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

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ABSTRACT

We report the discovery with *Fermi*/LAT of γ-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 γ rays, they may form an emerging new class of γ-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 γ rays. Specifically, the recent detection in the MeV–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 γ-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 γ 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 γ rays) and jet-like (perhaps aborted?, cf. Ghisellini et al. 2004) structures, whose emission at γ 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 γ-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 $R_L = f_{5\ \mathrm{GHz}}/f_{440\mathrm{nm}} = 50$, 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 Hβ < 2000 km s^{-1}), [O III]/Hβ < 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 γ 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 γ-ray detections of NLS1s (3 + 1 = 4 out of 29 sources, $\approx$14% of our sample), suggesting that they form a new class of γ-ray-emitting AGNs.

Throughout this work, we adopted a ΛCDM cosmology from the most recent *WMAP* results, which give the following values for the cosmological parameters: $h = 0.71$, $\Omega_m = 0.27$,

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Table 1
γ-Ray Characteristics of RL-NLS1s Detected by LAT with TS > 25

Name	z	α (deg)	δ (deg)	$r_{95\%}$[a] (deg)	F_γ[b] (10^{-8} photons cm^{-2} s^{-1})	Γ[c]	TS	L_γ[d] (10^{46} erg s^{-1})	Ass.[e] (%)
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[f]	0.585	147.28	+0.39	0.12	14.6 ± 0.9	2.78 ± 0.06	647	11	99

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] γ-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 γ-ray luminosity.

[e] Confidence level of the association according to the FoM.

[f] See Abdo et al. (2009a).

$\Omega_\Lambda = 0.73$ and with the Hubble–Lemaître constant $H_0 = 100\ h$ 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 subtraction[58]. The data analyzed span between MJD 54682 (2008 August 4) and 55048 (2009 August 5).

Four LAT sources with TS[59] greater than 25, which is equivalent[60] to $\sim 5\sigma$, 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). Particularly, we found in the case of 1H 0323+342, there is evidence of spectral variability in the X-ray energy band, even on timescales of a few days. The photon index is generally soft, as for a typical NLS1 (cf. Leighly 1999), but sometimes it displays a hard tail ($\Gamma \approx 1.3$–1.6) during a simultaneous increase of the optical/UV flux (Foschini et al. 2009a).

PKS 1502+036 was first observed in X-rays on 2009 July 25 (*Swift* ObsID 00031445001). No previous X-ray observations were available and even *ROSAT* measured just an upper limit, which was not very stringent ($< 2 \times 10^{-12}$ erg cm^{-2} s^{-1} in the 0.1–2.4 keV, see Yuan et al. 2008). We based our plans for the observation taking into account the similar optical characteristics shared with the better known PMN J0948+0022 (Abdo et al. 2009a). However, the effective exposure of 4.6 ks on XRT was not long enough to collect sufficient photons to apply the χ^2 test statistic. Therefore, we grouped the photons to have at least 10 counts per bin and applied the Cash statistic, which allows the parameters to be estimated through the likelihood ratio (Cash 1979).

In order to make a homogeneous data set, we have reanalyzed all the *Swift* and *XMM-Newton* data adopting the same procedures outlined in the previous works, but using the most recent software packages version (HEASOFT ver. 6.6.3 for *Swift* and SAS ver. 9.0.0 for *XMM-Newton*) and calibration databases (updated on 2009 June 5 for *Swift* and 2009 June 11 for *XMM-Newton*). X-ray data were fitted to power-law or broken power-law models with Galactic absorption from Kalberla et al. (2005), while optical/UV data were dereddened for the proper values calculated according to the extinction laws by Cardelli et al. (1989). None of the sources showed evidence of X-ray absorption in excess to the Galactic value. The X-ray photon indices are generally in agreement with those typical of blazars (cf., for example, Foschini et al. 2006; Maraschi et al. 2008). The results are summarized in Table 2. All the results of the present reanalysis are consistent with the previous ones already reported 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

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

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

[60] The significance of the detection in σ is roughly $\sqrt{TS}$.

Table 2
Summary of the *Swift* and *XMM-Newton* Analyses

					X-Rays			
Source	Inst.[a]	Exp.[b]	N_H[c]	Γ[d]	E_b[e]	Γ_2[f]	F[g]	Stat[h]
1H 0323+342	X	57.1	11.7	2.03 ± 0.02[i]	...	...	14.0 ± 0.1	1.06/313
PKS 1502+036	X	4.6	3.89	$1.0^{+0.9}_{-0.8}$	...	...	0.43 ± 0.10	2
PKS 2004−447	E	15, 22, 22	2.96	$2.0^{+0.2}_{-0.1}$	0.67 ± 0.08	1.50 ± 0.03	1.5 ± 0.1	1.05/315

				Optical/UV			
Source	Inst.[a]	A_V[l]	v	b	u	$uvw1$	$uvm2$	$uvw2$
1H 0323+342	U	0.62	15.82 ± 0.03	16.38 ± 0.03	15.50 ± 0.03	15.82 ± 0.04	16.01 ± 0.04	15.92 ± 0.04
PKS 1502+036	U	0.21	19.0 ± 0.2	19.5 ± 0.1	18.6 ± 0.1	18.54 ± 0.08	18.38 ± 0.08	18.40 ± 0.06
PKS 2004−447	O	0.16	...	18.91 ± 0.08	18.54 ± 0.09	18.65 ± 0.08	19.0 ± 0.2	...

Notes.
[a] Instrument used for the observation: X for XRT and U for UVOT onboard *Swift*; E for EPIC PN, MOS1, and MOS2 and O for OM onboard *XMM-Newton*.
[b] Net exposure in kiloseconds. In the case of EPIC, the exposures of PN, MOS1, and MOS2, respectively, are reported.
[c] Galactic absorption in units of 10^{20} cm^{-2} from Kalberla et al. (2005).
[d] Photon index of the power-law model or low-energy photon index in the case of broken power-law model.
[e] Break energy in the case of broken power-law model (keV).
[f] High-energy photon index in the case of broken power-law model.
[g] Observed flux in the 0.2–10 keV energy band in units of 10^{-12} erg cm^{-2} s^{-1}.
[h] Statistical parameters: $\tilde{\chi}^2$/dof for χ^2 or number of PHA bins for the Cash statistic.
[i] It is worth noting that the addition of an unresolved Gaussian emission line at $E = 6.5 \pm 0.3$ keV with equivalent width ∼147 eV gives a $\Delta\chi^2 = 9.3$.
[l] Magnitudes absorbed by the Galactic column in the visual filter (from Kalberla et al. 2005) and used as reference to calculate the absorption in other filters by means of the Cardelli et al. (1989) extinction law.

relativistic electron distribution with a broken power-law shape, of parameters $\gamma_e^{-s_1}$ for energies below the break $\gamma_{e,\text{break}}$ and $\gamma_e^{-s_2}$ above, where γ_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 $\gamma\gamma \rightarrow e^{\pm}$. The resulting distribution at the time $R/c \approx 0.1 R_{\text{diss}}/c$, where R_{diss} is the dissipation radius and $0.1 R_{\text{diss}}$ is the size of the emitting spherical blob, is used to generate the radiation emitted through the processes of synchrotron, 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 1993), from the broad-line region (BLR,[61] Sikora et al. 1994) and from the infrared torus (Błażejowski et al. 2000; Sikora et al. 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 γ-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) multiwavelength 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, particu-

larly 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 (∼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 optical/UV data sampling the synchrotron emission instead of the accretion disk. Indeed, the classification of this source is still open: while Oshlack et al. (2001) classified it as genuine RL-NLS1, Komossa et al. (2006) suggested it can be a narrow-line radio galaxy, on the basis that the bump of Fe II is weak. Gallo et al. (2006) noted that there is no specific prescription on the value of the strength of the Fe II bump and confirmed the NLS1 classification. The same authors noted that PKS 2004−447 is 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 γ-ray-emitting RL-NLS1s in our sample

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[61] In the case of NLS1s, the permitted emission lines from the BLR are narrower than usual, with FWHM(Hβ) $\lesssim$ 2000 km s^{-1}.
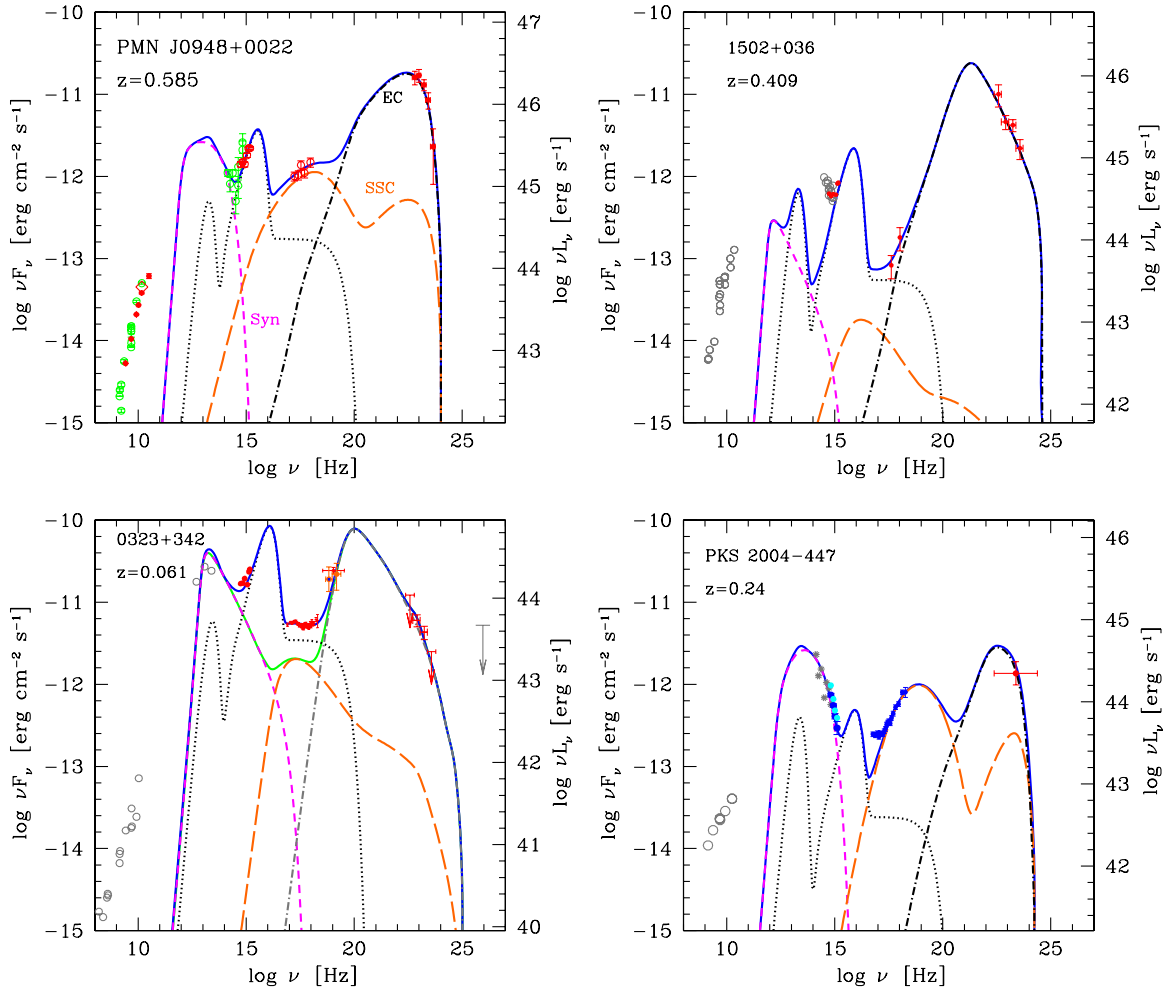
Figure 1. SEDs of the four RL-NLS1s detected by *Fermi*/LAT in order of decreasing γ-ray flux. The SED of PMN J0948+0022 is that from Abdo et al. (2009a). In the SED of 1H 0323+342, there are also detections in the hard X-rays by *Swift*/BAT (Cusumano et al. 2009) and *INTEGRAL*/ISGRI (Bird et al. 2007). 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
Parameters Used to Model the SEDs

Name	R_{diss}[a]	$\log M$[b]	R_{BLR}[c]	P_i'[d]	L_d[e]	B[f]	Γ_b[g]	θ_v[h]	$\gamma_{e,\mathrm{break}}$[i]	$\gamma_{e,\mathrm{max}}$[j]	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[n]	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 $\gamma_{e,\mathrm{break}}$.
[l] Slope of the injected electron distribution above $\gamma_{e,\mathrm{break}}$.
[m] Fixed from measurement with reverberation mapping method reported by Oshlack et al. (2001).
[n] See Abdo et al. (2009a).

Table 4
Power Carried Out by the Jet

Name	$\log P_\mathrm{r}$[a]	$\log P_\mathrm{B}$[b]	$\log P_\mathrm{e}$[c]	$\log P_\mathrm{p}$[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] Power in bulk motion of electrons (erg s^{-1}).
[d] 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 1.8×10^7 $M_\odot$ with $H\beta$ luminosity and 3×10^7 $M_\odot$ 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 4×10^6 $M_\odot$, by means of the virial method. These value 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 10^8 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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