γ-ray spectral slopes of FRI radio galaxies (red circles), FRII radio sources (green squares), BL Lac objects (open blue circles) and FSRQs (open black squares), are plotted as a function of their 100 MeV–10 GeV γ-ray luminosity [4]. The γ-ray emitting misaligned AGNs (MAGNs) are the red and green points. Right panel: core dominance (CD) *versus* total flux at 178 MHz of all the sources of the 3CRR sample (FRI—red circles; FRII—green squares) with a measured radio core. The MAGNs detected by *Fermi* (blue triangles in circles/squares) are characterized by large core dominances. The two FSRQs (blue triangles in empty black circles) belonging to the 3CRR and associated to LAT sources have much larger CD values than the misaligned FRII sources.

firmed that small beaming factors (δ(1) $\approx$ 2–3) are required when a simple SSC model is assumed. In the following, we present the results obtained by modeling the nuclear SED of the radio galaxy NGC6251.

2˙4. *The case of NGC6251*. – First, we modelled the nuclear SED of the radio galaxy NGC6251 ($z = 0.0247$) using a one-zone synchrotron self-Compton model. The important assumption is that the γ-ray emission is all produced in the nuclear region, as assumed for BL-Lac sources. The region dimensions (R: radius of the region), bulk motion (Γ) and inclination angle (θ), as also the shape of the electron energy distribution (EED, $N(\gamma)$ where γ is the Lorentz factor of the electrons) responsible for the emission can be partially constrained from the observations. Our best SSC model fit for the nuclear SED (in fig. 2, left panel) is obtained for the following main parameter values: $R \approx 10^{17}$ cm, $\Gamma = 2.4$, $\theta = 25°$, and $B = 0.037$ G. The EED, $N(\gamma)$, is a broken power law with an energy break $\gamma_b = 2 \times 10^4$ and $p1 = 2.76$ and $p2 = 4.04$ the power law spectral indexes below and above the break, respectively. The jet is relatively slow compared to the typical BL-Lac jet speeds [23-25]. A similar value is also reported in [26] and is in line with what has been found for the nuclear SED of CenA, NGC1275 and M87 when a one-zone SSC model is applied [11, 13, 14].

We then tested a spine-layer model (fig. 2, right panel), where the observed high-energy emission is given by the up-scattering of the spine synchrotron photons by the relativistic electrons of the layer [21]. The spine is modelled as a typical BL-Lac region ($R_{spine} = 10^{16}$ cm, $\Gamma_{spine} = 15$, $B_{spine} = 1.8$ G). At the given inclination angle, the direct spine emission is severely debeamed ($\delta_{spine} = 0.7$). The layer EED, θ and δ as also its dimensions respect the observational constraints.

(1) $\delta = [\Gamma(1 - \beta\cos(\theta)]^{-1}$, where $\Gamma = (1 - \beta^2)^{-1/2}$ is the Lorentz factor and $\beta = v/c$ is the bulk velocity of the jet. θ is the angle between the direction of the jet and the observer line of sight.

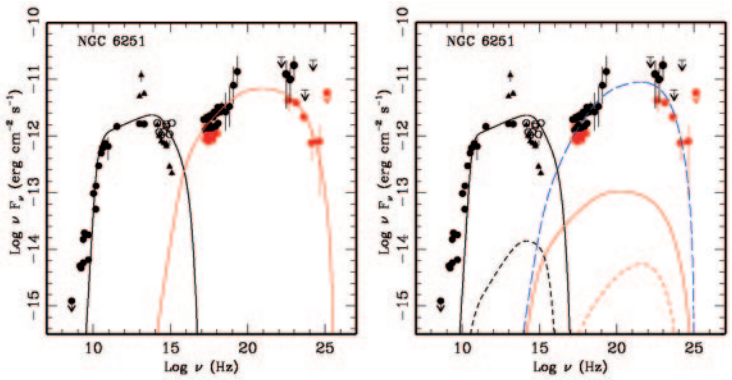

Fig. 2. – (Color online) Nuclear broadband SED of NGC6251 compiled using multi-epoch data. Left panel: the SED is modeled with a one-zone SSC model (solid black line: synchrotron curve, solid red line: IC emission). Right panel: the SED is modeled with the spine-layer model illustrated in [21]. Solid back and red lines reproduce the SSC emission of the layer. Dashed black and red curves are the SSC model for the spine. The long-dashed blue lines is the IC emission of the spine synchrotron photons off the layer relativistic electrons.

The two models reflect very different jet structures. In the SSC hypothesis, the jet is slow and heavy: the particle to magnetic field energy-density ratio is $U'_e/U'_B \geq 400$, with $U'_e = m_e c^2 n_e \langle\gamma\rangle$ (m_e: electron mass, $\langle\gamma\rangle$: average electron Lorentz factor) and $U'_B = B^2/8\pi$. The violation of the minimum-energy assumption is rather severe and could pose the question of how the jet is initially confined. Conversely, in the spine-layer model the jet is on average faster and lighter, with particles and magnetic field near to the equipartition conditions ($U'_e/U'_B(layer) \approx 0.2$ and $U'_e/U'_B(spine) \approx 0.3$ and ≈ 1 if protons are included). In this case, the magnetic field could be determinant for the jet confinement. We note however that the flux variability in the X-ray to γ-ray band predicted by the spine-layer model [21] is not observed.

2˙5. *FRI and FRII sources*. – In the LAT sample there is a slight dominance of FRI over FRII sources. The sample is limited but some considerations can be made. In fig. 1 (right panel) the core dominance(2) (CD) of the 3CRR sources, including the 3CRR LAT sources (blue triangles in circles/squares for FRI/FRII), is plotted as a function of the source total flux at 178 MHz. In general, the misaligned sources detected by *Fermi* have a large CD. When the redshift information is included we note that: i) the FRI LAT sources with small CDs (*i.e.* observed at relatively large inclination angles) are at low redshifts, ii) conversely, no FRII with a small CD has been so far detected by *Fermi*; iii) increasing luminosity distances seem to require larger CDs. The two sources at the highest redshift, 3C207 and 3C380 (table I), are SSRQs with small estimated inclination angles. At this stage it is not possible to determine whether the lower number of FRII detections is related to the fact that they are located at redshifts higher than FRIs or reflects an intrinsic difference in the jet structure.

(2) The core dominance is considered an indicator of the source inclination and defined as $CD = \log[S_{core}/(S_{tot} - S_{core})]$, where $S_{core,tot}$ is the core/total flux density referred to the source rest frame [27].

3. – Conclusions

The first 15 months of LAT activity have allowed us to increase the number of misaligned sources detected in the GeV band. The LAT sample is dominated by seven nearby FRI radio galaxies. The γ-ray spectrum of most of the sources is a simple soft power law and no significant γ-ray variability is usually detected (except for NGC1275). The dominance of FRI sources over FRII in the sample could be explained in terms of redshift distribution or invoking an intrisically different jet structure between the two classes. As the *Fermi* mission continues, further inputs to this and the other topics discussed here are expected.

* * *

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.

REFERENCES

[1] Urry C. M and Padovani P., *Publ. Astron. Soc. Pac.*, **107** (1995) 803.
[2] Atwood W. B. *et al.*, *Astrophys. J.*, **697** (2009) 1071.
[3] Abdo A. A. *et al.*, *Science*, **328** (2010) 725 (Cen A lobes).
[4] Abdo A. A. *et al.*, *Astrophys. J.*, **720** (2010) 912 (MAGN).
[5] Bennett A. S., *Mon. Not. R. Astron. Soc.*, **125** (1962) 75.
[6] Spinrad H., Marr J., Aguilar L. and Djorgovski S., *Publ. Astron. Soc. Pac.*, **97** (1985) 932.
[7] Laing R. A., Riley J. M. and Longair M. S., *Mon. Not. R. Astron. Soc.*, **204** (1983) 151.
[8] Burgess A. M. and Hunstead R. W., *Astron. J.*, **131** (2006) 100.
[9] Burgess A. M. and Hunstead R. W., *Astron. J.*, **131** (2006) 114.
[10] Abdo A. A. *et al.*, *Astrophys. J.*, **715** (2010) 429 (1LAC).
[11] Abdo A. A. *et al.*, *Astrophys. J.*, **699** (2009) 31 (NGC1275).
[12] Kataoka J., Stawarz L., Cheung C. C. *et al.*, *Astrophys. J.*, **715** (2010) 554.
[13] Abdo A. A. *et al.*, *Astrophys. J.*, **707** (2009) 55.
[14] Abdo A. A. *et al.*, *Astrophys. J.*, **719** (2010) 1433 (Cen A core).
[15] Grandi P. and Palumbo G. G. C., *Astrophys. J.*, **659** (2007) 235.
[16] Marscher A. P. *et al.*, *Astrophys. J.*, **710** (2010) 126.
[17] Agudo I. *et al.*, *Astrophys. J. Lett.*, **726** (2011) L13.
[18] Acciari V. A. *et al.*, *Science*, **325** (2009) 444A.
[19] Chiaberge M. *et al.*, *Astron. Astrophys.*, **358** (2000) 104.
[20] Stawarz L. and Ostrowski M., *Astrophys. J.*, **578** (2002) 763.
[21] Ghisellini G., Tavecchio F. and Chiaberge M., *Astron. Astrophys.*, **432** (2005) 401.
[22] Georganopoulos M. and Kazanas D., *Astrophys. J.*, **589** (2003) L5.
[23] Lister M. L. *et al.*, *Astron. J.*, **138** (2009) 1874.
[24] Tavecchio F. *et al.*, *Mon. Not. R. Astron. Soc.*, **401** (2010) 1570.
[25] Finke J. D., Dermer C. D. and Bottcher M., *Astrophys. J.*, **686** (2008) 181.
[26] Chiaberge M. *et al.*, *Astrophys. J.*, **597** (2003) 166.
[27] Scheuer P. A. G. and Readhead A. C. S., *Nature*, **277** (1979) 182.