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Relativistic jets in narrow-line Seyfert 1 galaxies. New discoveries and open questions

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Abstract. Before the launch of the *Fermi* satellite only two classes of AGNs were known to produce relativistic jets and thus emit up to the γ-ray energy range: blazars and radio galaxies, both hosted in giant elliptical galaxies. The first four years of observations by the Large Area Telescope 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 γ-ray emission from 5 radio-loud narrow-line Seyfert 1 galaxies revealed the presence of a possible emerging third class of AGNs with relativistic jets. Considering that narrow-line Seyfert 1 galaxies seem to be 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 discuss the radio-to-γ-rays properties of the γ-ray emitting narrow-line Seyfert 1 galaxies, also in comparison with the blazar scenario.

1 Introduction

Active galactic nuclei (AGN) are the most luminous persistent sources of high-energy radiation in the Universe. However, only a small percentage of 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. 13, 43]. Certainly relativistic jets are the most extreme expression of the power than can be generated by a SMBH in the center of an AGN, 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 produce these structures and thus to emit up to the γ-ray energy range: blazars and radio galaxies, both hosted in giant elliptical galaxies [12]. The point spread function and sensitivity of the Large Area Telescope (LAT) on board *Fermi* provided an unprecedented angular resolution at high energies for localizing a large number of newly detected γ-ray emitting sources. The first 4 years of observation by the *Fermi*-LAT confirmed that the extragalactic γ-ray sky is dominated by radio-loud AGNs, being mostly blazars and some radio galaxies [9, 44]. However, the discovery by *Fermi*-LAT 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 [1–3]. On the contrary, no radio-quiet Seyfert galaxies were detected in γ rays until now [8]. This finding poses intriguing questions about the nature of radio-loud NLSy1s, the onset of production of relativistic jets, the mechanisms of high-energy emission, and the cosmological evolution of radio-loud AGN.

NLSy1 is a class of AGN identified by [47] and characterized by their optical properties: narrow permitted lines (FWHM (Hβ) < 2000 km s^{-1}) emitted from the broad line region (BLR), [OIII]/Hβ < 3, and a bump due to Fe II [see e.g. 48, for a review]. They also exhibit strong X-ray variability, steep X-ray spectra, substantial soft X-ray excess and relatively high luminosity [14, 35]. 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. NLSy1s are generally radio-quiet (radio-loudness[1] R < 10), with only a small fraction of them [< 7%, 38] classified as radio-loud, and objects with high values of radio-loudness (R > 100) are even more sparse (∼2.5%), while generally ∼15% of quasars are radio-loud. In the past, several authors investigated the peculiarities of the radio-loud NLSy1s with non-simultaneous radio-to-X-ray data, suggesting similarities with the young stages of quasars or different types of blazars [e.g. 29, 38, 51].

The firm confirmation of the existence of relativistic jets also in this subclass of Seyfert galaxies opened a large

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[1] R being defined as the ratio between the 1.4 GHz and 4400 Å rest-frame flux densities

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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 emitting AGNs and blazars and radio galaxies? How do these objects fit into the blazar sequence? What is the origin of the radio-loudness? What are the parameters determining the jet formation? Is there a limiting BH mass above which objects are preferentially radio-loud? Five years after the announcement of the detection of the first NLSy1 in γ rays by *Fermi*-LAT, PMN J0948+0022 [1], only some indications about the nature of these objects have been obtained.

2 The γ-ray view of NLSy1

Five radio-loud NLSy1 galaxies have been detected at high significance by *Fermi*-LAT so far: 1H 0323+342, SBS 0846+513, PMN J0948+0022, PKS 1502+036, and PKS 2004−447 [20, 44], with a redshift between 0.061 and 0.585. Here we analyze the first four years of γ-ray observations of these sources in two energy ranges: 0.1–1 GeV, and 1–100 GeV. 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 v9r31p1. The LAT data were extracted within a 10° Region of Interest centred at the location of the 5 NLSy1s. Only events belonging to the "Source" class were used. The time intervals when the rocking angle of the LAT was greater than 52° were rejected. 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 `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 extragalactic and instrumental background were used to model the background[2]. 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 [42]. 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 < 25 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 the five NLSy1s, except for the analysis in the 0.1–1 GeV energy range of 1H 0323+342 and PMN J0948+0022, for which we used a log-parabola as in the 2FGL catalog [44]. 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 [7].

The results of the LAT analysis over 2008 August–2012 August in the energy range 0.1–1 GeV and 1–100 GeV are summarized in Table 1 and Table 2, respectively. It is worth noting that the detection significance of these NLSy1s is much higher in the 0.1–1 GeV energy range with respect to the 1–100 GeV energy range, except for SBS 0846+513. That source is detected at high significance above 1 GeV with a flat spectrum below 1 GeV, suggesting that during a strong flaring activity SBS 0846+513 could be detected also at Very High Energy with the current Cherenkov Telescopes (MAGIC, VERITAS, H.E.S.S.) and the future Cherenkov Telescope Array (CTA), as well as some flat spectrum radio quasars (FSRQs) at redshift comparable to that of this NLSy1 (i.e. 3C 279, 4C +21.35, and PKS 1510−089). On the contrary, only TS = 12 was obtained for 1H 0323+342 above 1 GeV, indicating that most of the γ-ray emission from this source is usually produced at low γ-ray energies. In addition, 1H 0323+342 and PMN J0948+0022 showed a photon index higher than 3 in the 1–100 GeV range, in agreement with a softening of the spectrum due to a significant spectral curvature [see 2FGL catalogue, 44].

As already reported in [22], the average apparent isotropic luminosity of the 5 γ-rays NLSy1s estimated in the 0.1–100 GeV energy band 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 small viewing angle with respect to the jet axis and thus a high beaming factor for the γ-ray emission, similarly to blazars. In particular, SBS 0846+513 and PMN J0948+0022 showed γ-ray flaring activity combined with a moderate spectral evolution [20, 30], a behaviour already observed in bright FSRQs and low-synchrotron-peaked (LSP) BL Lacs detected by *Fermi*-LAT [4]. On the contrary, most of the radio galaxies detected by LAT have an apparent isotropic γ-ray luminosity lower than 10^{44} erg s^{-1}, suggesting a smaller beaming factor and possibly a different structure of the jet [5]. Several strong γ-ray flares were observed from SBS 0846+513 and PMN J0948+0022, reaching at the peak an apparent isotropic γ-ray luminosity of $\sim 10^{48}$ erg s^{-1}, comparable to that of the bright FSRQs [20, 25, 30]. Variability and spectral properties of these two NLSy1s in γ rays indicate a blazar-like behaviour. Recently, an intense γ-ray flaring activity was observed by *Fermi*–LAT also from 1H 0323+342 [16]. This is another indication that radio-

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

Table 1. Results of the *Fermi*–LAT analysis of the NLSy1s in the 0.1–1 GeV energy range.

Source	Redshift z	Flux (0.1–1 GeV) $\times 10^{-8}$ ph cm^{-2} s^{-1}	Photon index Γ/α	Curvature β	TS
1H 0323+342	0.061	3.77±0.80	2.77±0.16	0.34±0.25	155
SBS 0846+513	0.5835	2.10±0.23	2.04±0.13	-	248
PMN J0948+0022	0.585	11.25±0.48	2.50±0.05	0.26±0.09	1763
PKS 1502+036	0.409	4.14±0.45	2.60±0.13	-	220
PKS 2004−447	0.240	1.23±0.38	2.08±0.25	-	56

Table 2. Results of the *Fermi*–LAT analysis of the NLSy1s in the 1–100 GeV energy range.

Source	Flux (1–100 GeV) $\times 10^{-9}$ ph cm^{-2} s^{-1}	Photon index Γ	TS
1H 0323+342	0.41±0.14	3.26±0.19	12
SBS 0846+513	2.02±0.16	2.54±0.09	447
PMN J0948+0022	2.71±0.23	3.46±0.04	410
PKS 1502+036	0.10±0.01	2.65±0.18	96
PKS 2004−447	0.42±0.12	2.63±0.32	22

loud NLSy1s are able to host relativistic jets as powerful as those in blazars.

3 X-ray observations

The X-ray spectra of NLSy1 are usually characterized by a steep photon index ($\Gamma_X > 2$) [35]. On the contrary, a relatively hard X-ray spectrum was detected in the *Swift*/XRT observations of SBS 0846+513 [20, 22], PMN J0948+0022 [30], 1H 0323+342 [23], and PKS 1502+036 [21]. This suggests a significant contribution of inverse Compton radiation from a relativistic jet, similar to what is found for FSRQs.

The high quality XMM-*Newton* observation of PMN J0948+0022 performed in 2011 May allowed us to study in detail its X-ray spectrum, as reported in detail in [24]. The spectral modelling of the XMM data of PMN J0948+0022 shows that emission from the jet most likely dominates the spectrum above ~2 keV, while a soft X-ray excess is evident in the low-energy part of the X-ray spectrum. The origin of the soft X-ray excess is still an open issue both in radio-quiet and radio-loud AGN [18, 33]. Such a Seyfert component is a typical feature in the X-ray spectra of radio-quiet NLSy1s, but quite unusual in jet-dominated AGNs, even if not unique [e.g. the FSRQ PKS 1510−089, 36]. It was not possible to distinguish between different models for the soft X-ray emission of PMN J0948+0022 on a statistical basis. Models where the soft emission is partly produced by blurred reflection, or Comptonisation of the thermal disc emission, or simply a steep power-law, all provide good fits to the data. A multicolor thermal disc emission also gives a comparable fit, but a too high temperature (kT = 0.18 keV) is necessary, which is incompatible with a standard Shakura & Sunyaev accretion disc [24]. A similar soft X-ray excess was observed also in the XMM-*Newton* observation of the other γ-ray NLSy1 PKS 2004−447 [32].

4 Radio properties

Only a small fraction of NLSy1s are known to be radio-loud. For these sources, flat radio spectrum and flux density variability suggested that several of them could host relativistic jets [28, 51, 52]. A core-jet structure on pc scale was observed for SBS 0846+513 [20], PKS 1502+036 [22], and PMN J0948+0022 [24, 34], although the jet structure in the last two sources is significantly fainter than that observed in SBS 0846+513. Based on VLBA data at 1.4 GHz the interpretation of the radio properties of PKS 2004−447 is more uncertain, with a bright and compact component at the easternmost edge of the source that may be either the core of a core-jet blazar or a bright hotspot of an asymmetric young radio source [45]. The possibility that PKS 2004−447 could be a compact steep-spectrum source was suggested also by [32].

The analysis of the 6-epoch data set of SBS 0846+513 collected by the Monitoring Of Jets in Active galactic nuclei with VLBA Experiments (MOJAVE) programme[3] during 2011–2013 indicates that a superluminal jet component is moving away from the core with an apparent angular velocity of (0.27±0.02) mas yr^{-1}, corresponding to (9.3±0.6)c [21]. This apparent superluminal velocity strongly suggests the presence of boosting effects for the jet of SBS 0846+513. On the contrary, VLBA observations did not detect apparent superluminal motion at 15 GHz for PKS 1502+036 during 2002–2012, although the radio spectral variability and the one-sided jet-like structure seem to require the presence of boosting effects in a relativistic jet [22].

In addition, strong variability was observed at 15 GHz during the monitoring of the Owens Valley Radio Observatory 40-m telescope of PMN J0948+0022 [24], PKS 1502+036 [21], and SBS 0846+513 [25]. An inferred variability

[3]The MOJAVE data archive is maintained at http://www.physics.purdue.edu/MOJAVE

brightness temperature of 2.5×10^{13} K and 1.1×10^{14} K for PKS 1502+03 and SBS 0846+513, respectively. These values are much larger than the brightness temperature derived for the Compton catastrophe [37], suggesting that the radio emission of the jet is Doppler boosted. A complex connection between the radio and γ-ray emission was observed for SBS 0846+513 and PMN J0948+0022, as discussed in detail in [25, 46], and [24, 31].

To understand if there are some peculiar characteristics in the 5 NLSy1s detected by *Fermi*-LAT, we have investigated the radio properties of the first sample of 23 radio-loud NLSy1s presented by [51]. We note that B3 1044+476, the object with the highest radio-loudness, was not detected by *Fermi*-LAT in γ rays so far, while e.g. PMN J0948+0022 shows a high but not extreme radio-loudness. This indicates that the radio-loudness is not necessarily a useful proxy for selecting the best candidates for γ-ray detection with LAT. In the same way, a high apparent brightness temperature of ~10^{13} K, comparable to that of SBS 0846+513 and PMN J0948+0022, was observed for TXS 1546+353. This should be an indication of Doppler boosted emission from a relativistic jet orientated close to our line-of-sight. However, no γ-ray emission has been detected from this source. Certainly also the flux variability should be taken into account when searching for NLSy1s in γ rays, but it is not the only factor playing a role. Indeed the discoveries of NLSy1s did not always occur during high γ-ray activity states (e.g. PKS 1502+036 and PKS 2004−447) [3, 22].

5 Spectral energy distribution of γ-ray NLSy1

The first spectral energy distributions (SEDs) collected for the four γ-ray NLSy1s detected in the first year of *Fermi* operation showed clear similarities with blazars: a double-humped shape with a first peak in the IR/optical band due to synchrotron emission, a second peak in the MeV/GeV band likely due to inverse Compton emission, and an accretion disk component in UV. The physical parameters of these NLSy1s are blazar-like, and the jet power is in the average range of blazars [2].

The comparison of the SED of PMN J0948+0022 during the 2010 July flaring activity with that of the FSRQ 3C 273 shows a more extreme Compton dominance in the NLSy1. The disagreement of the two SEDs may be due to the difference in BH masses and Doppler factor of the two jets [30].

We also compared the SED of SBS 0846+513 during the flaring state in 2012 May with that of a quiescent state. The SEDs of the two different activity states, modelled by an external Compton component of seed photons from a dust torus, could be fitted by changing the electron distribution parameters as well as the magnetic field [25], consistent with the modeling of different activity states of PKS 0208−512 [17]. A significant shift of the synchrotron peak to higher frequencies was observed during the 2012 May flaring episode, similar to FSRQs [e.g. PKS 1510−089; 19]. Contrary to what is observed in PMN J0948+0022, no significant evidence of thermal emission from the accretion disc has been observed in SBS 0846+513 [25].

6 Radio-loudness, host galaxies, 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 under debate yet. One fundamental parameter could be the BH mass, with only large masses allowing an efficient jet formation [see e.g. 49]. Therefore one of the most surprising fact related to the discovery of the NLSy1s in γ rays was the development of a relativistic jet in objects with a relatively small BH mass of 10^7-10^8 $M_\odot$ [51]. However, it is worth nothing that the mass estimation of these source has large uncertainties. In particular, [40] suggested that BLR clouds are subjected to radiation pressure from the absorption of ionizing photons, and applying a correction for this effect on the virial BH masses estimates higher masses are obtained for the NLSy1s, which are objects radiating close to their Eddington limit. In the same way, [26] proposed that the BLR may have a disk-like geometry oriented almost face-on, so that the Doppler shifted line velocity projected along the line-of-sight appears small. Recently, [15] modelling the optical/UV data of some radio-loud NLSy1s with a Shakura & Sunyaev disc spectrum have estimated BH masses higher than 10^8 $M_\odot$. In particular, they found a BH mass of 10^9 $M_\odot$ and 2×10^8 $M_\odot$ for PMN J0948+0022 and PKS 1502+036, respectively, in agreement with the typical BH mass of blazars. This may solve the problem of the minimum BH mass predicted in different scenarios of relativistic jet formation and development, but introduces a new problem. If the BH mass of these NLSy1s is 10^8-10^9 $M_\odot$, how is it possible to have such a large BH mass in a class of AGNs usually hosted in spiral galaxies?

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 [27] and [53] had z < 0.03 and z < 0.1, respectively, while four out five of the NLSy1s detected in γ rays have $z > 0.2$. Among the radio-loud NLSy1s detected by *Fermi*-LAT only for the closest one, 1H 0323+342, the host galaxy was clearly detected. *Hubble Space Telescope* (HST) and Nordic Optical Telescope observations seem to reveal a one-armed galaxy morphology or a circumnuclear ring, respectively, suggesting two possibilities: the spiral arms of the host galaxy [54] or the residual of a galaxy merging [10]. On the other hand, no significant resolved structures have been observed by HST for SBS 0846+513 [39], 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, unusual in disk/spiral galaxies, cannot be ruled out.

According to the “modified spin paradigm” proposed, another fundamental parameter for the efficiency of a relativistic jet production should 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. 11, 41]. We noted that BH masses of radio-loud NLSy1s are generally larger with respect to the entire sample of NLSy1s [$M_{BH} \approx(2\text{–}10) \times10^7$ $M_{\odot}$; 38, 51], even if still small if compared to radio-loud quasars. The larger BH masses of radio-loud NLSy1s with respect to radio-quiet NLSy1s could be related to prolonged accretion episodes that can spin-up the BHs. In this context, the small fraction of radio-loud NLSy1s with respect to radio-loud quasars could be an indication that not in all of the former the high-accretion regime lasted long enough to spin-up the central BH [50].

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, PMN J0948+0022, and 1H 0323+342 are strong indications of a relativistic jet in these objects as powerful as those of blazars. Variability and spectral properties in radio and γ-ray bands, together with the SED modeling, indicate blazar-like behaviour. These sources showed all the characteristics of the blazar phenomenon and they could be at the low tail of the blazar's BH mass distribution, although it must be taken into account the possibility that the masses of these radio-loud NLSy1s may be underestimated.

Further multifrequency observations of the 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 engine in radio-loud NLSy1s, which seem quite different from that in quasars and manifest in their peculiar optical characteristics, on the γ-ray production 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 so far.

Anyway, the lack of information about the host galaxy for four out five NLSy1s detected by LAT, together with the possible evidence the residual of a galaxy merging for 1H 0323+342, left open the possibility that at least some of the radio-loud NLSy1s are hosted in an early type elliptical/S0 galaxy. Further high-resolution observations of the host galaxy of γ-ray NLSy1s will be fundamental to obtain important insights into the formation of relativistic jets.

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References

[1] Abdo, A. A., Ackermann, M., Ajello, M., et al., ApJ **699**, 976 (2009)

[2] Abdo, A. A., Ackermann, M., Ajello, M., et al., ApJ **707**, 727 (2009)

[3] Abdo, A. A., Ackermann, M., Ajello, M., et al., ApJ **707**, L142 (2009)

[4] Abdo, A. A., Ackermann, M., Ajello, M., et al., ApJ **710**, 1271 (2010)

[5] Abdo, A. A., Ackermann, M., Ajello, M., et al., ApJ **720**, 912 (2010)

[6] Ackermann, M., Ajello, M., Baldini, L., et al., ApJ **721**, 1383 (2010)

[7] Ackermann, M., Ajello, M., Albert, A., et al., ApJS **203**, 4 (2012)

[8] Ackermann, M., Ajello, M., Allafort, A., et al., ApJ **747**, 104 (2012)

[9] Ackermann, M., et al., The Third Fermi-LAT catalog, in preparation

[10] Anton, S., Browne, I. W. A., Marcha, M. J., A&A **490**, 583 (2008)

[11] Böttcher, M., & Dermer, C. D., ApJ **564**, 86 (2002)

[12] Blandford, R. D., & Rees, M. J., in BL Lac Objects ed. A. M. Wolfe (Univ. Pittsburgh Press) **328** (1978)

[13] Blandford, R. D., Progress of Theoretical Physics Supplement **143**, 182 (2001)

[14] Boller, T., Bradt, W. N., & Fink, H., A&A **305**, 53 (1996)

[15] Calderone, G., Ghisellini, G., Colpi, M., Dotti, M., MNRAS **431**, 210 (2013)

[16] Carpenter, B., & Ojha, R., The Astronomer's Telegram **5344** (2013)
[17] Chatterjee, R., Fossati, G., Urry, C. M., et al., ApJ **763**, L11 (2013)
[18] Crummy, J., Fabian, A. C., Gallo, L., Ross, R. R., MNRAS **365**, 1067 (2006)
[19] D'Ammando, F., Raiteri, C. M., Villata, M., et al., A&A **529**, 145 (2011)
[20] D'Ammando, F., Orienti, M., Finke, J., et al., MNRAS **426**, 317 (2012)
[21] D'Ammando, F., Orienti, M., Doi, A., et al., MNRAS **433**, 952 (2013)
[22] D'Ammando, F., Tosti, G., Orienti, M., Finke, J., 2012 Fermi Symposium proceedings - eConf C121028 (2013)
[23] D'Ammando, F., Carpenter, B., Ojha, R., The Astronomer's Telegram **5352** (2013)
[24] D'Ammando, F., Larsson, J., Orienti, M., et al., submitted to MNRAS (2013)
[25] D'Ammando, Orienti, M., Finke, J., et al., MNRAS in press [arXiv:1308.3709] (2013)
[26] Decarli, R., Dotti, M., Fontana, M., Haardt, F., MNRAS **386**, L15 (2008)
[27] Deo, R. P., Crenshaw, D. M., Kraemer, S. B., AJ **132**, 321 (2006)
[28] Doi, A., Nagai, H., Asada, K., et al., PASJ **58**, 829 (2006)
[29] Foschini, L., Maraschi, L., Tavecchio, F., et al., Adv. Space Res. **43**, 889 (2009)
[30] Foschini, L., Ghisellini, G., Kovalev, Y. Y., et al., MNRAS **413**, 1671 (2011)
[31] Foschini, L., Angelakis, E., Fuhrmann, L., et al., A&A **548**, A106 (2012)
[32] Gallo, L. C., Edwards, P. G., Ferrero, E., et al., MNRAS **370**, 245 (2006)
[33] Gierliński, M., & Done, C., MNRAS **349**, L7 (2004)
[34] Giroletti, M., Paragi, Z., Bignall, H., et al., A&A **528**, L11 (2011)
[35] Grupe, D., Komossa, S., Leighly, K. M., Page, K. L., ApJS **187**, 64 (2010)
[36] Kataoka, J., Madjeski, G., Sikora, M., et al., ApJ **672**, 787 (2008)
[37] Kellermann, K. I., & Pauliny-Toth, I. I. K., ApJ **155**, L71 (1969)
[38] Komossa, S., Voges, W., Xu, D., et al., AJ **132**, 531 (2006)
[39] Maoz, D., Bahcall, J. N., Doxsey, R., et al., ApJ **402**, 69 (1993)
[40] Marconi, A., Axon, D. J., Maiolino, R., et al., ApJ **678**, 693 (2008)
[41] Marscher, A., in Lecture Notes in Physics 794, ed. T. Belloni (Berlin:Springer), **173** [arXiv:0909.2576] (2009)
[42] Mattox, J. R., Bertsch, D. L., Chiang, J., et al., ApJ **461**, 396 (1996)
[43] Meier, D. L., New Astron. Rev. **47**, 667 (2003)
[44] Nolan, P., Abdo, A. A., Ackermann, M., et al., ApJS **199**, 31 (2012)
[45] Orienti, M., D'Ammando, F., Giroletti, M., 2012 Fermi & Jansky Proceedings - eConf C1111101 (2012)
[46] Orienti, M., D'Ammando, F., Giroletti, M., et al., these proceedings (2013)
[47] Osterbrock, D. E., & Pogge, R. W., ApJ **297**, 166 (1985)
[48] Pogge, R. W. , New Astronomy Reviews **44**, 381 (2000)
[49] Sikora, M., Stawarz, L., Lasota, J.-P., ApJ **658**, 815 (2007)
[50] Sikora, M., AN **330**, 291 (2009)
[51] Yuan, W., Zhou, H.-Y., Komossa, S., et al., ApJ **685**, 801 (2008)
[52] Zhou, H.-Y., Wang, T.-G., Dong, X.-B., Zhou, Y.-Y., Li, C., ApJ **584**, 147 (2003)
[53] Zhou, H.-Y., Wang, T.-G., Yuan, W., et al., ApJS **166**, 128 (2006)
[54] Zhou, H.-Y., Wang, T.-G., Yuan, W., et al., ApJ **658**, L13 (2007)