Perseus in Sicily: From Black Hole to Cluster Outskirts
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Extragalactic relativistic jets

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Abstract. Relativistic jets are one of the most powerful manifestations of the release of energy produced around supermassive black holes at the centre of active galactic nuclei (AGN). Their emission is observed across the entire electromagnetic spectrum, from the radio band to gamma rays. Despite decades of efforts, many aspects of the physics of relativistic jets remain elusive. In particular, the location and the mechanisms responsible for the high-energy emission and the connection of the variability at different wavelengths are among the greatest challenges in the study of AGN. Recent high resolution radio observations of flaring objects locate the high energy emitting region downstream the jet at parsec scale distance from the central engine. Furthermore, monitoring campaigns of the most active blazars indicate that not all the high energy flares have the same characteristics in the various energy bands, even from the same source, making the interpretation of the mechanism responsible for the high-energy emission not trivial. Here I will discuss gamma-ray properties of blazars obtained by *Fermi* Large Area Telescope observations and the connection between radio and high-energy emission in relativistic jets, and I will focus on the importance of high angular resolution observations.

Keywords. radiation mechanisms: nonthermal, galaxies: active, galaxies: jets, gamma rays: observations

1. Introduction

Relativistic jets are one of the most powerful manifestation of the energy released by a super massive black hole at the centre of an active galactic nucleus (AGN). Only 10 per cent of AGN have powerful emission in the radio band connected with the presence of relativistic jets. These objects, termed jetted-AGN by Padovani (2016), are characterized by a bipolar outflow of relativistic particles that are produced in the central region of the AGN and may extend up to a few Mpc, well beyond the host galaxy.

The emission of relativistic jets is produced by non-thermal radiation processes and is observable throughout the electromagnetic spectrum, from radio wavelengths to gamma-ray energies. Their broad-band spectral energy distribution (SED) is characterized by two peaks: one peaking between infrared (IR) and soft X-rays, and the other at high energies (Fossati *et al.* 1998; Donato *et al.* 2001). The first hump is produced by synchrotron radiation from relativistic electrons in the jet magnetic field, while the second hump is likely due to inverse Compton (IC) scattering off photons of the radiation field by the same relativistic electron population responsible for synchrotron emission, indicating a possible correlation between the low-energy and high-energy emission. The origin of the seed photons for the IC scattering is still an open issue. A possibility is that seed photons are those produced by synchrotron by the same population of relativistic electrons. In this case the radiation mechanism is termed Synchrotron-self Compton (SSC). On the other hand, the process is termed external Compton if the seed photons are from an external radiation field, like the ultraviolet radiation from the accretion disk and/or broad line region, the IR emission from the dusty torus, cosmic microwave background (CMB) radiation, or synchrotron photons produced by a different population of relativistic electrons (see e.g. Joshi *et al.* 2014).

When the jet is observed at small angles to the line of sight its luminosity is boosted by projection and beaming effects, giving rise to the 'blazar phenomenon'. As a consequence of their small viewing angle, blazars look brighter than what they are, facilitating their detection. Depending on the optical spectrum, blazars are divided into two classes: flat spectrum radio quasars (FSRQ) and BL Lac objects. FSRQ have broad emission lines in their optical spectra, while the continuum spectra in BL Lacs is almost featureless. This is supposed to be directly connected to the efficiency of the accretion onto the super massive black hole, with the accretion being highly efficient in FSRQ which are characterized by high luminosity, while the accretion should be inefficient in BL Lacs, which also have low luminosity (Ghisellini *et al.* 2011). In the unified model, radio galaxies are the parent population of blazars at large viewing angles, being Fanaroff-Riley Type-I and Type-II radio sources the debeamed counterparts of BL Lacs and FSRQ, respectively (Urry & Padovani (1995); see also Torresi 2018, these Proceedings).

Since the EGRET era, jetted-AGN have dominated the extragalactic population of objects detected in gamma rays (Hartman *et al.* 1999). The advent of the Large Area Telescope (LAT) on board the *Fermi* satellite has dramatically increased the number of gamma-ray sources. *Fermi*-LAT is a pair-conversion telescope with a large field of view of ∼2.4 sr sensitive to energies from 20 MeV to energies above 300 GeV (Atwood *et al.* 2009). It operates in survey mode and completes an all-sky map every three hours. Giving its huge improvement in sensitivity and angular resolution, *Fermi*-LAT detected about 200 gamma-ray sources in only three months (Abdo *et al.* 2009a) and more than half of them are unambiguously associated with jetted-AGN (Abdo *et al.* 2009b). These numbers increased in the next release of *Fermi*-LAT catalogues which considered 11-month (First LAT AGN catalogue (1LAC), Abdo *et al.* 2010a) and 2-yr of *Fermi* observations (2LAC, Ackermann *et al.* 2011a), up to reaching 1591 extragalactic sources reported in the 3LAC (Ackermann *et al.* 2015) out of 3033 gamma ray sources detected in 4 years of sky surveying (Acero *et al.* 2015). It is worth noticing that during the EGRET era and the first period of *Fermi*-LAT observations, FSRQ was the dominant population, while BL Lacs started to dominate in the 2LAC, and this is likely a consequence of the improving sensitivity with observing time. Remarkably, the number of misaligned jetted-AGN (i.e. those radio sources whose jet forms a large angle to our line of sight, and therefore not subject to significant boosting effects) has increased, going from the detection of only Centaurus A by EGRET, up to about 30 objects listed in the 3LAC.

2. Radio and gamma-ray connection

As mentioned earlier, the same population of relativistic particles is responsible for both synchrotron emission at low energies and inverse Compton scattering at high energy. Therefore, radio and gamma-ray emission is expected to be connected. Several works have been undertaken with the aim of establishing a radio/gamma-rays correlation. Making use of the sources detected by *Fermi*-LAT during the first three months of operation, Abdo *et al.* (2009b) found a tentative correlation. Significant correlation was found between gamma-ray flux and radio flux density for the blazars in the 1LAC with a radio counterpart (e.g. Ghirlanda *et al.* 2010, Ackermann *et al.* 2011b). A similar correlation is also found for blazars in the 3LAC (Ackermann *et al.* 2015). Interestingly, the correlation holds also if FSRQ and BL Lacs are considered separately at least when gamma-ray flux between 0.3 and 300 GeV are considered. In fact, a dependence of the correlation strength on the considered gamma-ray energy band is also present and only BL Lacs with a synchrotron peak occurring in the soft X-rays seem to preserve a radio and gamma-ray correlation when energies above 10 GeV is considered (see e.g. Lico *et al.* 2017).

Mahony *et al.* (2010) pointed out that radio/gamma-ray correlation gets slightly stronger when non-variable sources are considered.

2.1. *Variability*

Variability is a key feature of blazars. Among the flaring gamma-ray sources detected by *Fermi*-LAT in 7.4 years of observations with a clear identification, the majority are blazars (Abdollahi *et al.* 2017). In particular, 69% of FSRQ is variable, while the percentage for BL Lacs is much lower on average (23%) and decreases with the increase of synchrotron peak frequency (Ackermann *et al.* 2015).

Changes in the luminosity are observed at all wavelengths and related to periods of different activity: quiescent states are interleaved with periods of enhanced activity. Sometimes abrupt outbursts occur and may be observed across the electromagnetic spectrum, or in a single band ('orphan' flares).

Variability timescale and the time-delay observed at different wavelength provide clues on the emitting region (size, location, seed photons) and the physics involved. A cross-correlation study between gamma-ray and radio light curves obtained at different frequencies of a sample of *Fermi*-LAT 54 blazars points out a time lag between the variability episodes in there two bands, with the gamma rays leading the radio variability. Furthermore, the time lag decreases with wavelengths, from 76±23 days at 11 cm to a few days or less at 3 mm (Fuhrmann *et al.* 2014). Similar results are found by dedicated multi-wavelength studies of individual blazars (e.g. Hughes *et al.* 2011, Orienti *et al.* 2013). These time lags are reflected into a spatial separation between the emitting regions, being the gamma-ray and the 3-mm emission almost co-spatial, whereas the emission at 11 cm arises a few parsecs downstream along the jet. The increase of the time lag with wavelength is consistent with the shock-in-jet model, in which compact regions at the base of the jet are self-absorbed in radio band, and their emission becomes optically thin at longer and longer wavelengths as the regions expand and move downstream the jet (e.g. Marscher & Gear 1985).

A different result was reported by León-Tavares *et al.* (2011) who found that for FSRQ the onset of the flare at 1 cm leads the peak of the gamma-ray flare, suggesting that the gamma-ray emitting region is located at several pc downstream the jet. On the other hand, no obvious radio/gamma-ray correlation is found for BL Lacs.

2.2. *VLBI observations of relativistic jets*

The studies mentioned earlier are based on single-dish observations where it is not possible to disentangle the contribution from different regions of the radio source, and changes in the pc-scale structure may be washed out by the contribution of stationary components. To circumvent this issue, high angular resolution observations are crucial. With (sub-)milliarcsecond resolution Very Long Baseline Interferometry (VLBI) observations provide insights into the innermost regions of relativistic jets and are fundamental for locating the site in which flares are produced.

VLBI monitoring campaigns of bright blazars during the EGRET era pointed out a connection between gamma-ray flares and the ejection of superluminal jet components (Jorstad *et al.* 2001). In the context of the shock-in-jet model, the superluminal components are the observable manifestation of shocks that are moving downstream along the jet. Given its all-sky scanning mode, *Fermi*-LAT has proved to be optimal in detecting flares from blazars. As a consequence, VLBI monitoring campaigns of selected objects, like the MOJAVE programme (Lister *et al.* 2018) and the VLBA-BU-BLAZAR Program (Jorstad *et al.* 2017), as well as triggered follow-up VLBI campaigns of individual objects caught by *Fermi*-LAT during a flare (e.g. 3C 454.3, Jorstad *et al.* 2013; PKS 1510-089,

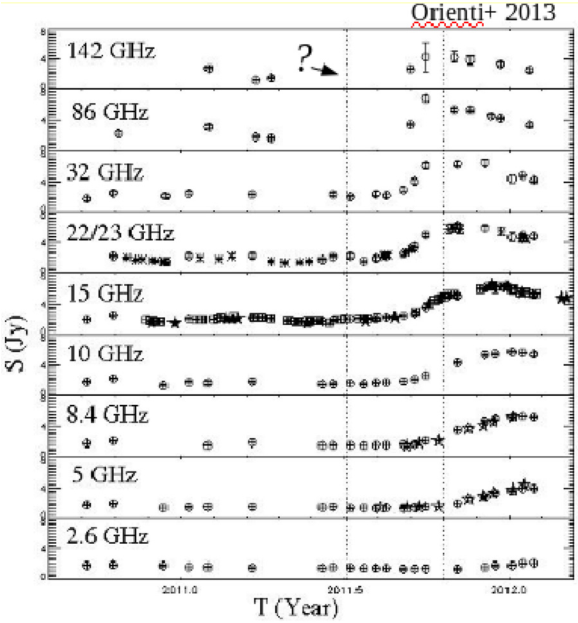

Figure 1. Multi-frequency light curves of PKS 1510−089. Dashed lines represent the epoch of gamma-ray flares. Adapted from Orienti *et al.* (2013).

Orienti *et al.* 2013, TXS 0536+145, Orienti *et al.* 2014; JVAS B0218+357, Spingola *et al.* 2016; BL Lacertae, Wehrle *et al.* 2016; 3C 273, Lisakov *et al.* 2017) have been undertaken. Remarkably, gamma-ray flares do show different multi-band properties even if they are from the same source (Fig. 1). For example, not all the gamma-ray flares are associated with a radio outburst and the ejection of a superluminal component, like in the case of BL Lacertae (Marscher *et al.* 2008), 3C 454.3 (Jorstad *et al.* 2013) and PKS 1510+089 (Orienti *et al.* 2013). In the case of the Narrow Line Seyfert 1 SBS 0846+513 there seems to be an anti-correlation between the radio and gamma-ray outbursts (D'Ammando *et al.* 2012). All these pieces of evidence suggests that the location of the gamma-ray emitting region may vary even within the same source. An outstanding example is the jet of the radio galaxy M87 where gamma-ray photons up to TeV energy may originate in the core (Hada *et al.* 2014), as well as in a jet region, HST-1, about 120 pc from the central engine (Cheung *et al.* 2007).

3. The gamma-ray emitting region

Locating the region where gamma-ray flares are produced is not trivial. As mentioned earlier, the time lag observed between radio and gamma rays can help us locate the site of the gamma-ray emitting region and determine the seed photons involved in the scatter process.

In the shock-in-jet model a perturbation is likely produced in the jet triggering an outburst. If the shock happens close to the central engine, well within the broad line region, the emission is still opaque at radio wavelengths. Therefore we expect to observe either a significant time lag between gamma rays and radio even at mm wavelengths, or no radio outburst at all (e.g. BL Lacertae Marscher *et al.* 2008; 3C 279 Abdo *et al.* 2010). On the contrary a close connection between gamma-rays and optical emission is observed, with the optical polarization angle experiencing significant rotation close in time with the gamma-ray outburst, that may be explained in terms of a shock that is moving in a helical jet (e.g. Marscher *et al.* 2010). In this case the seed photons should be the UV from BLR. However, it is worth mentioning that in a recent work Costamante *et al.* (2018) questioned the BLR as the site of gamma-ray emission because no sign of γ-γ absorption is found in the gamma-ray spectra of a sample of 100 objects from the 3LAC. However, in their work Costamante *et al.* (2018) consider an average activity state of the sources, and a different location of gamma-ray emission during outbursts cannot be excluded.

If no significant delay is observed between the outburst in gamma rays and in radio, at least in the mm regime, the emitting site should be at a distance in which the emission is already optically thin to short radio wavelengths. In this case the gamma-ray emitting region is at pc distance from the central engine and seed photons may be IR from the dusty torus (e.g. Sikora *et al.* 2008), or synchrotron photons produced by either the same population of relativistic electrons (SSC) or a different population of relativistic electrons (e.g. Marscher *et al.* 2010). A location about a few pc downstream the jet may be difficult to reconcile with the short (sub-daily) variability timescales observed in flaring blazars. However, the size of emitting region may be smaller than the jet cross section (e.g. Lister *et al.* 2013), and the outburst may be caused by turbulent relativistic flow crossing a standing conical shock (Marscher 2014), or alternatively by turbulent fast magnetic reconnection process (de Gouveia Dal Pino *et al.* 2018 these Procs. and references therein).

The shock-in-jet model is one of the leptonic models that have been proposed to explain high energy emission from relativistic jets. Other models assume that the jet has a velocity structure either transverse (e.g. Ghisellini *et al.* 2005) or radial (e.g. Georganopoulos & Kazanas 2003), and the synchrotron photons of the fast moving component are up-scattered by the electrons in the slower one.

In the spine-sheath scenario a fast spine is surrounded by a slower layer. The gamma-ray emission is produced by SSC and EC and no trivial correlation between gamma rays and radio variability is expected (Tavecchio & Ghisellini 2008). Jets with a limb-brightened structure, like that expected in spine-sheath model, have been observed in several BL Lacs and radio galaxies, supporting the structured jet scenario (e.g. Mrk 501, Giroletti *et al.* 2008; Mrk 421, Lico *et al.* 2014; M87, Hada *et al.* 2013). An outstanding example of limb-brightened jet structure is 3C 84.

4. The case of 3C 84

The radio source 3C 84 is an FR-I radio galaxy and is hosted by the early-type cD galaxy NGC 1275 in the Perseus cluster. Since 1965 the source had been monitored by the University of Michigan Blazar monitoring group and the long-term light curves point out different periods of activity with a major outburst at the beginning of the '80s, followed by a decrease of activity until about 2006 when the radio flux started to increase again (Aller *et al.* 2017). The recurrent radio activity pointed out by the long-term light curves seem connected with changes in the radio structure with the emergence of new components close in time with the beginning of high activity periods (e.g. Asada *et al.* 2006, and Nagai *et al.* 2010).

There seems to be a connection between high activity states observed in radio with those in X-rays and gamma rays (Dutson *et al.* 2014, Fabian *et al.* 2015). Remarkably, in the '90s the source was not detected by EGRET. However, *Fermi*-LAT could detected the source in 4 months of observations, with a flux that was significantly higher than the upper limit set by EGRET (Abdo *et al.* 2009c). VLBI observations of the central pc-scale jet indicate that during the EGRET era, before the emission of the new jet component, the jet had a ridge-brightened structure (Fig. 2), whereas in the *Fermi*-LAT era it shows a clear limb-brightened structure with a wide opening angle (Nagai *et al.* 2014, Giovannini *et al.* 2018).

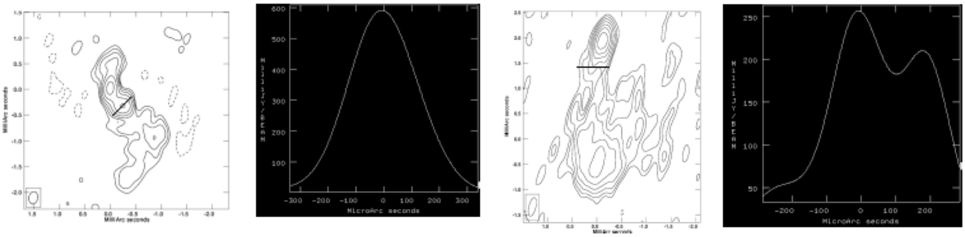

Figure 2. VLBI images at 43 GHz and transverse jet profile of 3C 84 obtained in 1995 (*left*) and in 2013 *right*. The solid line indicates the slice used to derive the jet profile.

Several works on radio, X-rays and gamma-ray variability suggests that short-term and long-term variability may be produced in different regions of the source. In particular, short-term variability seems related to injection of fresh particles accelerated in a shock in the core region, whereas long-term variability is more likely connected with the jet structure (e.g. Fukazawa *et al.* 2018, Hodgson *et al.* 2018). This scenario is supported by the change of gamma-ray hardness ratio around the beginning of 2011. Before 2011, the variability of hardness ratio is consistent with injection of fresh particles, while after 2011 the variability is better explained by a change in the Doppler factor and/or in the angle to our the line of sight (Tanada *et al.* 2018). Results of spectral energy distribution (SED) modelling using a SSC and considering data before and after 2011 support this scenario. It is also worth mentioning that the SED modelling is not unique, and the SED can be reproduced with a spine-sheath model, in agreement with the limb-brightened jet structure observed in VLBI images, in which the angle to our line of sight is about 18 degrees (Tavecchio & Ghisellini 2014).

5. Summary

Since the EGRET era, the extragalactic gamma-ray sky has been dominated by the population of jetted-AGN. The sub-population of blazars represents the largest fraction. Giving their characteristic multi-band variability, blazars have been studied to search for connection between the emission at low and high energy. Statistical studies of gamma-ray emitting blazars indicate significant correlation between radio and gamma-ray flux, indicating a common origin. When multi-wavelength light curves are compared, a time lag is usually observed with the gamma-ray leading the radio variability. Furthermore, the time lag increases with increasing the wavelength, as expected in case of opacity effects. The determination of the time lag between radio and gamma-ray is a useful tool for setting constraints on the location of the region responsible for the gamma ray emission: significant time lags or absence of a radio counterpart would locate the gamma ray emitting region within the broad line region, where the emission is opaque even at the short radio wavelengths. On the other hand, if no time lag is observed, the gamma-ray emission would take place at parsec distance from the central engine, in a region where the jet is already optically thin to radio emission.

Gamma-ray emission may be produced by perturbations that propagates downstream along the jet. In this scenario superluminal components, which are the observable manifestation of a propagating shock, should be ejected close in time with a gamma-ray flare. On the other hand, gamma-ray emission may be also produced in a structured jet. Observations of jets with a limb-brightened structured strongly support the existence of structured jet.

A peculiar case is represented by 3C 84. Since the ’60s, this radio sources has proved to be highly variable. Gamma-ray emission shows both short-term and long-term variability which are likely to be produced in different regions: the former in the core region, whereas the latter in the jet.

All these pieces of evidence clearly point out that a unique scenario capable to reproduce the gamma-ray emission and its connection with the other energy band in blazars in general, and in 3C 84 in particular, is still far to be achieved, and multi-band monitoring campaigns have proved to be the first and necessary step for shedding a light on the 'blazar' phenomenon.

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