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

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Before the launch of the *Fermi* satellite only two classes of 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 are the most numerous classes of identified sources in the extragalactic gamma-ray sky, but the discovery of variable gamma-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 that NLSy1s are thought to be hosted in spiral galaxies, this finding poses intriguing questions about the nature of these objects, the knowledge of the development of relativistic jets, and the evolution of radio-loud AGN. In this context the study of the radio-loud NLSy1s from radio to γ-rays has received increasing attention. 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.

The gamma-ray view of NLSy1s

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 (Abdo et al. 2009, ApJ, 707, L142; D'Ammando et al. 2012, MNRAS, 426, 317), with a redshift between 0.061 and 0.585. The average apparent isotropic luminosity of these sources 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 (D'Ammando et al. 2012; Foschini et al. 2011, MNRAS, 413, 1671).

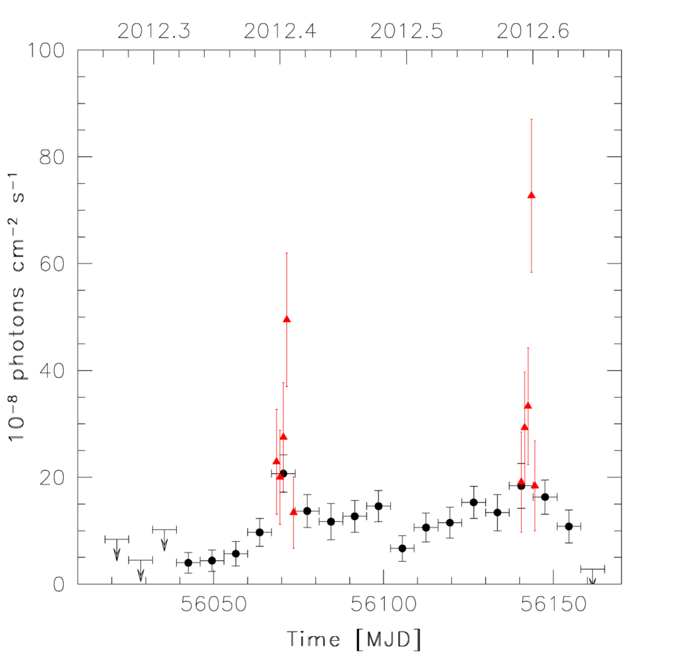

Fig. 1: *Fermi*-LAT flux (E > 100 MeV) light curve of SBS 0846+513 obtained during 2012 April 1-August 28 with 7-day or 1-day time bins. Arrows refer to 2-σ upper limits on the source flux. Upper limits are computed when TS<10 [D'Ammando et al. 2013a].

Several strong γ-ray flares were observed from SBS 0846+513 and PMN J0948+0022, reaching at the peak an apparent γ-ray luminosity of ~10^{48} erg s^{-1}, comparable to that of bright FSRQs (D'Ammando et al. 2012, Foschini et al. 2011, D'Ammando et al. 2013a, MNRAS, 436, 191). 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 (Carpenter & Ojha 2013, ATel 5344). This is another indication that radio-loud NLSy1 are able to host relativistic jets as powerful as those in blazars.

X-ray properties

The X-ray spectra of NLSy1 are usually characterized by a steep photon index (Γ_X > 2, Grupe et al. 2010, ApJS, 187, 64). On the contrary, a relatively hard X-ray spectrum was detected in the *Swift*/XRT observations of SBS 0846+513 (D'Ammando et al. 2012, 2013a), PMN J0948+0022 (Foschini et al. 2011, D'Ammando et al. 2014a), 1H 0323+342 (D'Ammando et al. 2013c, ATel 5352), and PKS 1502+036 (D'Ammando et al. 2013b). This suggests a significant contribution of inverse Compton radiation from a relativistic jet, similar to what is found for FSRQs.

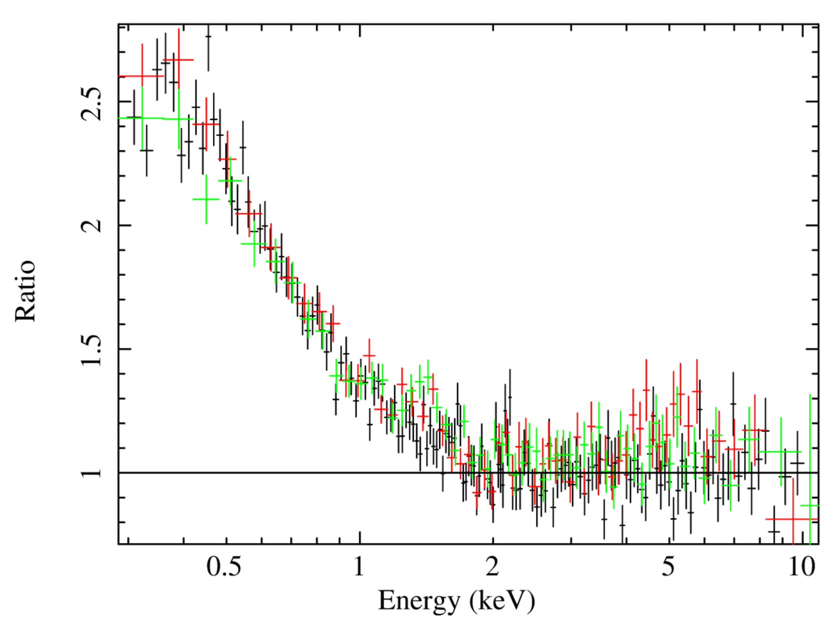

Fig. 2: XMM–Newton EPIC pn (black), MOS1 (red) and MOS2 (green) data shown as a ratio to a power law with Γ = 1.48 [D'Ammando et al. 2014a].

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 D'Ammando et al. (2014a). 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 (e.g. Gierlinksi & Done 2004, MNRAS, 349, L7). 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. PKS 1510-089, Kataoka et al. 2008, ApJ 672, 787). 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 (D'Ammando et al. 2014a).

Radio properties

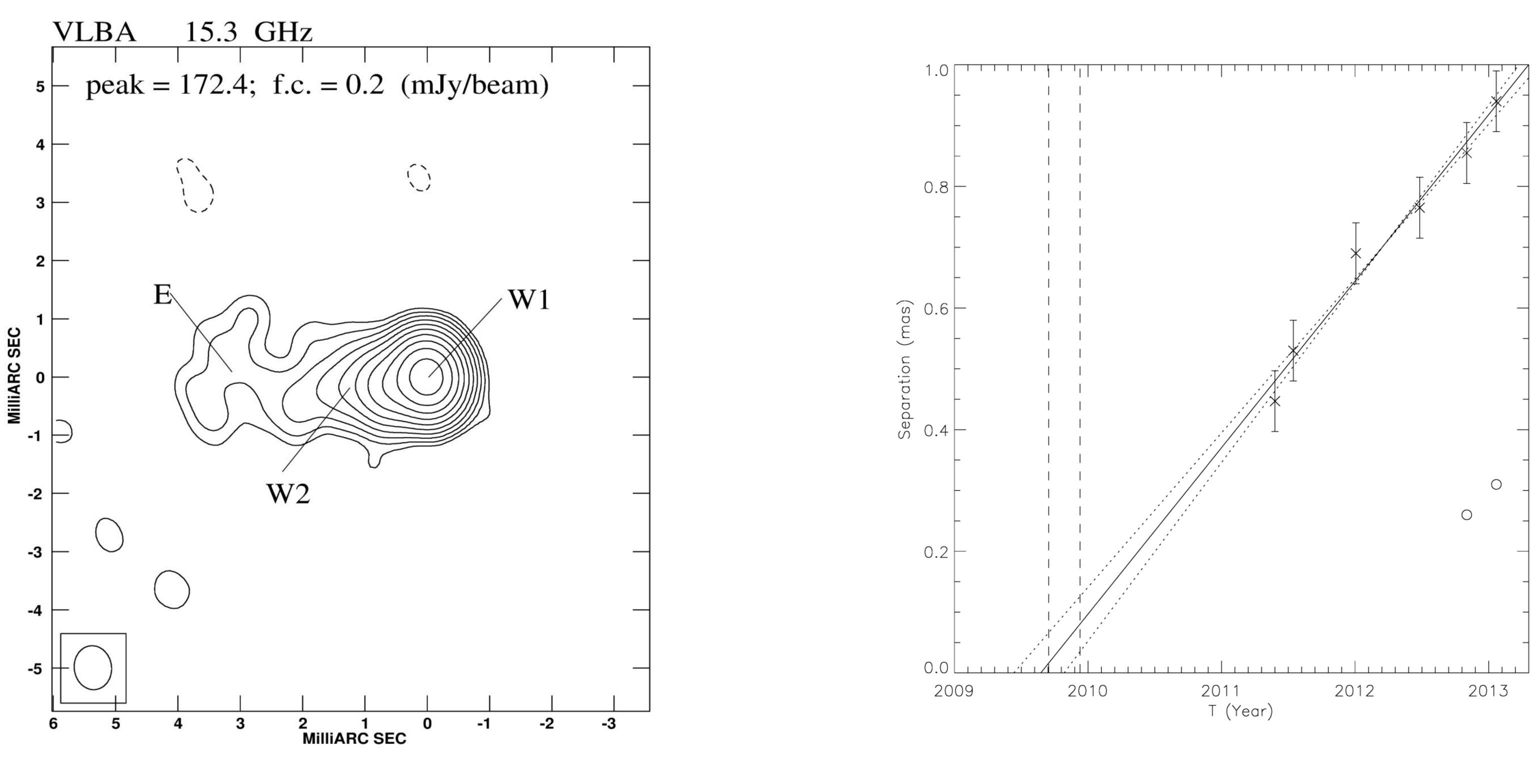

Fig. 3, *left*: 15.4 GHz VLBA image of SBS 0846+513. On the image we provide the peak flux density, in mJy/beam, and the first contour intensity (f.c., in mJy/beam) that corresponds to three times the noise measured on the image plane. Contour levels increase by a factor of 2. The beam is plotted on the bottom left corner of the image. Component W1 is the core region, W2 is a knot, and E is the jet structure [D'Ammando et al. 2012]. *Right*: the separation between the core component of SBS 0846+513 and the knot ejected in 2009 as a function of time. The solid line represents the regression fit to the 15 GHz VLBA MOJAVE data, while the dotted lines represent the uncertainties from the fit parameters [D'Ammando et al. 2013a].

A core-jet structure on pc scale was observed for SBS 0846+513 (D'Ammando et al. 2012), PKS 1502+036 (D'Ammando et al. 2013b, MNRAS, 433, 952) and PMN J0948+0022 (Giroletti et al. 2011, A&A, 528, L11; D'Ammando et al. 2013a), although the jet structure in the last two sources is significantly fainter than that observed in SBS 0846+513. 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±0.02) mas yr^{-1}, corresponding to (9.3±0.6)c (D'Ammando et al. 2013a). 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 (D'Ammando et al. 2013b). In addition, strong variability was observed at 15 GHz during the monitoring of the OVRO 40-m telescope of PMN J0948+0022 (D'Ammando et al. 2014, MNRAS, 438, 3521), PKS 1502+036 (D'Ammando et al. 2013b), and SBS 0846+513 (D'Ammando et al. 2013a). An inferred variability brightness temperature of 2.5x10^{13} K and 1.1x10^{14} K was obtained for PKS 1502+036 and SBS 0846+513, respectively. These values are much larger than the brightness temperature derived for the Compton catastrophe, 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 γ-ray NLSy1s, 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 so far (Orienti, D'Ammando, et al. in preparation).

Multifrequency variability and SED modelling

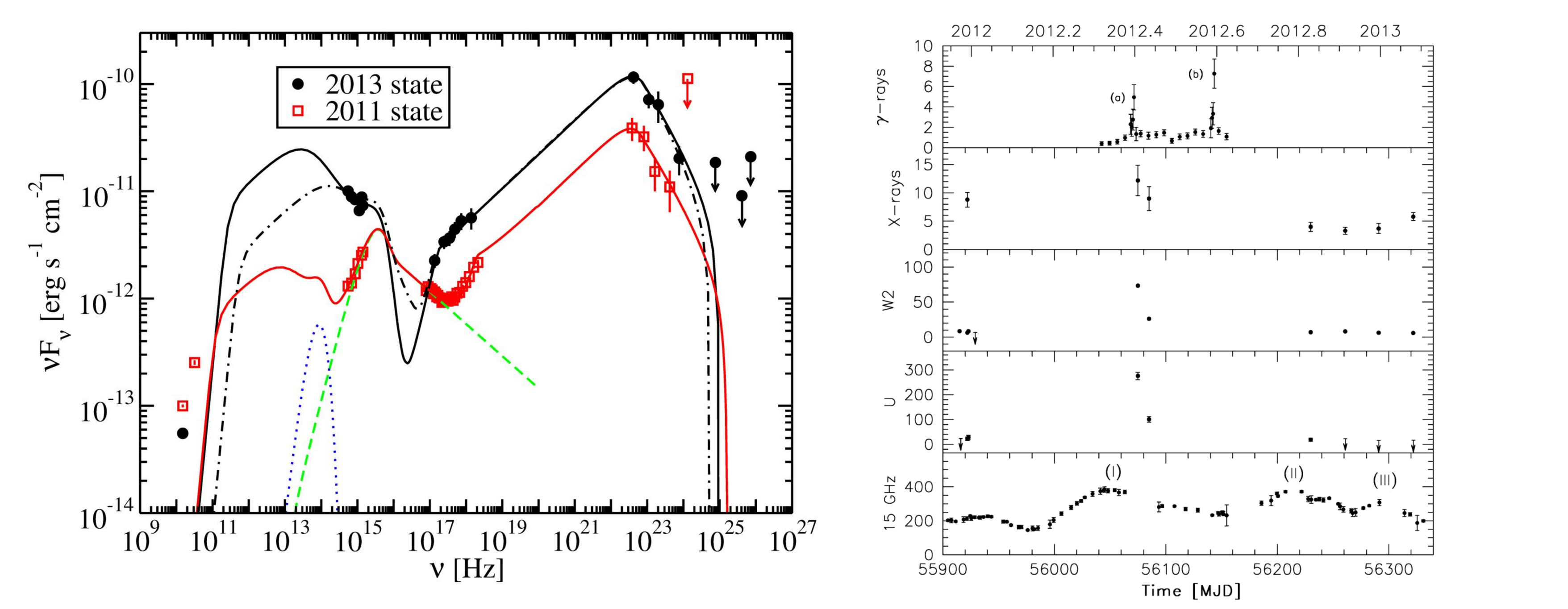

Fig. 4, *left*: SED and model fit for the 2013 and 2011 activity states of PMN J0948+0022. The filled circles are the data from the 2013 flaring state, and the open squares are the data from the 2011 intermediate state taken from D'Ammando et al. (2014a). The dashed curve indicates the disc and coronal emission, and the dotted line indicates the thermal dust emission. Solid lines represent models consistent with scattering dust torus radiation, while the dashed-dotted curve represents a model consistent with the scattering of BLR radiation. Arrows refer to 2σ upper limits on the source flux. The VERITAS upper limits are corrected for EBL absorption using the model of Finke et al. (2010, ApJ, 712, 238) [D'Ammando et al. 2014b, MNRAS, in press, arXiv:1410.7144]. *Right*: Multifrequency light curve for SBS 0846+513 during 2011 December–2013 January. The data sets were collected (from top to bottom) by *Fermi*-LAT (γ-rays, 0.1-100 GeV; in units of 10^{-7} ph cm^{-2} s^{-1}), *Swift*-XRT (0.3-10 keV; in units of 10^{-13} erg cm^{-2} s^{-1}), *Swift*-UVOT (*w2* and *u* bands; in units of μJy) and OVRO (15 GHz; in units of mJy). Arrows refer to 3σ upper limits on the source flux densities for the *w2* and *u* bands, and to 2σ upper limits on the source fluxes for the γ-ray light curve [D'Ammando et al. 2013b].

We compared the broad-band SED of the 2013 flaring activity state with that from an intermediate activity state of PMN J0948+0022 observed in 2011. Contrary to what was observed for some FSRQs (e.g., PKS 0537-441; D'Ammando et al. 2013d, MNRAS, 431, 2481) the two SEDs, modelled as an external Compton component 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 modelling the high activity state of PMN J0948+0022. We also modeled the 2013 flaring state with parameters consistent with Compton-scattering of BLR line radiation. The model reproduces the data approximately equally as well as the dust scattering model. However, we note the BLR scattering model is farther from equipartition.

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 (D'Ammando et al. 2013a), consistent with the modeling of different activity states of PKS 0208-512 (Chatterjee et al. 2013, ApJ, L11). 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;D'Ammando et al. 2011, A&A, 529, 145). 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.

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 D'Ammando et al. (2013a), Orienti et al. (2013, EPJWC, 6104009), and D'Ammando et al. (2014a), Foschini et al. (2012, A&A, 548, A106).

The mechanism at work for producing a relativistic jet is not 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 (e.g., Sikora et al. 2007, ApJ, 658, 815). Therefore one of the most surprising fact related to the discovery of NLSy1s in γ-rays was the development of a relativistic jet in objects with a relatively small BH mass of 10^7-10^8 solar masses. However, it is worth noting that the mass estimation of these sources has large uncertainties (e.g., Marconi et al. 2008, ApJ, 678, 693; Decarli et al. 2008, MNRAS, 386, L15). Recently, Calderone et al. (2013, MNRAS, 431, 210) modelling the optical/UV data of some radio-loud NLSy1s with a Shakura & Sunyaev disc spectrum have estimated higher BH masses. In particular, they found a BH mass of 10^9 and 2x10^8 solar masses 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. How is it possible to have such a large BH mass in a class of AGNs usually hosted in spiral galaxies? Only very sparse observations of the host galaxy of radio-loud NLSy1s are available up to now. Among the NLSy1s 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 (Zhou et al. 2007, ApJ, 658, L13) or the residual of a galaxy merging (Anton et al. 2008, A&A, 490, 583; Leon-Tavares et al. 2014, ApJ, 795, L58). 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.