Received: 6 October 2021 | Accepted: 7 October 2021 | Published on: 20 October 2021

DOI: 10.1002/asna.20210041

Astronomische Nachrichten

PROCEEDING

The gamma-ray emission from young radio galaxies and quasars

Giacomo Principe[1,2,3] | **Leonardo Di Venere**[4,5] | **Giulia Migliori**[3] | **Monica Orienti**[3] | **Filippo D'Ammando**[3] | **on behalf of the the *Fermi*-LAT Collaboration**

[1]Dipartimento di Fisica, Universitá di Trieste, Trieste, Italy

[2]Istituto Nazionale di Fisica Nucleare, Trieste, Italy

[3]Istituto Nazionale di Astrofisica—Istituto di Radioastronomia, Bologna, Italy

[4]Dipartimento di Fisica "M. Merlin", dell'Università e del Politecnico di Bari, Bari, Italy

[5]Istituto Nazionale di Fisica Nucleare, Bari, Italy

Correspondence
Giacomo Principe, Dipartimento di Fisica, Universitá di Trieste, I-34127 Trieste, Italy.
Email: giacomo.principe@ts.infn.it

Funding information
Universita degli Studi di Trieste

Abstract

According to radiative models, radio galaxies are predicted to produce γ-rays from the earliest stages of their evolution onwards. The study of the high-energy emission from young radio sources is crucial for providing information on the most energetic processes associated with these sources, the actual region responsible for this emission, as well as the structure of the newly born radio jets. Despite systematic searches for young radio sources at γ-ray energies, only a handful of detections have been reported so far. Taking advantage of more than 11 years of *Fermi*-large area telescope (LAT) data, we investigate the γ-ray emission of 162 young radio sources (103 galaxies and 59 quasars), the largest sample of young radio sources used so far for a γ-ray study. We analyzed the *Fermi*-LAT data of each source separately to search for a significant detection. In addition, we performed the first stacking analysis of this class of sources in order to investigate the γ-ray emission of the young radio sources that are undetected at high energies. In this note, we present the results of our study and we discuss their implications for the predictions of γ-ray emission from this class of sources.

KEYWORDS

galaxies: evolution, galaxies: active, galaxies: jets, radio continuum: galaxies, gamma-rays: galaxies

1 | INTRODUCTION

One of the greatest questions investigated by modern astrophysics is understanding the origin of the γ-ray emission in radio galaxies and quasars. While the extragalactic γ-ray sky is dominated by blazars, due to their small jet inclination to the line of sight and by relativistic beaming, only a few radio galaxies have been detected so far (4LAC, Ajello et al. 2020). Due to their misaligned jets, they offer a unique tool to investigate some of the nonthermal processes at work in unbeamed regions in active galactic nuclei (AGN).

According to the evolutionary scenario, the size of a radio galaxy is strictly related to its age (Fanti et al. 1995). Therefore extragalactic compact radio objects (i.e. radio objects with projected linear size LS < 20 kpc), are expected to be the progenitors of extended radio galaxies (Readhead et al. 1996). Support to the young nature of these objects is given by the determination of kinematic and radiative

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ages in some of the most compact sources ($t \sim 10^2 - 10^5$ years) (Phillips & Mutel 1982). Compact radio objects reside either in galaxies or quasars. While for the latter the γ-ray emission is favored by their smaller jet-inclination angle and beaming effects, the origin of γ-ray emission in galaxies is still a matter of debate.

In the model proposed by Stawarz et al. (2008), young radio galaxies are expected to produce isotropic high-energy emission through IC scattering of the UV photons by the electrons in the compact radio lobes. Depending on the sources' physical parameters (e.g. jet power, UV luminosity), the model predicted that young radio sources could constitute a class of γ-ray emitters detectable by *Fermi*-large area telescope (LAT). However, systematic searches for γ-rays from young radio sources have so far been unsuccessful (D'Ammando et al. 2016). Dedicated studies reported a handful of detections: three young radio galaxies (NGC 6328 (Migliori et al. 2016), NGC 3894 (Principe et al. 2020), and TXS 0128 + 554 (Lister et al. 2020)), and five compact steep spectrum (CSS) sources (3C 138, 3C 216, 3C 286, 3C 380, and 3C 309.1) all associated with quasars (4FGL, Abdollahi et al. 2020). The search for high-energy emission from young radio galaxies and quasars is crucial for investigating the energetic processes in the central region of the host galaxy, as well as the origin and the structure of the newly born radio jets.

Taking advantage of the increased sensitivity provided by more than 11 years of LAT data, we investigate the γ-ray properties of a sample of 162 young radio sources (103 galaxies and 59 quasars). In addition to the γ-ray analysis of each young radio object, we perform the first stacking analysis of this class of sources in order to investigate the γ-ray emission of the young radio sources still below the detection threshold in the high-energy regime.

Throughout this work, we assume $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$ in a flat Universe.

2 | SAMPLE OF YOUNG RADIO SOURCES AND ANALYSIS DESCRIPTION

We selected the young radio sources for our study from the following resources, which contain radio galaxies and quasars with LS < 50 kpc: de Vries et al. (2009); Liao & Gu (2020); Orienti & Dallacasa (2014); Wójtowicz et al. (2020). We also added to our sample the sources NGC 3894, TXS 0128 + 554, and 3C 380, since they were already detected at high energy and investigated in Principe et al. (2020), Lister et al. (2020), and Zhang et al. (2020), respectively. Our final sample consists of 162 sources (103 galaxies and 59 quasars) with known position, redshift, LS, radio luminosity, and peak frequency.

The selected sources have redshift values between 0.001 and 3.5 and LS spanning from less than 1 pc up to a few tens of kpc. Most (129) of the sources have redshift below 1, with seven sources located in the local Universe ($z < 0.05$, $D_\mathrm{L} \lesssim 200$ Mpc). Considering the morphological classification, about half (79) of the sources are classified as compact symmetric objects (CSOs, LS <1 kpc), 70 sources as medium symmetric objects (MSOs, LS $\sim 1 - 20$ kpc), and 13 large symmetric objects (LSOs) with LS between 20 and 50 kpc. Concerning their radio spectra and peak frequency (ν_p), 52 sources are classified as GHz-peaked spectrum (GPS, $\nu_\mathrm{p} > 0.5$ GHz), with the remaining 110 being classified as CSS ($\nu_\mathrm{p} < 0.5$ GHz). For several CSS sources, only upper limits on the peak frequency have been found in the literature. The radio luminosity ($\nu L_{\nu=5\ \mathrm{GHz}}$) of the sources contained in our sample varies by more than eight orders of magnitude ($\nu L_{\nu=5\ \mathrm{GHz}} \sim 10^{38} - 10^{46}$ erg s^{-1}).

2.1 | Analysis description

We performed a dedicated analysis of each source in our sample using more than 11 years of *Fermi*-LAT data between August 5, 2008, and November 1, 2019. We selected LAT data from the P8R3 source class events (Bruel et al. 2018), and P8R3_SOURCE_V2 instrument response functions (IRFs), in the energy range between 100 MeV and 1 TeV, in a region of interest (ROI) of 20° radius centered on the source position. The lower limit for the energy threshold is driven by the large uncertainties in the arrival directions of the photons below 100 MeV, which may be confused with the Galactic diffuse component. See Principe & Malyshev (2017); Principe et al. (2018) for a different analysis technique to solve this and other issues at low energies with *Fermi*-LAT.

The analysis procedure applied in this work is mainly based on two steps. First, we investigate the γ-ray data of each individual source with a standard likelihood analysis (see e.g. EHT MWL Science Working Group et al. 2021; Principe et al. 2020). The likelihood analysis, which consists of model optimization, source localization, spectrum, and variability study, was performed with `fermipy`[1] (Wood et al. 2017). Subsequently, we performed a stacking analysis of the sources, which was not significantly detected in the individual study, in order to investigate the general properties of the population of young radio galaxies and quasars.

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[1] http://fermipy.readthedocs.io/en/latest/.

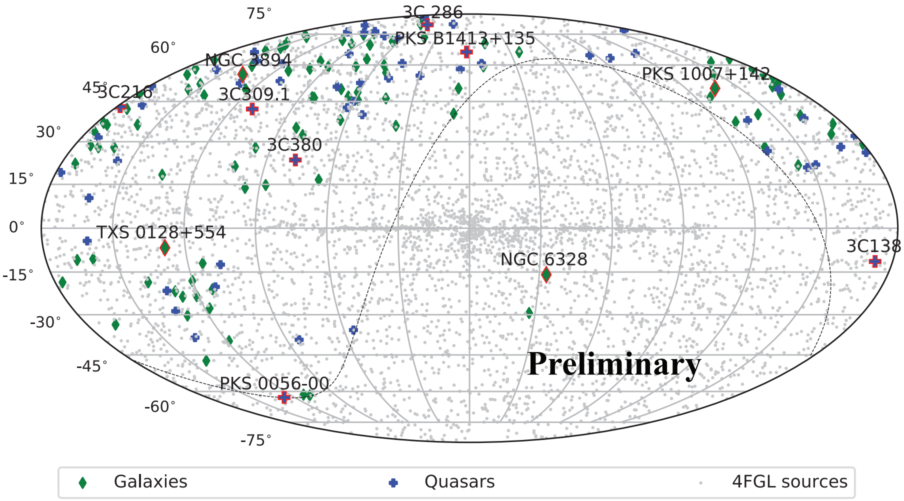

FIGURE 1 Sky map, in Galactic coordinates and Mollweide projection, showing the young radio sources in our sample. The detected sources are labeled in the plot. All the 4FGL sources (Abdollahi et al. 2020) are also plotted, with gray points, for comparison

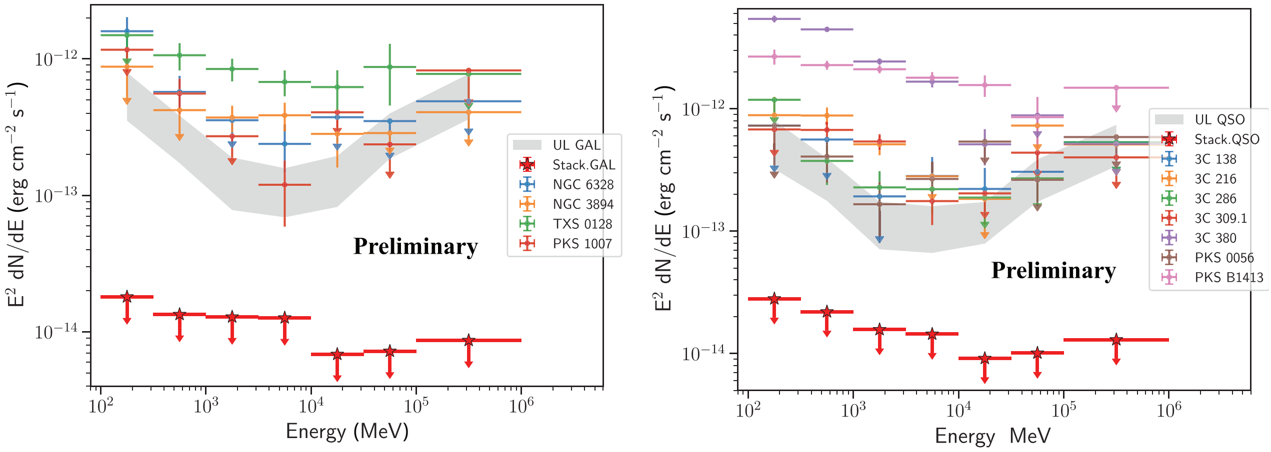

FIGURE 2 *Left panel*: upper limits for the undetected young radio galaxies as determined from the stacking analysis, compared to the averaged upper limits of the individual undetected radio galaxies (gray band), and the spectral energy distributions of the detected ones. *Right panel*: the same as for the left panel but for quasars

3 | *FERMI*-LAT RESULTS

In our study, we detect significant γ-ray emission (Test Statistic $\mathrm{TS} > 25$, corresponding to a significance $< 4.6\sigma$) at the positions of 11 young radio sources (see Figure 1).

In particular, we detected four galaxies: NGC 6328 (LS = 2 pc), NGC 3894 (LS = 10 pc), TXS 0128 + 554 (LS = 12 pc), and PKS 1007 + 142 (LS = 3.3 kpc); and seven quasars: 3C 138 (LS = 5.9 kpc), 3C 216 (LS = 56 kpc), 3C 286 (LS = 25 kpc), 3C 309.1 (LS = 17 kpc), 3C 380 (LS = 11 kpc), PKS 0056–00 (LS = 15 kpc), and PKS B1413 + 135 (LS = 0.03 kpc). Nine out of the 11 detected sources were present in previous *Fermi*-LAT catalogs, while PKS 0056-00 has recently been reported in the latest release of LAT sources 4FGL-DR2[2] (Abdollahi et al. 2020). In addition to the sources already included in the 4FGL-DR2, we report here the discovery of γ-ray emission from the young radio galaxy PKS 1007 + 142 ($z = 0.213$). PKS 1007 + 142 presents a soft γ-ray spectrum with best-fit photon index $\Gamma = 2.55 \pm 0.18$ and flux $F = (4.65 \pm 1.55) \times 10^{-9}$ ph cm^{-2} s^{-1}.

Considering the detected sources, all the galaxies are GPS ($\nu_\mathrm{p} > 0.5$ GHz), while all the quasars are CSS, with the exception of the peculiar GPS PKS B1413 + 135. Five quasars (3C 138, 3C 216, 3C 309.1, 3C 380, and PKS B1413 + 135) present significant variability ($\mathrm{TS}_\mathrm{var} > 23$) on a yearly scale of the γ-ray emission. The presence of γ-ray flares in these sources suggests that their high-energy emission is due to a relativistic jet and beaming effect, confirming their nonmisaligned nature.

We searched for a signal from the population of the 151 undetected young radio sources by applying the stacking procedure (see Principe et al. 2021, for more information on the stacking analysis). The stacking analysis on the LAT data of the undetected sources did not result in the detection of significant emission. The upper limits obtained

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[2] https://fermi.gsfc.nasa.gov/ssc/data/access/lat/10yr_catalog/.

with this procedure are, however, about one order of magnitude below than those derived from the individual sources (see Figure 2).

This allowed a comparison with the model proposed by Stawarz et al. (2008), based on an isotropic γ-ray emission from the compact lobes of young radio galaxies, excluding jet powers $\left(\gtrsim 10^{42}–10^{43}\ \mathrm{erg\ s^{-1}}\right)$ coupled with UV luminosities $>10^{45}\ \mathrm{erg\,s^{-1}}$. More information on the obtained results can be found in Principe et al. (2021).

4 | CONCLUSION

Before the launch of *Fermi*-LAT, young radio sources were predicted to emerge as a new class of γ-ray emitting objects. However, after more than 10 years of observations, only a handful of sources have been unambiguously detected (Ackermann et al. 2015; Ajello et al. 2020; Lister et al. 2020; Migliori et al. 2016; Principe et al. 2020), with the quasars playing a major role. The goal of our study was to investigate the γ-ray properties of young radio sources. To this end, we analyzed 11.3 years of *Fermi*-LAT data for a sample of 162 sources. We analyzed the γ-ray data of each source individually to search for a significant detection. We report the detection of 11 young radio sources, including the discovery of significant γ-ray emission from the compact radio galaxy PKS 1007 + 142. In addition, we perform the first stacking analysis of this class of sources in order to investigate the γ-ray emission of the young radio sources that are undetected at high energies, without finding significant emission. The upper limits obtained with this procedure are, however, tighter than those derived from the individual sources. This enabled a comparison with the model proposed by Stawarz et al. (2008), predicting isotropic γ-ray emission from the compact lobes of young radio galaxies. As a result, we can rule out jet powers $\gtrsim 10^{42}–10^{43}\ \mathrm{erg\ s^{-1}}$ coupled with UV luminosities $>10^{45}\ \mathrm{erg\,s^{-1}}$. More information on this project can be found in Principe et al. (2021).

ACKNOWLEDGMENTS

The *Fermi*-LAT Collaboration acknowledges support from NASA and DOE (United States), CEA/Irfu, IN2P3/CNRS, and CNES (France), ASI, INFN, and INAF (Italy), MEXT, KEK, and JAXA (Japan), and the K.A. Wallenberg Foundation, the Swedish Research Council, and the National Space Board (Sweden). Open Access Funding provided by Universita degli Studi di Trieste within the CRUI-CARE Agreement.

ORCID

Giacomo Principe https://orcid.org/0000-0003-0406-7387

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AUTHOR BIOGRAPHY

Giacomo Principe. Graduated in Physics in 2015 at Università di Padova, Italy. PhD degree in Astroparticle physics between January 2016 and September 2018 at University of Erlangen-Nuremberg, graduated in March 2019. Research fellow at INAF-IRA Bologna between October 2018 and September 2020. Since October 2020 he is a research fellow at Università di Trieste, Italy.

How to cite this article: Principe, G., Di Venere, L., Migliori, G., Orienti, M., D'Ammando, F., & Principe, G. 2021, *Astron. Nachr.*, *342*, 1176. https://doi.org/10.1002/asna.20210041