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Acceleration and propagation of cosmic rays from the radio galaxy Fornax A

I. Parillo[1] & V. de Souza[1]

[1] Instituto de Física de São Carlos, Universidade de São Paulo, e-mail: isadora.parillo@usp.br, e-mail: vitor@ifsc.usp.br

Abstract. In this work, we study the behavior of active galactic nuclei (AGN) from the perspective of ultra high energy cosmic ray (UHECR) acceleration in their structures. To this end, we characterize a specific radio galaxy in the local Universe, Fornax A (NGC 1316). Finally, we examine the energy loss effects that cosmic rays encounter during their propagation through the Universe, focusing on interactions with the cosmic microwave background radiation and extragalactic background light. For this purpose, we use the computational framework CRPropa3 to perform a simplified simulation of cosmic ray propagation accelerated from Fornax A, generating a plausible energy spectrum. We conclude that Fornax A is a promising candidate for UHECR acceleration.

Resumo. Neste trabalho, estudamos o comportamento de núcleos ativos de galáxias sob a perspectiva de aceleração de raios cósmicos de ultra-alta energia (UHECR) em suas estruturas. Para tanto, caracterizamos uma radiogaláxia específica do Universo local, Fornax A (NGC 1316). Por fim, examinamos os efeitos de perda de energia que os raios cósmicos enfrentam durante sua propagação pelo Universo, com foco nas interações com a radiação cósmica de fundo em micro-ondas e a luz de fundo extragaláctica. Para tal, utilizamos o framework computacional CRPropa3 a fim de realizar uma simulação simplificada da propagação de raios cósmicos acelerados a partir de Fornax A, gerando um espectro de energia plausível. Concluimos que Fornax A é uma promissora candidata à aceleração de UHECRs.

Keywords. Astroparticle physics – Cosmic rays – Galaxy: active

1. Introduction

Cosmic rays are particles or nuclei accelerated in galactic or extragalactic environments that propagate through the Universe and potentially reach Earth. Their energies span a wide range, from relatively low values to extremely high levels. Specifically, astroparticles with energies above 10^{18} eV are referred to as ultra high energy cosmic rays (UHECRs). The origin of UHECRs remains an open question in Astrophysics, particularly regarding the acceleration processes they undergo. In this context, a category of galaxies with active nuclei stands out: radio galaxies, as they present promising sites for acceleration by satisfying the Hillas criterion.

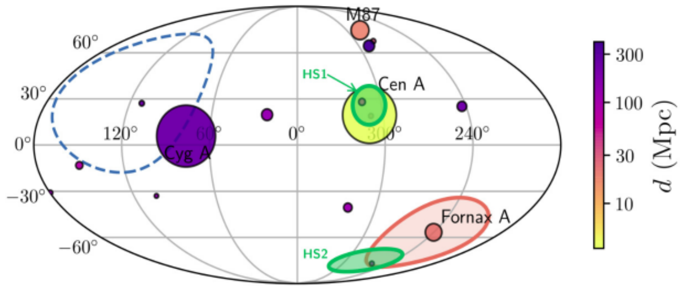

Figure 1. 16 brightest radio galaxies in galactic coordinates. The green areas represent an accumulation of events detected with energies exceeding 6×10^{19} eV, according to the Pierre Auger Observatory (Matthews et al. (2018)).

2. The radio galaxy Fornax A

Fornax A is a large elliptical galaxy located in the Fornax Cluster. It is one of the most luminous radio galaxies in the local Universe, particularly at 1.44 GHz, and is situated at a distance of 20.8 Mpc (Cantiello et al. (2013)). The galaxy exhibits an “s”-shaped jet and counter-jet structure extending approximately 6 kpc from the central emission region, as well as two large lobes that span over 120 kpc. Since its jets terminate within the galactic environment, it can be classified as an FRI radio galaxy. However, the presence of large lobes with bright terminal features also suggests similarities with FRII galaxies, indicating a different, possibly more active past for its nuclei.

The luminosity of Fornax A’s jets reaches approximately 2.4×10^{42} erg s^{-1} (Maccagni et al. (2021)). Furthermore, the estimated equipartition magnetic field strength in its jets is about 23 μG; in the lobes, it is around 3 μG; and in the central emission region, it is approximately 50 μG (Maccagni et al. (2020)). Another noteworthy aspect of this galaxy is its morphology, which shows strong observational evidence of past merging events with other galaxies, the most recent occurring about 3 Gyr ago. This suggests a potential enrichment of the galactic environment with disturbances capable of generating shock waves.

Fornax A is an important candidate for extragalactic cosmic ray acceleration due to its size, luminosity, and magnetic fields. Another key factor is its relative proximity, which minimizes energy losses for astroparticles accelerated within it during their propagation to Earth. Moreover, the galaxy’s location near a region of the sky associated with a significant accumulation of particles with energies exceeding 6×10^{19} eV, known as Hotspot 2 (HS2), detected by the Pierre Auger Observatory, adds further interest, as shown in Figure 1.

We focus specifically on acceleration in Fornax A’s jets, as they exhibit significant magnetic fields and dimensions. Moreover, the propagation of the jets through the galactic medium can cause disturbances that lead to the generation of shock waves – creating a favorable environment for the diffusive shock acceleration mechanism (DSA).

Based on the developments by Eichmann (2019), the maximum rigidity of cosmic rays can be related to the jet power of a galaxy with active nuclei (Q_{jet}) through the expression:

$$R_{max} = 5.4 g_{ac} \sqrt{1 - g_{cr}} \left(\frac{Q_{jet}}{10^{43}\ erg/s} \right)^{1/2} \times 10^{18}\ \mathrm{V}, \quad (1)$$

where g_{ac} is a parameter characterizing the efficiency of acceleration based on the plasma properties in the acceleration region, and g_{cr} relates the energy contained in hadrons to the magnetic energy of the acceleration region, using the magnetic field strength (B) and the equipartition magnetic field (B_m).

Using characteristic values of Fornax A, we arrive at the result:

$$R_{max} \simeq 1.45 \times 10^{18}\ \ \mathrm{V}. \quad (2)$$

This result represents an upper limit for the maximum rigidity of particles accelerated in the jets of Fornax A and is a key parameter for the computational simulation performed. It is related to the maximum energy of cosmic rays accelerated in the radio galaxy's jets by $E_{max} = ZeR_{max}$.

The emission model for the source, considering that cosmic rays are accelerated by the DSA mechanism, is:

$$J(E) = \left. \frac{dN}{dE} \right|_0 = f E_0^{-2} e^{-E_0/E_{máx}}. \quad (3)$$

In which N stands for the number of particles and f for the composition of the accelerated cosmic rays in the galaxy.

3. Propagation effects

During their propagation through the Universe, cosmic rays lose energy through various processes. Notably, they interact with photon fields: the cosmic microwave background radiation (CMB) and the extragalactic background light (EBL), which includes infrared, optical, and ultraviolet wavelengths. Examples of relevant processes include photopion production, pair production, and photodisintegration of nuclei. Additionally, all propagating particles undergo adiabatic energy loss due to the expansion of the Universe.

Specifically, photopion production leads to a suppression in the cosmic ray energy spectrum near $E_{GZK} \approx 10^{19.6}$ eV. Due to this effect, it is inferred that, in order to explain the arrival of nuclei with extremely high energies on Earth, the astrophysical sources that originate them might be located in the nearby Universe.

4. `CRPropa3` simulation

Considering the key features of Fornax A and the emission model of this source, we conducted the propagation of cosmic rays accelerated within it using `CRPropa3`. Through this computational framework, we accounted for the energy loss effects aforementioned. Additionally, we assigned the composition estimated by the Pierre Auger Collaboration to the accelerated cosmic rays, thereby obtaining the energy spectrum shown in Figure 2.

5. Conclusions

As we can observe from the energy spectrum of cosmic rays originating in Fornax A and propagating to Earth, we conclude that this radio galaxy is a prominent candidate for the production of UHECRs in the local Universe, presenting a maximum rigidity of $R_{max} \simeq 1.45 \times 10^{18}$ V, and may contribute to the flux observed on Earth by major experiments such as the Pierre Auger Observatory and the Cherenkov Telescope Array Observatory (CTAO), currently under construction. In this context, we aim to incorporate different compositions and estimate the flux of astroparticles accelerated in its jets as a natural continuation of this work.

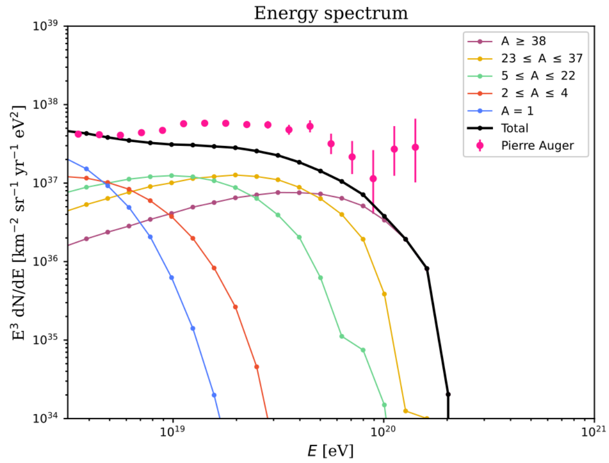

Figure 2. Energy spectrum of cosmic rays originating from Fornax A and detected on Earth: results from the simulation.

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