RADIO-LOUD NARROW-LINE SEYFERT 1 AS A NEW CLASS OF GAMMA-RAY ACTIVE GALACTIC NUCLEI

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We report the discovery with Fermi/LAT of $\gamma$-ray emission from three radio-loud narrow-line Seyfert 1 galaxies: PKS 1502+036 ($z = 0.409$), 1H 0323+342 ($z = 0.061$), and PKS 2004−447 ($z = 0.24$). In addition to PMN J0948+0022 ($z = 0.585$), the first source of this type to be detected in $\gamma$ rays, they may form an emerging new class of $\gamma$-ray active galactic nuclei (AGNs). These findings can have strong implications on our knowledge about relativistic jets and the unified model of the AGN.

**Key words:** galaxies: active – galaxies: Seyfert – gamma rays: observations – quasars: general

1. INTRODUCTION

The advent of the Fermi Gamma-ray Space Telescope (hereafter, Fermi), with its excellent performance, is changing our perception of the sky at high-energy $\gamma$ rays. Specifically, the recent detection in the radio–GeV energy range of the radio-loud narrow-line Seyfert 1 (RL-NLS1) quasar PMN J0948+0022 strongly supports the presence of a closely aligned relativistic jet in this peculiar system (Abdo et al. 2009a, 2009c; Foschini et al. 2009b). This is quite surprising, since NLS1s are generally hosted in spiral galaxies and the presence of a fully developed relativistic jet is contrary to the well-known paradigm that this type of system is associated with ellipticals (e.g., see Marscher 2009 for a recent review).

Already in the past, several authors inferred from the multiwavelength properties of RL-NLS1s some parallelism between this type of source and blazars (e.g., Komossa et al. 2006; Yuan et al. 2008; Foschini et al. 2009a), suggesting similarities with different flavors of the blazar types (quasars or BL Lacs). What was missing in these previous studies is the $\gamma$-ray detection, which is important to confirm the presence of a relativistic jet, to measure its power, and to study the characteristics of this type of sources by modeling their spectral energy distributions (SEDs). Indeed, blazar-like radio emission from radio-quiet AGNs has been already reported (e.g., Brunthaler et al. 2000, 2005; Lister et al. 2009; see also the review by Ho 2008), but no $\gamma$ rays have been yet detected from these sources. This suggests some evident differences between fully developed relativistic jets (i.e., emitting over the whole electromagnetic spectrum, from radio to $\gamma$ rays) and jet-like (perhaps aborted?, cf. Ghisellini et al. 2004) structures, whose emission at $\gamma$ rays in the MeV–TeV energy range—if any—has not been yet reported.

Understanding these differences could give important insights into jet formation. Therefore, we started a larger program aiming at the detection of $\gamma$-ray emission from other RL-NLS1s. Since no complete sample of RL-NLS1s is available in the literature, we have built a sample by merging all the sources of this type in the catalog of Zhou & Wang (2002) and in the lists of Komossa et al. (2006) and Yuan et al. (2008). We have adopted a threshold in the radio loudness $R_L = f_{\nu_{GHz}}/f_{440\mu m} = 50$, in order to avoid doubtful sources at the border ($R_L = 10$) with radio quietness. The optical properties are those typical of NLS1s, i.e., narrow permitted lines (FWHM H$\alpha$ < 1000 km s$^{-1}$), [OIII]/H$\beta < 3$ and the bump of Fe II (see Pogge 2000 for a review). At radio frequencies, RL-NLS1s display strong and variable radio emission, with brightness temperature well above the inverse-Compton limit (see, e.g., Yuan et al. 2008; Table 3). This selection resulted in a list of 29 sources, most of them selected from the Sloan Digital Sky Survey (SDSS). This low number should not be a surprise. According to Komossa et al. (2006), RL-NLS1s are more rare than quasars: 7% of NLS1s have $R_L > 10$ and only 2.5% exceed $R_L = 50$, while generally 10%–20% of quasars are radio loud. Although based on a small sample of objects (128), these results have been confirmed by studies on larger samples from the SDSS (Zhou et al. 2006; Whalen et al. 2006). It is worth noting that this sample is not complete, although the fact that it is based on the SDSS ensures a minimum degree of representativeness.

Here we report three new detections at $\gamma$ rays of RL-NLS1s obtained with Fermi/LAT. In addition to the already known PMN J0948+0022 (reported by Abdo et al. 2009a, 2009c; Foschini et al. 2009b), this increases the number of $\gamma$-ray detections of NLS1s ($3 + 1 = 4$ out of 29 sources, $\approx 14$% of our sample), suggesting that they form a new class of $\gamma$-ray-emitting AGNs.

Throughout this work, we adopted a $\Lambda$CDM cosmology from the most recent WMAP results, which give the following values for the cosmological parameters: $h = 0.71$, $\Omega_m = 0.27$, $\Omega_{\Lambda} = 0.73$. 

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In order to build SEDs, we retrieved all the publicly available data of these sources. In the case of PKS 1502+036, no X-ray data were found and, therefore, we asked for a 5 ks snapshot satellite, which was performed on 2009 July 25 (ObsID 00031445001). We retrieved from the public Swift archives, optical/UV/X-rays data also for PMN J0948+0022 (Abdo et al. 2009a). The three remain-

"Notes.

a Error radius at 95% confidence level. To take properly into account systematic effects in the calculation of the error radii, we added the absolute systematic error of 0.0075 in quadrature to the 68%, then we convert to 95% by multiplying by 1.62 and, finally, we multiply by 1.2, which is the relative systematic error (Abdo et al. 2010, in preparation).

b y-ray flux for E > 100 MeV. We quoted only statistical errors, while the systematics to be considered are 10% at 100 MeV, 5% at 500 MeV and 20% at 10 GeV (Rando et al. 2009).

c Photon index of the power-law model used to fit LAT data.

d Observed y-ray luminosity.

e Confidence level of the association according to the FoM.

f See Abdo et al. (2009a)."

ΩL = 0.73 and with the Hubble–Lemaître constant H0 = 100 h
km s−1 Mpc−1 (Komatsu et al. 2009).

2. DATA ANALYSIS

The data from the Large Area Telescope (LAT; Atwood et al. 2009) onboard Fermi were analyzed following the same scheme described in Abdo et al. (2009a), but using a more recent version of the software (Science Tools v 9.15.2), Instrument Response Function (IRF P6_V3_DIFFUSE, Rando et al. 2009) and background subtraction38. The data analyzed span between MJD 54682 (2008 August 4) and 55048 (2009 August 5).

Four LAT sources with TS59 greater than 25, which is equivalent to ~5σ, can be associated with RL-NLS1s by using the figure-of-merit (FoM) method outlined in Abdo et al. (2009b) and already used to associate other LAT sources with radio counterparts. One of them is the already well-known PMN J0948+0022 (Abdo et al. 2009a). The three remaining new sources were associated with the RL-NLS1 objects: PKS 1502+036 (z = 0.409), 1H 0323+342 (z = 0.061), and PKS 2004−447 (z = 0.24). The results are summarized in Table 1.

In order to build SEDs, we retrieved all the publicly available data of these sources. In the case of PKS 1502+036, no X-ray data were found and, therefore, we asked for a 5 ks snapshot with the Swift satellite, which was performed on 2009 July 25 (ObsID 00031445001). We retrieved from the public Swift archives, optical/UV/X-rays data also for PMN J0948+0022 (Abdo et al. 2009a) and 1H 0323+342. For the latter, we analyzed all the observations performed between 2006 July 6 and 2008 November 16 (15 observations) and averaged the results (total exposure on XRT was 57 ks). In the case of PKS 2004−447, one XMM-Newton observation was found (ObsID 0200360201, performed on 2004 April 11; 42 ks exposure on EPIC, see Gallo et al. 2006) and analyzed.

PMN J0948+0022 was extensively studied in Abdo et al. (2009a, 2009c), while the data of 1H 0323+342 and PKS 2004−447 were already discussed in Foschini et al. (2009a).

3. SPECTRAL ENERGY DISTRIBUTIONS (SEDs)

The SEDs built with all the available data are displayed in Figure 1. As for PMN J0948+0022, these SEDs show clear similarities with blazars and therefore we fitted them with the synchrotron and inverse-Compton model developed by Ghisellini & Tavecchio (2009). Basically, it adopts an injected

Table 1

| Name          | z    | α (deg) | δ (deg) | r_{90%} (deg) | P_{E>30} (10^{-8}) photons cm^{-2} s^{-1} | Γ | TS | L_{\gamma} \cdot \Omega (10^{46} \text{ erg s}^{-1}) | Ass. (%) |
|---------------|------|---------|---------|---------------|------------------------------------------|---|-----|---------------------------------|---------|
| 1H 0323+342   | 0.061| 51.27   | +34.19  | 0.21          | 5.7 ± 0.3                                 | 2.74 ± 0.03 | 78  | 0.02                          | 92      |
| PKS 1502+036  | 0.409| 226.26  | +3.37   | 0.18          | 7.5 ± 0.3                                 | 2.81 ± 0.03 | 186 | 2.1                           | 93      |
| PKS 2004−447  | 0.24 | 301.99  | −44.51  | 0.09          | 2.3 ± 0.3                                 | 2.5 ± 0.4 | 43  | 0.2                           | 81      |
| PMN J0948+0022 | 0.585| 147.28  | +0.59   | 0.12          | 14.6 ± 0.9                                | 2.78 ± 0.06 | 647 | 11                            | 99      |

38 We adopted the same version of software and calibration database that is publicly available at http://fermi.gsfc.nasa.gov/ssc/data/analysis/software/.

39 Likelihood test statistic, see Mattox et al. (1996) for a definition of this test.

60 The significance of the detection in σ is roughly \sqrt{TS}.
In the case of NLS1s, the permitted emission lines from the BLR are above, where $\gamma$ is the random Lorentz factor of electrons. This relativistic electron distribution with a broken power-law shape, of parameters $\gamma_{e}^{-51}$ for energies below the break $\gamma_{e,\text{break}}$ and $\gamma_{e}^{-\infty}$ above, where $\gamma_{e}$ is the random Lorentz factor of electrons. This distribution is iteratively modified to take into account electron cooling and the possibility of producing pairs through synchrotron self-Compton (SSC), and external Compton (EC). The seed photons for the latter are the sum of several contributions: photons directly radiated from the accretion disk (Dermer & Schlickeiser 2002). We refer to Ghisellini & Tavecchio (2009) for more details. The model parameters and the calculated powers are listed in Tables 3 and 4.

Archival radio data are displayed in Figure 1 for completeness, but are not used in the model fit. Indeed, the one-zone model used in the present work has to explain the bulk of the emission and, therefore, necessarily requires a compact source. This, in turn, is self-absorbed for synchrotron radiation (at $\approx 10^{11–12}$ Hz). The radio emission is detectable only when the blob becomes optically thin and this occurs as it moves and expands, further out in the jet (e.g., Blandford & Königl 1979).

Given the scarce, non-simultaneous data and the weakness of the $\gamma$-ray emission for the three newly discovered sources, it is not possible to tightly constrain the selection of parameters. As a guide to the selection of the initial values of the model parameters (Table 3), we were driven by the recent (March–July 2009) mult wavelength study of PMN J0948+0022 (Abdo et al. 2009c), our knowledge of blazars, and the mass measurements performed with other methods (particularly in the case of PKS 2004−447, for which the optical/UV data are not sampling the accretion disk emission). When more information, particularly from multiwavelength variability studies, will be available, it will be possible to improve the estimation of the parameter values.

### 4. DISCUSSION

The analysis of the individual sources reveals some things worth noting. In 1H 0323+342, the dissipation region needs to be located very close to the central black hole ($\sim 650$ times the Schwarzschild radius $R_{S}$) and hence a quite high magnetic field (up to 30 gauss) is needed. We note that PKS 2004−447 seems to be different with respect to the three other RL-NLS1s, with a compact steep-spectrum (CSS) radio source. On the other hand, this source is also in the CRATES catalog of flat spectrum radio sources (Healey et al. 2007), which also includes the three other NLS1s in this work. From the present study, the estimated jet power of PKS 2004−447 is well above the range typical of radio galaxies and, therefore, we favor the hypothesis of a genuine NLS1. However, in this case the classification remains uncertain and should be studied with further observations.

A synoptic analysis of the 4 RL-NLS1s in the present work shows that PKS 1502+036 carries a jet power comparable to PMN J0948+0022, while the remaining two sources are significantly less powerful—even two order of magnitudes for proton powers (Table 4). The comparison with the large sample of blazars reported in Celotti & Ghisellini (2008) and Ghisellini et al. (2009b) shows that the jet powers of PKS 1502+036 and PMN J0948+0022 are in the region of quasars, while 1H 0323+342 and PKS 2004−447 are in the range typical of BL Lac Objects. The $\gamma$-ray-emitting RL-NLS1s in our sample

| Source          | Inst. | Exp. | $N_{H}$ | $n_{H}$ | $\Gamma$ | $E_{0}$ | $\Gamma_{e}$ | $F_{\text{UV}}$ | Stat. |
|-----------------|-------|------|---------|---------|---------|---------|-------------|----------------|-------|
| 1H 0323+342     | X     | 57.1 | 11.7    | 2.03±0.02 | ...     | ...     | 14.0±0.1 | 1.06/313         |       |
| PKS 1502+036    | X     | 4.6  | 3.89    | 1.0±0.9 | ...     | ...     | 0.43±0.10 | 2                  |       |
| PKS 2004−447    | E     | 15.22 | 2.96    | 2.0±0.1 | 0.67±0.08 | 1.50±0.03 | 1.5±0.1   | 1.05/315         |       |

Notes.
61 In the case of NLS1s, the permitted emission lines from the BLR are narrower than usual, with FWHM(H$\beta$) $\lesssim$ 2000 km s$^{-1}$. 

Figure 1. SEDs of the four RL-NLS1s detected by Fermi/LAT in order of decreasing γ-ray flux. The SED of PMN J0948+0022 is that from Abdo et al. (2009a). In the SED of 1H 0323+342, there are also detections in the hard X-rays by Swift/BAT (Cusumano et al. 2009) and INTEGRAL/ISGRI (Bird et al. 2007). The TeV upper limit is derived from observations with Whipple (Falcone et al. 2004). Archival radio data are from NED, but are displayed just for completeness, since they are not used in the model fit. The synchrotron self-absorption is clearly visible around $10^{11–12}$ Hz. The short dashed light blue line indicates the synchrotron component, while the long dashed orange line is the SSC. The dot-dashed line refers to EC and the dotted black line represents the contribution of the accretion disk, X-ray corona and the IR torus. The continuous blue line is the sum of all the contributions.

Table 3

| Name             | $R_{diss}$ | $log M$ | $R_{BLR}$ | $P_i^d$ | $L_i^c$ | $\beta$ | $\Gamma_i$ | $\theta_i^h$ | $\gamma_{c,\text{break}}$ | $\gamma_{c,\text{max}}$ | $s_1^k$ | $s_2^l$ |
|------------------|------------|---------|-----------|---------|---------|---------|-----------|---------------|--------------------------|--------------------------|---------|---------|
| 1H 0323+342      | 1.9 (650)  | 7.0     | 116       | 1.0     | 1.4 (0.9) | 30      | 12        | 3             | 60                       | 6000                     | –1      | 3.1     |
| PKS 1502+036     | 24 (4000)  | 7.3     | 155       | 21      | 2.4 (0.8) | 1.6     | 13        | 3             | 50                       | 3000                     | 1       | 3.2     |
| PKS 2004–447     | 6 (4000)   | 6.7$m$  | 39        | 3.1     | 0.15 (0.2) | 6.9     | 8         | 3             | 120                      | 1500                     | 0.2     | 2       |
| PMN J0948+0022$m$| 72 (1600)  | 8.2     | 300       | 240     | 9 (0.4)   | 3.4     | 10        | 6             | 800                      | 1600                     | 1       | 2.2     |

Notes.

$a$ Dissipation radius in units of $10^{15}$ cm and (in parenthesis) in units of the Schwarzschild radius.

$b$ Black hole mass in units of $M_\odot$ (details and caveats about the mass estimation used in this work can be found in Ghisellini et al. 2009a; the error with this method is generally about 50%).

$c$ Size of the BLR in units of $10^{15}$ cm.

$d$ Power injected in the blob calculated in the comoving frame, in units of $10^{41}$ erg s\(^{-1}\).

$e$ Accretion disk luminosity in units of $10^{45}$ erg s\(^{-1}\) calculated by integrating the thermal component (black dotted line) of the SEDs in Figure 1 and (in parenthesis) in Eddington units.

$f$ Magnetic field in Gauss.

$g$ Bulk Lorentz factor at $R_{diss}$.

$h$ Viewing angle in degrees.

$i$ Break random Lorentz factors of the injected electrons.

$j$ Maximum random Lorentz factors of the injected electrons.

$k$ Slope of the injected electron distribution below $\gamma_{c,\text{break}}$.

$l$ Slope of the injected electron distribution above $\gamma_{c,\text{break}}$.

$m$ Fixed from measurement with reverberation mapping method reported by Oshlack et al. (2001).

$n$ See Abdo et al. (2009a).
Table 4

| Name               | log $P_x^a$ | log $P_y^b$ | log $P_z^c$ | log $P_{ei}^d$ |
|--------------------|------------|------------|------------|--------------|
| 1H 0323+342        | 42.8       | 43.3       | 42.7       | 44.3         |
| PKS 1502+036       | 44.0       | 43.0       | 44.1       | 46.2         |
| PKS 2004+447       | 42.9       | 42.6       | 42.9       | 44.1         |
| PMN J0948+0022$^e$ | 45.3       | 44.3       | 44.7       | 46.7         |

Notes.

$^a$ Radiative power (erg s$^{-1}$).

$^b$ Poynting flux power (erg s$^{-1}$).

$^c$ P Power in bulk motion of electrons (erg s$^{-1}$).

$^d$ P Power in bulk motion of protons, assuming one proton per emitting electron (erg s$^{-1}$).

$^e$ See Abdo et al. (2009a).

have small masses and high accretion rates. This is in contradiction to the larger masses and smaller accretion rates expected from low-power blazars (HFSRQs) with strong emission lines, as suggested by Yuan et al. (2008). Anyway, when comparing the calculated powers with the distribution of powers in blazars (quasars plus BL Lacs; see Ghisellini et al. 2009b), RL-NLS1s are in the average range.

The main differences with respect to blazars are in the masses and accretion rates. The masses of the three newly discovered RL-NLS1s are around $10^7 M_\odot$, in agreement within one order of magnitude with the values obtained with other methods. In the case of 1H 0323+342, Zhou et al. (2007) found values of $1.8 \times 10^7 M_\odot$ with Hβ luminosity and $3 \times 10^7 M_\odot$ with the luminosity of the continuum at 5100 Å. In the case of PKS 1502+036, Yuan et al. (2008) estimate the mass to be $4 \times 10^9 M_\odot$ by means of the virial method. These values are about 1–2 orders of magnitude lower than the typical blazar masses ($\approx 10^9 M_\odot$, see Ghisellini et al. 2009b). The accretion rates can reach extreme values, up to 80% or even 90% of the Eddington values in the cases of PKS 1502+036 and 1H 0323+342, respectively. These values are the most extreme ever found in any γ-ray-emitting AGNs, but usual for NLS1s.

What is at odds with this scenario is the type of host galaxy, which is elliptical in all blazars, while is likely to be spiral in RL-NLS1s (see, e.g., Zhou et al. 2006). In the case of 1H 0323+342, analysis of optical observations suggests two possibilities: Zhou et al. (2007) show the spiral arms of the host galaxy by means of observations with the Hubble Space Telescope, while Antòn et al. (2008), on the basis of ground-based observations with Nordic Optical Telescope (NOT), suggest that these structures are the residual of a merging that occurred within the past 108 years. This means that relativistic jets can form and develop independently of their host galaxies, with quasars, BL Lacs and, now, RL-NLS1s jointly characterized by the presence of a relativistic jet and with the differences in their observed SEDs mainly determined by their masses and accretion rates.

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