PROCEEDINGS OF SCIENCE

Low-luminosity jetted AGN as particle multi-messenger sources

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Gamma rays, high-energy neutrinos and cosmic rays (CRs) impinging on Earth signal the existence of environments in the Universe that allow acceleration of particle populations into the extremely energetic regime. In order to understand these observable signatures from putative CR sources in-source acceleration of particles, their energy and time-dependent transport including interactions in an evolving environment and their escape from source have to be considered, in addition to source-to-Earth propagation.
Low-luminosity jets of Active Galactic Nuclei (AGN) constitute the most abundant persistent jet source population in the local Universe. The dominant subset of these, Fanaroff-Riley 0 (FR0) galaxies, have recently been proposed as sources contributing to the ultra-high-energy cosmic ray (UHECR) flux observed on Earth. In this work we consider the workings of UHECRs in low-luminosity jet environments, with focus on FR0 galaxies. By multi-messenger modelling these we predict potentially observable, distinct photon signatures at MeV energies from the core of FR0s, and expect FR0s to be rather weak neutrino emitter. For this purpose we use our recently developed, fully time-dependent CR particle and photon propagation framework CR-ENTREES which takes into account all relevant secondary particle production and energy loss processes, and allows for an evolving source environment and efficient treatment of transport non-linearities.

XVIII International Conference on Topics in Astroparticle and Underground Physics (TAUP2023)
28.08-01.09.2023
University of Vienna

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PoS(TAUP2023)119

1. Introduction

Despite the many advances after several decades of research in the field of cosmic-ray (CR) astrophysics (thanks to recent exciting developments lately extended into multi-messenger astrophysics), there still remains uncertainty about the most fundamental issue: The question of the cosmic ray origin, in particular of those at ultra-high energies (UHEs; E≥ EeV). The present work, in conjunction with the article of [1] (this proceedings), aims to contribute to the question in how far the dominant jet population in the local extragalactic Universe, so-called Fanaroff-Riley 0 radio galaxies (FR0s), a subtype of jetted low-luminosity active galactic nuclei (LLAGN), may contribute to the observed UHECR-flux observed at Earth. Owing to their weak luminosity, FR0s have only recently been discovered in larger number (e.g., [2]).

Fig. 1 compares the broadband spectral energy distribution (SED) of FR0s with that of the well-known FRI-population. Their SEDs appear similar in the core X-ray range, possibly pointing to a similar nuclear environment. Indeed, accretion in LLAGN (defined by a low nuclear H_α-luminosity ($L_{H_\alpha} < 10^{40}$erg/s; [3]) is typically of the ADAF (advection-dominated accretion flow; [5]) type. At radio wavelengths FRI jets appear morphologically notably extended, whereas FR0s seem more compact, and lack such extended jets (e.g., [4]). This is reflected in a significantly larger power range that is covered in the SED of FRIs as compared to FR0s.

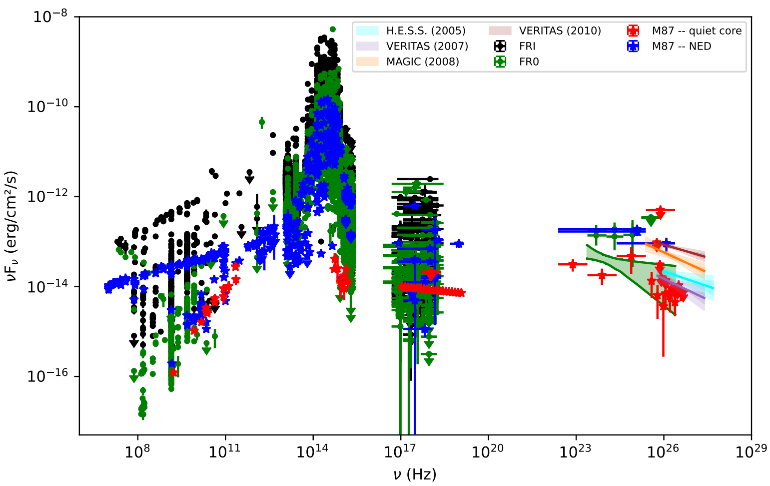

Figure 1: Broadband SED of FRIs (black dots), FR0s (green dots/butterfly), all available observations of M87 (blue stars) and M87 in its 2017 quiet state (red stars). M87 flaring observations in the VHE range are indicated by cyan, purple, brown and orange butterfly plots. The fluxes from FRIs have been rescaled from their mean distance to the mean distance of FR0s. Similarily, M87's distance was rescaled to the mean distance of FR0s. For more information see [6].

With the recent detection of two FR0 galaxies at GeV energies (see Fig. 1; [7], [8]) this source class has now entered unambiguously the non-thermal Universe. Moreover, they are able to contain ≤ EeV CR-protons in a μG magnetized emission region (Hillas criterion), with a typical jet power of ∼ a few $10^{42...43}$erg/s and radiatively dilute environment allow CR acceleration up to 10 EeV [9], and - as the most abundant jet class in the local Universe - are sufficient numerous (∼ 10^{-4}Mpc^{-3}; [4]) to be able to potentially contribute significantly to the overall UHECR flux detected. In the following we shall verify whether the assumption of relativistic CR-protons contained in their jets is in agreement with the observed broadband emission from FR0s, both as a class and individually. For this modelling purpose we use CR-ENTREES [10], a code for fully time-dependent Cosmic-Ray ENergy TRansport in timE-Evolving astrophysical Settings (and base code for the heavy nuclei propagation code of [11]).

2. CR-ENTREES

CR-ENTREES [10] evolves the coupled time- and energy-dependent kinetic equations for CR nucleons, pions, muons, electrons/positrons, photons and neutrinos in a homogeneous one-zone emission region co-moving with the jet, with user-defined particle/photon injection laws. All relevant interactions (inverse Compton scattering, Bethe-Heitler pair production, synchrotron radiation - including backreaction effects - of charged particles, photomeson production, particle decay), particle/photon escape and adiabatic losses are considered in a radiation-dominated, homogeneously magnetized environment that is itself evolving in time. The assumed isotropic target photon density distribution is discretized on a fixed 161 log-equal spacing energy grid in the range $10^{-10...6}$eV. Particles and photon number densities, discretized on a fixed 300 log-equal spacing energy grid in the range $10^{-3...12}$GeV, which is extended to $10^{-18...-3}$GeV for photons with the same binning, propagate in energy space using the matrix multiplication method advanced by e.g., [12] in the context of CR transport. Here, particle and photon interaction yields are pre-calculated using event generators assuring an accurate interactions and secondary particle production description. Transfer matrices are then created from the aforementioned yields and interaction probabilities which describe the change after a given time step of the density of a given particle type upon all the interactions pre-set by the user. This method allows an efficient treatment of transport non-linearities due to the produced particles/photons being fed back into the simulation chain.

3. Modelling the multi-messenger emission from FR0s

Motivated by the striking similarity between the quiet core broadband radiation from the famous FRI M87 and the FR0 population (see Fig. 1), we explored a one-zone jet with ADAF emission model to represent the FR0 photon data. This lepto-hadronic model was able to fit all fluxes observed from M87 during the EHT-lead multifrequency campaign in 2017 with a core jet magnetic field strength that agrees with the synchrotron-self absorption frequency constraints implied by the EHT-data [13]. It explained the radio-to-optical/UV and γ-ray data by electron and proton synchrotron emission, respectively, in a close-to equipartition setup between fields and particle energy densities, while the X-ray emission mainly originates from the ADAF. We then modelled the γ-ray detected FR0 LEDA 55267 and LEDA 58287 as well as the remaining FR0 population using such ADAF-jet model with parameter settings similar to that derived from the M87 modelling [6]. Fig. 2 shows the resulting emission of a slowly moving (bulk Lorentz factor ~ 1.2), compact (a few 10^{15}cm), strongly magnetized ($\sim 25-50$G) jet emission region which contains non-thermal, rather hard-spectrum (index ~ 1.7) proton and electron populations. In the close-to-equipartition composition of these jets CR-protons reach energies up to a few EeV. The ADAF accretes at sub-Eddington rates ($\dot{M}_{\rm max} \propto 10^{-3}\dot{M}_{\rm Edd}$) with viscosity parameter $\alpha \approx 0.1$. Our modelling predicts a distinct signature of ADAF-emission at MeV-energies, and a > 0.3TeV-flux below the sensitivity of current and near-future Cherenkov telescope systems (see Fig. 2).

4. Conclusion

We find that FR0s as the most abundant jet sources in the local Universe, is a promising source class to contribute significantly to the CR-flux up to a few EeV, however, are weak ν- and VHE-

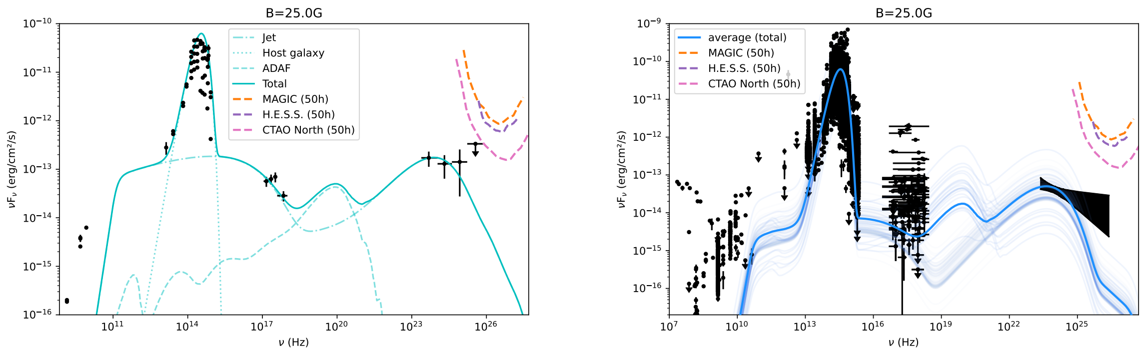

Figure 2: Left: SED of LEDA 55267 modelled by a jet-disc (ADAF) model [6]. A modified blackbody models the host galaxy emission (dotted line), dashed line represents the ADAF emission, dashed–dotted line the total emission from a 25G-magnetized region in the jet, solid line represents the sum of the three components. Right: SEDs of the 112 sources that are not individually detected at γ-rays modelled by a jet-disc model [6] for a jet magnetic field strength of 25G. Faint blue lines represent individual fluxes of the 112 sources, the solid blue line is the average of the 112 models (see [6] for more information). The differential fluxes sensitivities are taken from [14] (H.E.S.S.), [15] (MAGIC), [16] (CTA North).

photon emitter. Close-to-equipartition condition in these AGNs' core region, and a characteristic MeV-feature (from their accretion flow) in the photon SED of those sources is predicted.

Acknowledgements

Financial support for this project was received from the Austrian Science Fund (FWF) under grant agreement number I 4144-N27 and the Slovenian Research Agency-ARRS (project no. N1-0111). MB has for this project received funding from the European Union's Horizon 2020 research and innovation program under the Marie Sklodowska-Curie grant agreement No 847476. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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