A panchromatic view of relativistic jets in γ-ray emitting narrow-line Seyfert 1 galaxies

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Before the launch of the Fermi satellite only two classes of Active Galactic Nuclei (AGN) were known to generate relativistic jets and thus to 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 (LAT) on board Fermi confirmed that these two populations represent the most numerous identified sources in the extragalactic γ-ray sky, but the discovery of variable γ-ray emission from 5 radio-loud Narrow-Line Seyfert 1 (NLSy1) galaxies revealed the presence of a possible emerging third class of AGN with relativistic jets. Considering that NLSy1 are thought to be hosted in spiral galaxies, this finding poses intriguing questions about the nature of these sources, the production of relativistic jets, the mechanisms of high-energy emission, and the cosmological evolution of radio-loud AGN.

1. Introduction

Relativistic jets are the most extreme expression of the power that can be generated by a superluminal black hole (SMBH) in the center of an active galactic nucleus (AGN), with a large fraction of the power emitted in γ-rays. Before the launch of the Fermi satellite only two classes of AGN were known to generate these structures and thus to emit up to the γ-ray band: blazars and radio galaxies, both hosted in giant elliptical galaxies [11]. The first 4 years of observation by the Large Area Telescope (LAT) on board Fermi confirmed that the extragalactic γ-ray sky is dominated by radio-loud AGN, being mostly blazars and some radio galaxies [4]. However, the discovery by Fermi-LAT of variable γ-ray emission from a few radio-loud narrow-line Seyfert 1 (NLSy1) galaxies revealed the presence of a possible third class of AGN with relativistic jets [1].

NLSy1 are a class of AGN identified by [43] and characterized by their optical properties: narrow permitted lines (FWHM (Hβ) < 2000 km s⁻¹), [OIII]/Hβ < 3, and a bump due to Fe II (e.g., [44]). They also exhibit strong X-ray variability, steep X-ray spectra, relatively high luminosity, and substantial soft X-ray excess (e.g., [31]). These characteristics point to systems with smaller masses of the central black hole (10⁶–10⁸ M☉) than blazars and radio galaxies, and higher accretion rates (close to or above the Eddington limit). NLSy1 are generally radio-quiet (radio-loudness R < 10), with only a small fraction (< 7%; [34]) classified as radio-loud. Objects with high values of radio-loudness (R > 100) are even more sparse (∼2.5%), while generally ∼15% of quasars are radio-loud. Considering also that NLSy1 are thought to be hosted in spiral galaxies, their detection in γ-rays poses intriguing questions about the nature of these sources, the production of relativistic jets, the mechanisms of high-energy emission, and the cosmological evolution of radio-loud AGN.

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 2004–47 [1, 4, 16], with a redshift between 0.061 and 0.585. The average apparent...
isotropic luminosity of these sources in the 0.1–100 GeV energy band is between $10^{44}$ erg s$^{-1}$ and $10^{47}$ erg s$^{-1}$, a range of values typical of blazars [18]. This may be an indication of a small viewing angle with respect to the jet axis and thus a high beaming factor for the $\gamma$-ray emission, similarly to blazars. Several strong $\gamma$-ray flares were observed from SBS 0846+513 (Fig. 1) and PMN J0948+0022, reaching a peak apparent isotropic $\gamma$-ray luminosity of $\sim10^{48}$ erg s$^{-1}$, comparable to that of the bright FSRQ [21, 23, 27]. In particular, SBS 0846+513 and PMN J0948+0022 showed a $\gamma$-ray flaring activity combined with a moderate spectral evolution [16, 27], a behaviour that was already observed in bright flat spectrum radio quasars (FSRQ) and low-synchrotron-peaked BL Lacs [2]. Variability and spectral properties of these two NLSy1s in $\gamma$-rays indicate a blazar-like behaviour. An intense $\gamma$-ray flaring activity was observed by LAT also from 1H 0323+342 [13]. This is another indication that radio-loud NLSy1 are able to host relativistic jets as powerful as those in blazars.

3. X-ray properties

The X-ray spectra of NLSy1 are usually characterized by a steep photon index ($\Gamma_X > 2$, [31]). On the contrary, a relatively hard X-ray spectrum was detected in the Swift/XRT observations of SBS 0846+513 [16, 20], PMN J0948+0022 [22, 23, 27, 28], 1H 0323+342 [19], and PKS 1502+036 [17]. This suggests a significant contribution of inverse Compton radiation from a relativistic jet, similar to what is found for FSRQ.

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 [22]. The spectral modelling of the XMM-Newton data of PMN J0948+0022 shows that emission from the jet most likely dominates the spectrum above $\sim2$ keV, while a soft X-ray excess is evident below $\sim2$ keV (Fig. 2). The origin of the soft X-ray excess is still an open issue both in radio-quiet and radio-loud AGN (e.g., [29]). Such a Seyfert component is a typical feature in the X-ray spectra of radio-quiet NLSy1, but it is quite unusual in jet-dominated AGN, even if not unique (e.g., PKS 1510-089; [33]). In the case of PMN J0948+0022, the statistics did not allow us to distinguish between different models for the soft X-ray emission. 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 the temperature is too high ($kT = 0.18$ keV) and is incompatible with a standard Shakura & Sunyaev accretion disc [22].

4. Radio properties

On pc scale a core-jet structure was observed for SBS 0846+513 [16] (Fig. 3), PKS 2004−447 [41], PKS 1502+036 [17], and PMN J0948+0022 [22, 23, 27], although the jet in the two latter sources is significantly fainter than that observed in the former two sources.

![Figure 3: 15.3 GHz VLBA image of SBS 0846+513. On the image we provide the peak flux density, in mJy/beam, and the first contour intensity (f.c., in mJy/beam) that corresponds to three times the noise measured on the image plane. Contour levels increase by a factor of 2. The beam is plotted on the bottom left corner of the image. Component W1 is the core region, W2 is a knot, and E is the jet structure. Adapted from [20].](image-url)
The analysis of the 6-epoch data set of SBS 0846+513 collected by the MOJAVE programme during 2011-2013 indicates that a superluminal jet component is moving away from the core with an apparent angular velocity of $(0.27 \pm 0.02) \text{ mas yr}^{-1}$ (Fig. 4), corresponding to $(9.3 \pm 0.6) \text{c}$ [20]. This apparent superluminal velocity indicates 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 [17].

Strong radio variability was observed at 15 GHz during the monitoring of the OVRO 40-m telescope of PMN J0948+0022 [22, 23], PKS 1502+036 [17], and SBS 0846+513 [10, 20]. An inferred variability brightness temperature of $2.5 \times 10^{13}$ K, $1.1 \times 10^{14}$ K, and $3.4 \times 10^{14}$ K was obtained for PKS 1502+036, SBS 0846+513, and PMN J0948+0022, respectively. These values are larger than the brightness temperature derived for the Compton catastrophe [15], suggesting that the radio emission of the jet is Doppler boosted. On the other hand, a high apparent brightness temperature of $10^{13}$ K, comparable to that of the $\gamma$-ray NLSy1, was observed for TXS 1546+353. However, no $\gamma$-ray emission has been detected from this source, so far [22]. Moreover, an intensive monitoring of these $\gamma$-ray NLSy1 from 2.6 GHz to 142 GHz with the Effelsberg 100-m and IRAM 30-m telescopes showed, in addition to an intensive variability, spectral evolution across the different bands following evolutionary paths explained by travelling shocks, typical characteristics seen in blazars [8].

5. Multifrequency variability and SED modelling

The first spectral energy distributions (SED) collected for the four 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 additional component related to the accretion disc in UV for three of the four sources. The physical parameters of these NLSy1 are blazar-like, and the jet power is in the average range of blazars [1].

For PMN J0948+0022 we compared the broadband SED of the 2013 flaring activity state with that from an intermediate activity state observed in 2011 (Fig. 5). Contrary to what was observed for some FSRQ (e.g., PKS 0537–441; [21]), the SED of the two activity states, modelled as synchrotron emission and as an external Compton scattering of seed photons from a dust torus, could not be modelled by changing only the electron distribution parameters. A higher magnetic field is needed for the high activity
Optical intraday variability has been reported for PMN J0948+0022 by \[32\], sometimes associated with a significant increase of the optical polarisation percentage, indicating a relativistic jet as the most likely origin for the optical emission in this object.

At Very High Energy (VHE; \(E > 100\) GeV), VERITAS observations of PMN J0948+0022 were carried out during 2013 January 6–13, after the \(\gamma\)-ray flare observed by Fermi-LAT on 2013 January 1. These observations resulted in an upper limit of \(F_{\gamma} < 4 \times 10^{-12}\) ph cm\(^{-2}\) s\(^{-1}\) [23]. The lack of detection at VHE could be due to different reasons: 1) The distance of the source \((z = 0.5846)\) is relatively large and most of the GeV/TeV emission may be absorbed due to pair production from \(\gamma\)-ray photons of the source and the infrared photons from the extragalactic background light (EBL). However, we must note that the most distant FSRQ detected at VHE up to now, 3C 279 [5] is at a comparable distance. 2) The VERITAS observations were carried out a few days after the peak of the \(\gamma\)-ray activity, thus covering only the last part of the MeV/GeV flare. 3) Considering the similarities with FSRQ, a BLR should be present in these NLSy1. The presence of a BLR could produce a spectral break due to pair production, suppressing the flux beyond a few GeV and preventing a VHE detection. However, the detection at VHE of the FSRQ 3C 279, PKS 1510–089 [2, 7], and 4C +21.35 [6] have shown that the spectrum of some FSRQ extends to VHE energies during some flares, indicating that the \(\gamma\)-rays may be produced outside the BLR during those high-activity periods. The same scenario may apply to the \(\gamma\)-ray emitting NLSy1.

6. Radio-loudness, host galaxy, and jet formation

The mechanism at work for producing a relativistic jet is not clear. In particular, the physical parameters that drive the jet formation is still under debate. By considering that NLSy1 are thought to be hosted in spiral galaxies (e.g., \[25\]) the presence of a relativistic jet in these sources seems to be in contrast to the paradigm that such structures could be produced only in elliptical galaxies (e.g., \[37\]). The most powerful jets are found in luminous elliptical galaxies with very massive central BH and low accretion rates (e.g., \[33, 46\]). This was interpreted as an indirect evidence that a high spin is required for the jet production, since at least one major merger seems to be necessary to spin up the SMBH. At the same time, low accretion rates, which are associated with geometrically thick advection dominated accretion flows, may be important in jet formation by creating large-scale poloidal magnetic fields \[45\].
Therefore one of the most surprising facts related to the discovery of NLSy1 in γ-rays is the development of a relativistic jet in objects with a relatively small BH mass of $10^7$–$10^8$ $M_\odot$. However, it is worth noting that the mass estimation of the BH in these sources may have large uncertainties due to the effect of radiation pressure and the possible disc-like structure of their BLR modelling the optical/UV data of some radio-loud NLSy1 with a Shakura & Sunyaev disc spectrum have estimated higher BH masses than those reported in the past, for PMN J0948+0022 and PKS 1502+036 comparable to the values estimated for 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. How is it possible to have such a large BH mass in a class of AGN usually hosted in spiral galaxies? Only very sparse observations of the host galaxy of radio-loud NLSy1 are available up to now. Among the NLSy1 detected by LAT only for the closest one, 1H 0323+342, the host galaxy was clearly detected, suggesting two possible scenarios: the spiral arms of the host galaxy or the residual of a galaxy merger. Therefore the possibility that the production of relativistic jets in these objects could be due to strong merger activity, unusual in disc/spiral galaxies, cannot be ruled out.

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 form only in elliptical galaxies. We noted that the BH masses of radio-loud NLSy1 are generally larger than those in the whole sample of NLSy1 ($M_{BH} \approx (2–10) \times 10^7 M_\odot$), even if still small if compared to radio-loud quasars. The larger BH masses of radio-loud NLSy1 with respect to radio-quiet NLSy1 may be related to prolonged accretion episodes that can spin-up the BHs. In this context, the small fraction of radio-loud NLSy1 with respect to radio-loud quasars could be an indication that not in all the former the high-accretion regime lasted long enough to spin-up the central BH.

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