Four Years of *Fermi* LAT Observations of Narrow-Line Seyfert 1 Galaxies

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Before the launch of the *Fermi* satellite only two classes of AGN were known to generate relativistic jets and thus emit up to the γ-ray energy range: blazars and radio galaxies, both hosted in giant elliptical galaxies. The first two years of observations by the Large Area Telescope (LAT) on board *Fermi* confirmed that these two are the most numerous classes of identified sources in the extragalactic γ-ray sky, but the discovery of variable γ-ray emission from 5 radio-loud Narrow-Line Seyfert 1 galaxies (NLSy1s) revealed the presence of a possible emerging third class of AGN with relativistic jets. Considering also that NLSy1s are typically hosted in spiral galaxy, this finding poses intriguing questions about the nature of these objects, the onset of production of relativistic jets, and the cosmological evolution of radio-loud AGN. Here, we report on a preliminary investigation of the properties of this sample of radio-loud NLSy1 at MeV-GeV photon energies, utilizing the four-year accumulation of *Fermi* LAT data. In addition we briefly discuss some radio-to-gamma-rays properties of the γ-ray emitting NLSy1 in the context of the blazar scenario.

1. Introduction

Only a small percentage of Active Galactic Nuclei (AGNs) are radio-loud, and this characteristic is commonly ascribed to the presence of a relativistic jet, roughly perpendicular to the accretion disk. Accretion of gas onto the super-massive black hole (SMBH) is thought to power these collimated jets, even if the nature of the coupling between the accretion disk and the jet is still among the outstanding open questions in high-energy astrophysics [e.g. Meier 2003]. Certainly relativistic jets are the most extreme expression of the power than can be generated by a SMBH in the center of an AGN. These objects have a total bolometric luminosity of up to 10^{49-50} erg s^{-1} [e.g. Ackermann et al. 2010, Bonnoli et al. 2011], with a large fraction of the power emitted in γ rays. Before the launch of the *Fermi* satellite only two classes of AGNs were known to generate these structures and thus to emit up to the γ-ray energy range: blazars and radio galaxies, both hosted in giant elliptical galaxies [Blandford & Rees 1978]. The first 2 years of observation by *Fermi*-LAT confirmed that the extragalactic γ-ray sky is dominated by these two classes [Nolan et al. 2012]. However, the discovery by the Large Area Telescope (LAT) on board the *Fermi* satellite of variable γ-ray emission from a few radio-loud Narrow-Line Seyfert 1s (NLSy1s) revealed the presence of a possible third class of AGNs with relativistic jets [Abdo et al. 2009a,b,c]. On the contrary, no radio-quiet Seyfert galaxies were detected in γ rays until now [Ackermann et al. 2012b]. This finding poses intriguing questions about the knowledge of the development of relativistic jets, the disk/jet connection, the Unification model for AGNs and the evolution of radio-loud AGNs.

Even if the physics necessary to explain the generation, collimation and evolution of the jet is still to be known [e.g. Blandford 2001, 2008], there is increasing evidence that the properties of jets in AGNs could be related to the properties of the accretion flow that feeds the central SMBH. Recently, Ghisellini et al. [2008, 2011] suggested a transition between BL Lac objects and Flat Spectrum Radio Quasars (FSRQs) that can be mainly justified by the different accretion regimes: sub-Eddington in the first class of objects, leading to radiatively inefficient accretion flows and relatively weak jets, whereas near-Eddington in the second class, giving rise to bright disks and powerful jets. This scenario seems to be also in agreement with the separation of their "non-beamed" counterparts, Fanaroff-Riley I and Fanaroff-Riley II radio galaxies. In this context, the case of the peculiar radio-loud NLSy1s has received increasing attention.

NLSy1 is a class of AGN identified by Osterbrock & Pogge [1985] and characterized by their optical properties: narrow permitted lines (FWHM (Hβ) $<$ 2000 km s^{-1}) emitted from the broad line region, [OIII]/Hβ $<$ 3, and a FeII bump [for a review see e.g. Pogge 2000]. They also exhibit strong X-ray variability, steep X-ray spectra, substantial soft X-ray excess and relatively high luminosity. These characteristics point to systems with smaller masses of the central BH (10^6-10^8 M$_\odot$) and higher accretion rates (close to or above the Eddington limit) with respect to blazars and radio galaxies. NLSy1 are generally radio-quiet, with only a small fraction of them [$<$ 7%, Komossa et al. 2006] classified as radio-loud, and objects with high values of radio-loudness (R > 100) are even more sparse (∼2.5%), while ∼15% of quasars are radio-loud. In the past, several authors inferred from studies of non-simultaneous radio to X-ray data different possibilities on the nature of these objects. Komossa et al. [2006] argued that radio-loud NLSy1s could be some young stage of quasars, while Yuan et al. [2008] claimed that some NLSy1 might be high-frequency-peaked flat spectrum radio quasars conjectured by Padovani [2007] and not predicted by the blazar sequence, but no conclusive evidence has been presented. However, as shown with preliminary results in Foschini et al. [2009], some radio-loud NLSy1s show similarities with FSRQs, while others are like BL Lacs. Moreover, as in the case of blazars and radio galaxies, there should be a "parent population" with the jet viewed at large angles. The first source of this type could be PKS 0558−504 [Gliozzi et al. 2010]. Other candidates have been detected by Doi et al. [2012]. Therefore, it is possible that NLSy1s are a set of low-mass systems parallel to blazars and radio galaxies.

The firm confirmation of the existence of relativistic jets also in Seyfert galaxies, provided by the LAT detection of NLSy1s, opened a large and unexplored research space for important discoveries for our knowledge of the AGNs, but brought with itself new challenging questions. What are the differences between this class of γ-ray AGNs and blazars and radio galaxies? What is the origin of the radio-loudness? What are the parameters determining the jet formation and how it is possible to have the formation of a jet in a population of AGN mostly radio-quiet such as the NLSy1s? Is there a limiting BH mass above which objects are preferentially radio-loud? How do these objects fit into the blazar sequence? Four years after the announcement of the detection of the first γ-ray NLSy1 by *Fermi*-LAT, PMN J0948+0022 [Abdo et al. 2009a], only a few indications about the nature of these objects have been obtained. In Section 2 we report the LAT data analysis and results of the 5 γ-ray NLSy1s over 4 years of *Fermi* observations, focusing on the two flaring sources SBS 0846+513 and PMN J0948+0022 in Section 3. In Section 4 and 5 we discuss the host galaxies and the jet formation, respectively, for the NLSy1s. In Section 6 we report about searching new γ-ray NLSy1s, while concluding remarks are presented in Section 7.

2. The γ-ray view of NLSy1

Up to now 5 radio-loud NLSy1 galaxies have been detected at high significance by *Fermi*-LAT: PMN J0948+0022, PKS 1502+036, 1H 0323+342, PKS 2004−447, and SBS 0846+513. Here we analyze the first four years of γ-ray observations of these sources. The LAT data reported in this paper were collected from 2008 August 4 (MJD 54682) to 2012 August 4 (MJD 56143). During this time the LAT instrument operated almost entirely in survey mode. The analysis was performed with the `ScienceTools` software package version v9r27p1. The LAT data were extracted within a 10° Region of Interest (RoI) centred at the location of the 5 NLSy1s. Only events belonging to the "Source" class were used. In addition, a cut on the zenith angle (< 100°) was also applied to reduce contamination from the Earth limb γ rays, which are produced by cosmic rays interacting with the upper atmosphere. The spectral analysis was performed with the instrument response functions (IRFs) `P7SOURCE_V6` using an unbinned maximum likelihood method implemented in the Science tool `gtlike`. A Galactic diffuse emission model and isotropic component, which is the sum of an extragalactic and instrumental background were used to model the background[1]. The normalizations of both components in the background model were allowed to vary freely during the spectral fitting.

We evaluated the significance of the γ-ray signal from the sources by means of the Test Statistics TS = 2Δlog(likelihood) between models with and without the source [Mattox et al. 1996]. The source model used in `gtlike` includes all the point sources from the 2FGL catalogue that fall within 20° from the target source. The spectra of these sources were parametrized by power-law functions, $dN/dE \propto (E/E_0)^{-\Gamma}$, where Γ is the photon index, or log-parabola, $dN/dE \propto (E/E_0)^{-\alpha-\beta\,\log(E/E_0)}$, where E_0 is a reference energy, α the spectral slope at the energy E_0, and the parameter β measures the curvature around the peak. A first maximum likelihood was performed to remove from the model the sources having TS < 10 and/or the predicted number of counts based on the fitted model $N_{pred} < 3$. A second maximum likelihood was performed on the updated source model. The fitting procedure has been performed with the sources within 10° from the target source included with the normalization factors and the photon indices left as free parameters. For the sources located between 10° and 20° from our target we kept the normalization and the photon index fixed to the values of the 2FGL catalog. We used a power-law model for PKS 1502+036 and PKS 2004−447, and a log-parabola for 1H 0323+342 and PMN J0948+0022, as in the 2FGL catalog. For SBS 0846+513 we used a power-law model as in D'Ammando et al. [2012a] for the third year of *Fermi* observation.

The results of the LAT analysis over the entire period are summarized in Table I. The average observed isotropic luminosity of the 5 objects in the 0.1–100

[1] http://fermi.gsfc.nasa.gov/ssc/data/access/lat/Background Models.html

GeV energy range spans between 10^{44} erg s^{-1} and 10^{47} erg s^{-1}, a range of values typical of blazars. This could be an indication of a similar viewing angle with respect to the jet axis and beaming factor for the γ-ray emission between blazars and γ-ray NLSy1s. In particular, SBS 0846+513 and PMN J0948+0022 showed γ-ray flaring activity combined with a moderate spectral evolution [D'Ammando et al. 2012a, Foschini et al. 2011], a behaviour already observed in bright FSRQs and low-synchrotron-peaked (LSP) BL Lacs detected by *Fermi* LAT [Abdo et al. 2010]. The average photon index of the 5 NLSy1s spans a range (Γ = 2.2–2-6) narrower than those observed in Misaligned AGNs [Γ = 1.9–2.7, Grandi & Torresi 2012] and similar to the average values observed for FSRQs and LSP BL Lacs [Nolan et al. 2012].

Figures 1 to 5 show the γ-ray light curves of the 5 NLSy1s for the period 2008 August 4 –2012 August 4 using 3-month time bins. For each time bin the spectral parameters of the target source and all sources within 10° from it were frozen to the value resulting from the likelihood analysis over the entire period. If TS < 10 the value of the fluxes were replaced by the 2-σ upper limits. The systematic uncertainty in the flux is energy dependent: it amounts to 10% at 100 MeV, decreasing to 5% at 560 MeV, and increasing again to 10% above 10 GeV [Ackermann et al. 2012a]. A different level of activity has been clearly observed in these five objects, with significant variability in SBS 0846+513 and PMN J0948+0022.

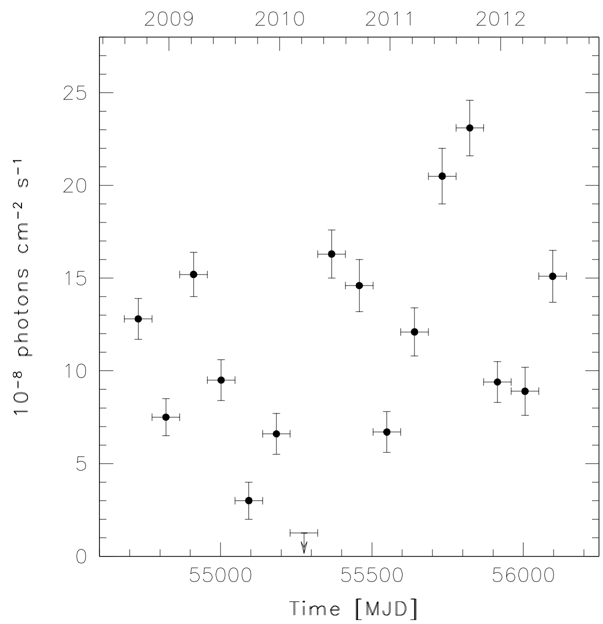

Figure 1: Integrated flux light curve of PMN J0948+0022 obtained in the 0.1–100 GeV energy range during 2008 August 4 – 2012 August 4 with 3-month time bins. Arrows refer to 2-σ upper limits on the source flux. Upper limits are computed when TS < 10.

3. Flaring NLSy1s: PMN J0948+0022 and SBS 0846+513

One of the key question is the maximum power released by the jets of radio-loud NLSy1, and for this reason γ-ray flaring activities from these sources are catalyzing a growing interest in the astrophysical community. The first answers arrived in 2010 July when PMN J0948+0022 underwent a γ-ray flaring activity with a daily peak flux of $\sim 1\times 10^{-6}$ ph cm^{-2} s^{-1} [Foschini et al. 2011]. The first spectral energy distributions (SEDs) collected for the 4 γ-ray NLSy1s detected in the first year of *Fermi* operation showed clear similarities with blazars: a double-humped shape with disk component in UV, physical parameters blazar-like and jet power in the average range of blazars [Abdo et al. 2009c]. The comparison of the SED of PMN J0948+0022 during the 2010 July flaring activity with that of 3C 273, a typical FSRQ, shows a more extreme Compton dominance in the NLSy1. The disagreement of the two SEDs can be due to the difference in BH masses and Doppler factor of the two jets. Further γ-ray flaring episodes from PMN J0948+0022 have been observed in 2011 June [D'Ammando & Ciprini 2011] and 2013 January [D'Ammando & Orienti 2013].

A strong γ-ray flare was observed also from SBS 0846+513 in 2011 June, reaching an isotropic γ-ray luminosity (0.1–300 GeV) of $\sim 10^{48}$ erg s^{-1}, comparable to that of the bright FSRQs [D'Ammando et al. 2012a]. Variability and spectral properties of SBS 0846+513 in radio and γ rays indicate a blazar-like behaviour. In addition, from the model-fitting of 4-epoch MOJAVE data of this source in 2010-2012 we found that the jet components are separating with an apparent velocity of (10.9±1.4)c. This value suggest the presence of boosting effect as well as in blazars [D'Ammando et al. 2012b]. The power released during the flaring activity and the apparent superluminal motion velocity are strong indications of the presence of a relativistic jets as powerful as those in blazars, despite the lower BH masses.

4. Host galaxy

The discovery of a relativistic jet in a class of AGN usually hosted in spiral galaxies such as the NLSy1s was a great surprise. Unfortunately only very sparse observations of the host galaxy of radio-loud NLSy1s are available up to now and the sample of objects studied by Deo et al. [2006] and Zhou et al. [2006] had z < 0.03 and z < 0.1, respectively, including both radio-quiet and radio-loud sources.

Among the γ-ray emitting NLSy1s detected by

Table I Gamma-ray characteristics of radio-loud NLSy1 galaxies detected by *Fermi*-LAT.

Source	Redshift z	Flux (E > 100 MeV) $\times 10^{-8}$ ph cm^{-2} s^{-1}	Photon index Γ/α	Curvature β	TS	L_γ $\times 10^{46}$erg s^{-1}
1H 0323+342	0.061	3.52±0.42	2.62±0.13	0.63±0.17	199	0.01
SBS 0846+513	0.5835	2.63±0.22	2.18±0.05	-	658	2.95
PMN J0948+0022	0.585	11.32±0.43	2.37±0.05	0.23±0.03	2287	10.02
PKS 1502+036	0.409	4.14±0.39	2.60±0.06	-	309	1.25
PKS 2004−447	0.24	1.37±0.33	2.56±0.14	-	49	0.11

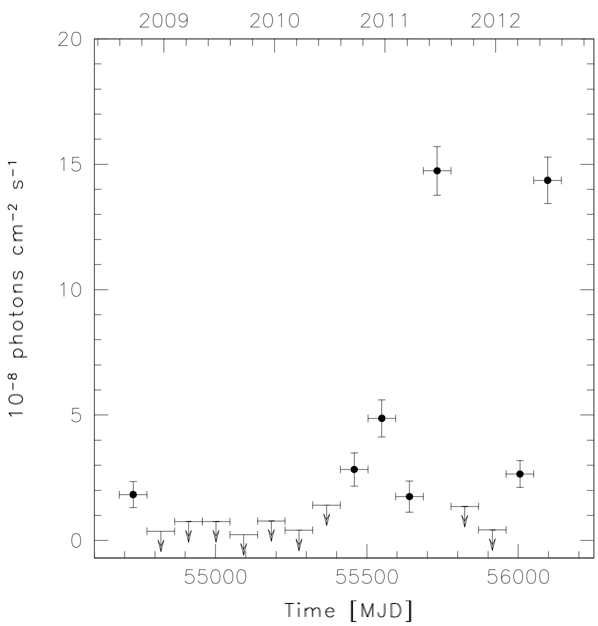

Figure 2: Integrated flux light curve of SBS 0846+513 obtained in the 0.1–100 GeV energy range during 2008 August 4 – 2012 August 4 with 3-month time bins. Arrows refer to 2-σ upper limits on the source flux. Upper limits are computed when TS < 10.

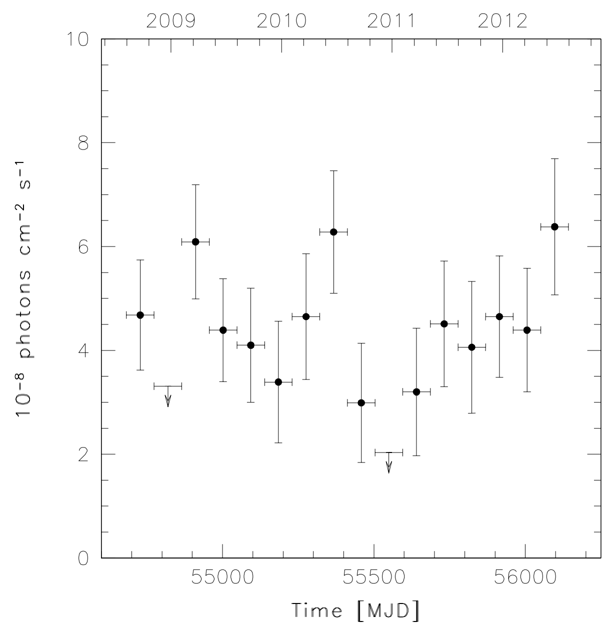

Figure 3: Integrated flux light curve of PKS 1502+036 obtained in the 0.1–100 GeV energy range during 2008 August 4 – 2012 August 4 with 3-month time bins. Arrows refer to 2-σ upper limits on the source flux. Upper limits are computed when TS < 10.

Fermi LAT only for 1H 0323+342 *Hubble Space Telescope* (HST) and Nordic Optical Telescope observations are available. These observations revealed a one-armed galaxy morphology or a circumnuclear ring, suggesting two possibilities: the spiral arms of the host galaxy [Zhou et al. 2007] or the residual of a galaxy merging [Anton et al. 2008]. On the other hand, no significant resolved structures have been observed instead by HST for SBS 0846+513 [Maoz et al. 1993], and no high-resolution observations are available for the remaining γ-ray NLSy1s. Thus the possibility that the development of relativistic jets in these objects could be due to strong merger activity, not so usual in disk/spiral galaxies, cannot be ruled out. Further high-resolution observations of the host galaxy of γ-ray NLSy1s will be fundamental to obtain important insights into the onset of production of relativistic jets.

5. Radio-loudness and jet formation

The mechanism at work for producing a relativistic jet is not still clear. In particular the physical parameters that drive the jet formation is still under debate. One fundamental parameter could be the BH mass, with only large masses that can allow efficient formation of a relativistic jet. Sikora et al. [2007] suggested that AGN with $M_{BH} > 10^8$ $M_\odot$ have a radio loudness 3 orders of magnitude greater than the AGN with $M_{BH} < 3 \times 10^7$ $M_\odot$. According to the "modified spin paradigm" proposed, another fundamental parameter for the efficiency of a relativistic jet production should

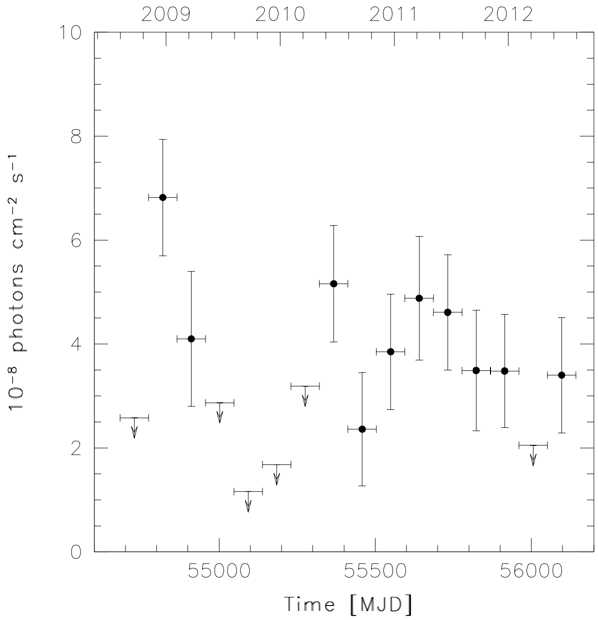

Figure 4: Integrated flux light curve of 1H 0323+342 obtained in the 0.1–100 GeV energy range during 2008 August 4 – 2012 August 4 with 3-month time bins. Arrows refer to 2-σ upper limits on the source flux. Upper limits are computed when TS $<$ 10.

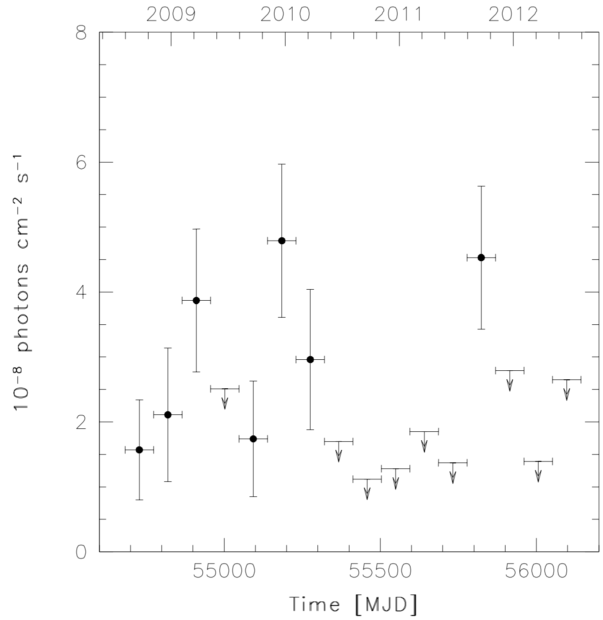

Figure 5: Integrated flux light curve of PKS 2004−447 obtained in the 0.1–100 GeV energy range during 2008 August 4 – 2012 August 4 with 3-month time bins. Arrows refer to 2-σ upper limits on the source flux. Upper limits are computed when TS $<$ 10.

be the BH spin, with SMBHs in elliptical galaxies having on average much larger spins than SMBHs in spiral galaxies. This is due to the fact that the spiral galaxies are characterized by multiple accretion events with random angular momentum orientation and small increments of mass, while elliptical galaxies underwent at least one major merger with large matter accretion triggering an efficient spin-up of the SMBHs. The accretion rate (thus the mass) and the spin of the BH seem to be related to the host galaxy, leading to the hypothesis that relativistic jets can develop only in elliptical galaxy [e.g. Böttcher & Dermer 2002, Marscher 2009]. In this context the large radio-loudness of SBS 0846+513 could challenge this idea if the BH mass (8.2×10^6-5.2×10^7 M_{odot}) estimated by Zhou et al. [2005] is confirmed.

We noted that BH masses of radio-loud NLSy1s are generally larger with respect to the entire sample of NLSy1s [$M_{BH} \approx$(2–10) $\times10^7$ $M_\odot$; Komossa et al. 2006, Yuan et al. 2008], even if still small when compared to radio-loud quasars. The larger BH masses of radio-loud NLSy1s could be related to prolonged accretion episodes that can spin-up the BHs. The small fraction of radio-loud NLSy1s with respect to radio-loud quasars could be an indication that not in all of the formers the high-accretion regime lasted long enough to spin-up the central BH [Sikora 2009].

6. New γ-ray emitting NLSy1?

In addition to the 5 NLSy1s already observed new γ-ray emitting NLSy1 could be detected accumulating more and more *Fermi*-LAT data. For this reason we started from a list of 39 NLSy1s reported in Komossa et al. [2006], Oshlack et al. [2001], Whalen et al. [2006], Yuan et al. [2008], Zhou & Wang [2002] with a radio-loudness $R > 20$ and analyzed 4 years of LAT data to search systematically for GeV emission from them. No significant (TS $>$ 25) detection of new γ-ray NLSy1s over the entire 4-year period was obtained.

Anyway the variability could be a key ingredient to take into account for a high-significance detection of these sources, as clearly showed by SBS 0846+513 that after two years of very low γ-ray activity [and for this reason not included in the First or Second *Fermi*-LAT catalog, Abdo et al. 2010, Nolan et al. 2012] started an increase of the flux up to the flaring activity detected in 2011 June–July [D'Ammando et al. 2012a]. For this reason the next step will be an investigation of the activity of these candidates γ-ray NLSy1 on different time scales (e.g. 1 month, 3 months, 1 year).

7. Concluding remarks

The presence of a relativistic jet in some radio-loud NLSy1 galaxies, first suggested by their variable radio emission and flat radio spectra, is now confirmed by the *Fermi*-LAT detection of five NLSy1s in γ rays. The flaring episodes observed in γ rays from SBS 0846+513 and PMN J0948+0022 are strong indications of the presence of a relativistic jet as powerful as those of blazars. These two sources showed all the characteristics of the blazar phenomenon and they could be a relatively low mass (and possibly younger) version of blazars. Further multifrequency observations of these and the other γ-ray emitting NLSy1s will be fundamental for investigating in detail their characteristics over the entire electromagnetic spectrum. The impact of the properties of the central engines in radio-loud NLSy1s, which seem quite different of those of quasar and manifest in their peculiar optical characteristics, on the γ-ray emission mechanisms is currently under debate. In addition, the detection of relativistic jets in a class of AGN usually hosted in spiral galaxies is very intriguing, challenging the theoretical scenario of relativistic jet formation proposed up to now. The detection of new NLSy1s in γ rays by *Fermi*-LAT will be important for extending the sample and better characterizing this new class of γ-ray emitting AGN.

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