*Perseus in Sicily: From Black Hole to Cluster Outskirts*
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# Young radio sources at high-energies and the $\gamma$-ray CSO PKS 1718−649

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**Abstract.** Observations at high-energies are important to define the first stages of the evolution of extragalactic radio sources and to characterize the interstellar medium of their host galaxies. In some of the X-ray-observed Compact Symmetric Objects (CSOs, among the youngest and most compact radio galaxies), we measured values of the total hydrogen column densities large enough to slow or prevent the radio source growth. The $\gamma$-ray window has the potential to constrain the non-thermal contribution of jets and lobes to the total high-energy emission. However, so far, young radio sources remain elusive in $\gamma$-rays, with only a handful of detections (or candidates) reported by *Fermi*. I present our $\gamma$-ray study of the CSO PKS 1718−649, and draw comparison with the restarted, $\gamma$-ray detected, radio galaxy 3C 84.

**Keywords.** galaxies: active — galaxies: individual (PKS 1718−649) — radiation mechanisms: non-thermal — gamma-rays: galaxies

## 1. Young radio sources at high-energies

Compact radio sources with radio structures fully contained within the central regions of their host galaxies (< 1 kpc) are thought to be the progenitors of the large-scale radio galaxies (see a review by Orienti 2016). Among young radio sources (YRSs), Compact Symmetric Objects (CSOs) have sub-kpc-scale structures, symmetric radio morphologies, total radio emission dominated by the mini-lobes, and kinematical ages smaller than a few thousand years.

Radiation at the high-energies (X-ray to $\gamma$-rays) traces the most energetic processes taking place in the YRSs: this energy band is important to define the intrinsic properties of the expanding source, such as the accretion process and the power channeled into the radio structures, but also to characterize the environment where the source is embedded.

### 1.1. *X-rays*

*Chandra* and *XMM-Newton* observations of samples of CSOs have demonstrated that these sources are X-ray emitters and short observations are enough to obtain a detection (Tengstrand *et al.* 2009, Siemiginowska *et al.* 2016, hereafter S16, and references therein). The CSOs in the X-ray sample of S16 have X-ray luminosities in the range of $10^{41}$ to $10^{45}$ erg $s^{-1}$. X-ray observations allow us to probe the host galaxy environment via measurements of the total hydrogen column densities, $N_H$. The S16 sample displays moderate or low $N_H$ for the majority of the targets ($N_H \approx 10^{22}$ cm$^{-2}$), except for a few sources whose X-ray spectra are compatible with being Compton-thick candidates ($N_H > 10^{24}$ cm$^{-2}$). Investigating the relation between the linear sizes of the radio structure and the density of ambient gas can help us to understand how the source will evolve: a predominance of obscured sources among the most compact and young ones could be indicative of confinement by a dense environment (Sobolewska *et al.* 2019), which could ultimately frustrate the radio source growth. Indeed, X-ray observations of large and complete samples of CSOs are necessary to test this scenario. Interestingly, the positive correlation between X-ray/$N_{\rm H}$ and radio/$N_{\rm HI}$ absorbing columns reported in Ostorero *et al.* (2017) suggests that the X-ray and radio absorbers are physically connected and could be part of the same, possibly perturbed, hundred-parsec scale structure. A multi-phase gas with complex kinematics, perturbed by the interaction with the YRSs is also supported by the detection of outflowing HI and molecular (CO) gas (see e.g. Morganti *et al.* in these proceedings).

The observed X-ray emission can be produced by thermal Comptonization in the disc-corona of the AGN powering the radio source, by shock-heated ISM by the expanding radio structure or via non-thermal processes within the radio jets and lobes (Tengstrand *et al.* 2009, Heinz *et al.* 1998, Migliori *et al.* 2014, Stawarz *et al.* 2008, Kino *et al.* 2009). In most of the cases, in lack of distinctive spectral features, the spectral and morphological X-ray studies cannot typically discriminate among the different phenomena. However, radiative models predict copious non-thermal, high-energy emission being produced in the jets and lobes of YRSs via inverse Compton (IC) scattering of the synchrotron photons and of the thermal photons radiated by the accretion disc, the torus, and the stellar population of the host galaxy. Depending on the jet and photon fields' parameters, this process could yield luminosities up to $10^{45}$ erg $s^{-1}$ in the 0.1 – 100 GeV band (Stawarz *et al.* 2008). Given that the accretion disc and corona emission drastically drops in the $\gamma$-ray band, a detection of a YRS at these energies is a robust proof of a non-thermal, high-energy component.

### 1.2. *Gamma-rays*

The launch of the *Fermi* telescope in 2008 has opened the quest for YRSs in the $\gamma$-ray window. However, so far searches performed on selected samples have mainly reported upper limits (Migliori *et al.* 2014; D'Ammando *et al.* 2016; Migliori 2016a). A handful of $\gamma$-ray sources with uncertain classification show CSO-like features and are currently under investigation (see for example PMN J1603−4904, Müller *et al.* 2015). The notable exceptions are the bona-fide CSO, PKS 1718−649 (here after PKS 1718, Migliori *et al.* 2016b) and the restarted radio source 3C 84 at the center of the Perseus cluster (Abdo *et al.* 2009). In the following, I will focus on PKS 1718, highlighting similarities and differences with 3C 84.

## 2. PKS 1718−649

PKS 1718 is the closest (z=0.014) confirmed CSO (Tingay *et al.* 1997). It displays a compact (∼2 pc), double-lobed, radio structure and has a kinematically estimated age of about 100 yrs (Giroletti & Polatidis 2009). The third *Fermi* Gamma-ray Large Area Telescope (LAT) catalog (3FGL, Acero *et al.* 2015) reported an unassociated source, 3FGL J1728.0−6446, close to PKS 1718. The analysis of ∼7 yrs of LAT data, using the Pass 8 calibration, allowed us to confirm that PKS 1718 lies 0.13° from the best fit position of the $\gamma$-ray source, within the 68% confidence radius, and is the most likely counterpart to the unassociated LAT source (Fig. 1, left). In $\gamma$-rays, the source yields a $>5\sigma$ detection with a best fit photon spectral index $\Gamma=2.9\pm0.3$ and a 0.1-100 GeV photon flux density $F_{0.1-100{\rm GeV}}=(11.5\pm0.3)\times10^{-9}$ ph cm$^{-2}$ s$^{-1}$ (Migliori *et al.* 2016b). Clues on the nature of the $\gamma$-ray emission of PKS 1718 come from the comparison of its $\gamma$-ray properties with those of blazar sources and radio galaxies reported in the 3FGL. The $\gamma$-ray emission of blazars, i.e. AGN with jets oriented close to the line of sight of the observer, is produced

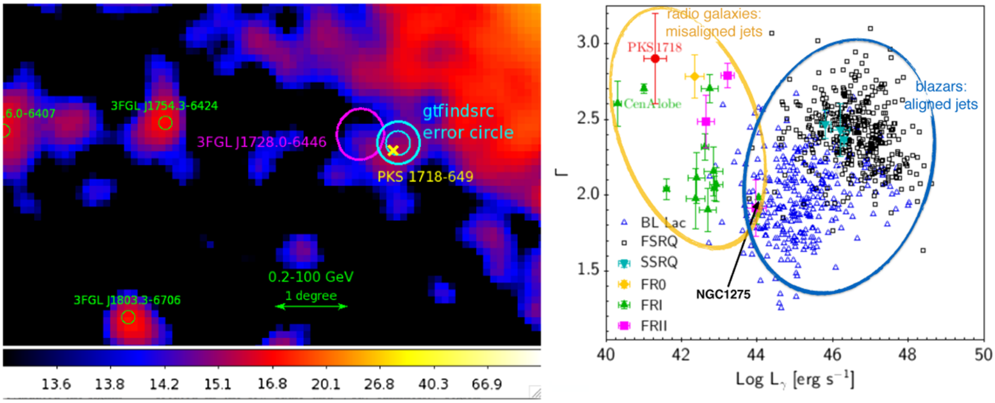

**Figure 1.** Left: *Fermi*-LAT 0.2-100 GeV count map of the sky. The yellow cross is the radio position of PKS 1718, the magenta ellipse gives the 3FGL position (95% confidence level) of 3FGL J1728.0−6446. The cyan circles are the best fit position (68% and 95% confidence levels) defined with *gtfindsrc*. Right: $\gamma$-ray spectral index versus 1-100 GeV luminosity. PKS 1718 is located in the MAGN region of the diagram, while 3C 84 (NGC 1275) is at the border with BL Lac sources (figures adapted from Migliori *et al.* 2016b).

in a compact, relativistically moving jet region close to the AGN. The emission is boosted by relativistic effects and in fact, they represent the vast majority of AGNs in the 3FGL. Conversely, there is a limited number of LAT detected misaligned AGNs (MAGNs), whose jets point away from the observer, such as radio galaxies (see Abdo *et al.* 2010a and the review by Torresi in these proceedings). In MAGNs, the site of production of the $\gamma$-ray emission, or the radiative mechanism responsible for it, could be possibly different from blazars. The two classes populate different regions of the radio (1.4 GHz) vs. $\gamma$-ray (>1 GeV) luminosity plot and of the $\Gamma$ vs. $L_\gamma$ plot. PKS 1718 is located in the region of low $\gamma$-ray luminosity and soft photon index which is predominantly occupied by MAGNs (Fig. 1, right). For a comparison, 3C 84 is the brightest radio galaxy detected in the GeV band and displays a harder $\gamma$-ray spectrum, which place it in the border region between low-power aligned and misaligned sources.

The $\gamma$-ray emission of PKS 1718 appears faint and steady in time, whereas the source is not significantly ($\geq 3\sigma$) detected on yearly timescales, suggesting a low level of variability. The broad-band radio spectrum is shaped by the combination of two effects, synchrotron self-absorption and free-free absorption (Tingay *et al.* 2015). Engulfment of gas clouds of difference size and density by the adiabatically expanding radio lobes (see Bicknell *et al.* 2018, and references therein) can account for the observed moderate radio flux and spectral variability. This scenario is also in agreement with the dynamical model that predicts isotropic high-energy emission from the compact lobes (Stawarz *et al.* 2008). Modeling of PKS 1718's non-thermal broadband spectral energy distribution (SED) can provide us with constraints on the jet's physical parameters (Sobolewska *et al.*, in prep). Estimates of the jet power and characterization of the source environment via multi-band, high-resolution observations (see e.g. Maccagni *et al.* 2014) are crucial to understand the radio source's fate.

3C 84 exhibits a more complex temporal behavior than PKS 1718. A progressive brightening of the $\gamma$-ray flux on long timescales is accompanied by short-term (days to week) flaring activity. The source has been also detected at very high energies (>100 GeV, Aleksić *et al.* 2014). Very long baseline interferometry (VLBI) has revealed that the radio outburst, which is ongoing since 2005, coincided with the ejection of a new, possibly hot spot-like component (Nagai *et al.* 2010). The small-scale jet displays an evolving, limb-brightened radio morphology down to few hundreds of gravitational radii from the central engine (Giovannini *et al.* 2018, and references therein), pointing to a stratified jet structure. These features suggest the intriguing possibility of multiple sites of production of the $\gamma$-rays (Hodgson *et al.* 2018, Tanada *et al.* 2018).

## 3. Conclusions

While YRSs remain elusive in $\gamma$-rays, the CSO PKS 1718, the restarted radio galaxy 3C 84 and a few other candidates display a range of different $\gamma$-ray properties. This fact makes it difficult to identify the most favorable CSOs for a detection in $\gamma$-rays. Interestingly, such diversity could reflect the different stages in the evolution of the sources, with 3C 84 being in a more unstable and rapidly evolving phase than PKS 1718. The faint and steady $\gamma$-ray emission of PKS 1718 is compatible with an origin in the compact radio lobes. If confirmed, this would be an interesting case of isotropic $\gamma$-ray emission such as that associated with the radio lobes of Cen A (Abdo *et al.* 2010b).

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