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Multi-messenger emission from radio-galaxies

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Abstract. Ultrahigh-energy cosmic rays (> EeV) are astrophysical phenomena whose sources are unknown, with many potential candidates. Near Earth radio galaxies (< 50Mpc distance), in particular Centaurus A, M87, Fornax A and NGC1275, constitute the most intriguing group regarding the potential as sources of ultra-high-energy cosmic rays, as indicated by the Pierre Auger Collaboration through anisotropy studies. Cosmic rays experience deflections in the intergalactic environment due to interactions with magnetic fields and other particles, generating secondary particles such as gamma rays. In this work we study in detail the secondary gamma rays with CRPropa3 software to generate and propagate them through the extragalactic medium and describe how radio-galaxies may contribute to the cosmic-ray spectra. Our simulated results are then compared with data obtained from the Pierre Auger Observatory

Resumo. Raios cósmicos de altíssimas energias (> EeV) são fenômenos astrofísicos sem uma origem definida, com diversos candidatos de fontes. Rádio-galáxias próximas à Terra (< 50Mpc de distância), especialmente a Centaurus A, M87, Fornax A e NGC1275, que compõem o grupo de maior interesse das possibilidades de fontes de raios cósmicos ultra-energéticos, conforme apresentado pela Colaboração Pierre Auger através de estudos de anisotropia. Raios cósmicos sofrem desvios no ambiente intergaláctico ocasionados por interações com campos magnéticos e outras partículas, gerando partículas secundárias, como a radiação gama. Neste trabalho estudamos a radiação gama secundária, utilizando o software CRPropa3 para gerá-los e propagá-los pelo ambiente extragaláctico e descrevermos como rádio-galáxias podem contribuir ao espectro de raios cósmicos, comparando com os dados obtidos pelo Observatório Pierre Auger.

Keywords. gamma rays: galaxies – astroparticle physics – cosmic rays

1. Introduction

Cosmic rays are particles that come from space without a defined origin, although there is a certainty that ultrahigh-energy cosmic rays (UHECR) come from outside the Milky Way, as shown by the Hillas (1984) diagram, which relates the size of possible sources to their magnetic field strength to determine a maximum energy threshold at which a source can accelerate a particle, and anistropy studies (Pierre Auger Collaboratio, 2007) that show that higher-energy particles arrival directions are opposite from the galactic center, as observed on figure 2.

The Pierre Auger Observatory in Argentina was built to detect cosmic rays, and its data suggest that the directions of incidence of higher-energy cosmic rays coincide with the directions of active galactic nuclei (AGNs) (Pierre Auger Collaboration, 2008). This makes it interesting to investigate AGNs as possible sources of ultrahigh-energy cosmic rays. More specifically, radio galaxies have relativistic jets that can also accelerate particles to high energies.

2. Cosmic rays propagation

Particles with higher energies accelerated at possible sources must travel through the extragalactic medium until they arrive on Earth and are detected. Numerous factors contribute to the non-linear nature of its propagation. The existence of magnetic fields both inside and outside of our galaxy, which deviate charged particles (cosmic rays) from their track due to the Lorentz force, is one of the main causes of this non-straight line propagation. Initially, we considered a simple 1.0 nG magnetic field in our computations..

The interactions of these particles with background photons, such as the cosmic microwave background (CMB) and the cosmic infrared background (IRB), which produce secondary particles like neutrinos, muons, pions, and electrons, are another reason why the course of cosmic rays is not straight. These interactions cause energy losses in addition to altering the particle's trajectory. Because of this, we consider them in our simulations, and secondary gamma rays are also spread throughout the universe.

3. Simulation setup

We employ the open-source CRPropa3 (Batista et al. 2016) software for our simulations. This program allows for some individual inputs and simulates particle propagation through the universe using the Monte Carlo approach. For instance, the kind of injected particles (nuclei, photons, or neutrinos), the distance to the source, the maximum energy of the particles, the energy losses, and the cosmic ray composition can all be altered. Our initial source is Centaurus A (NGC 5128), one of the closest radio galaxies (~ 3.66 Mpc) with a wealth of literature, aside from the discovery of a particle hotspot originating from Centaurus A's direction(Matthews 2018).

Three factors are taken into account in order to compute the maximum energy that any source can provide: g_{ac}, g_{cr}, and L_ν (Eichmann, 2018). The efficiency with which the particles accelerate within their sources is related to the factor g_{ac}. Stated differently, the relationship between the energy a particle can absorb and the energy a source can release. In contrast, the efficiency with which accelerated particles transform into cosmic rays that travel across the universe is shown by the g_{cr} factor. The source's luminosity at a frequency of ν is indicated by L_ν. The chosen frequency is 1.1 GHz, which is present in radio spectra, since we are simulating radio galaxies. All these factors are used to obtain

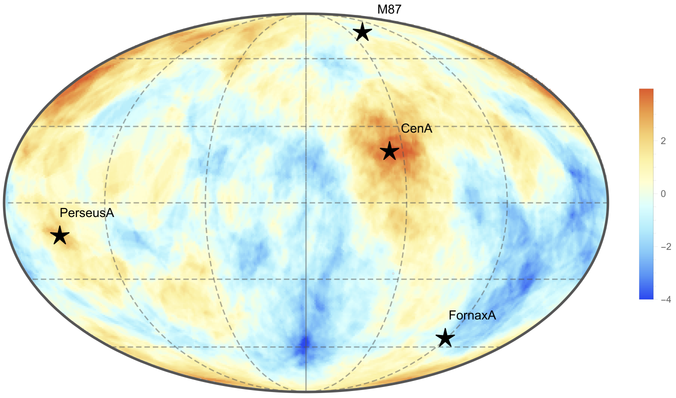

Figure 1. Skymap with the 4 of the most bright radio-galaxies and arrival directions hotspots.
Source: Adapted from Anjos et al. (2018)

the equation 1 (Oliveira, 2021), which is used to calculate R_{max},

$$R_{max} = 15 g_{ac} \sqrt{1 - g_{cr}} \left(\frac{L_{1.1}}{10^{40} erg/s} \right)^{3/8} eV, \tag{1}$$

a new parameter that represents the stiffness of the accelerating environment (Eichmann, 2018). It is impossible to accelerate particles to energies above $E_{max} = ZeR_{max}$, our limit given by Hilla's plot, where Z is the atomic number of the nucleus and e is the elementary charge. Thus, the maximum energy with which a source can accelerate a particle depends on its electromagnetic environment. For Centaurus A $g_{ac} \in [0.1, 0.8]$ and $g_{cr} \in [0.1, 0.8]$, where $g_{cr} = 4/7$ is the ideal value due to the energy equipartition (Eichmann, 2018). The luminosity of $L_{1.1}$ (GHz) was taken from van Velzen's 2012 catalog (van Velzen 2012).

The generated data do not take into account the Earth's rotation or the Observatory location, resulting in a source exposure of 100%. For this reason, the simulated data must be weighted, which is calculated via the equation 2, where D_s is the distance between the source and the Earth, z is the redshift of the source, and W_s is the source weighting, which is given by the equation 3 (Anjos 2014):

$$P_s = \frac{W_s}{4\pi D_s^2 (1+z)}, \tag{2}$$

$$W_s = \frac{\omega_s}{\pi \sin^2 \theta_{max}}. \tag{3}$$

The relative exposure of the source, or the "percentage" of time that the Observatory may see a certain direction, is denoted by the term ω_s. This value is dependent upon the zenith of the Observatory, θ_{max}, and its right ascension, α. In other words, the highest maximum energy a particle may be accelerated to is $E_{max} = 10^{21.21}$ eV, which is the result of combining the highest value of g_{ac} with the lowest value of g_{cr}. Conversely, the lowest feasible maximum energy, $E_{max} = 10^{19.98}$, is achieved with the lowest g_{ac} and highest g_{cr}. $8.18 \cdot 10^{-4}$ is the final weight P_s applied to the simulated data. Table 1 illustrates the four distinct cosmic ray compositions that were injected at the source and subsequently propagated.

4. Results and analysis

Plotting the observed particle flux by energy enables us to examine several features of the source's acceleration mechanisms.

Table 1. Distinct injections at the source components that are modeled on CRPropa3. These were selected to reflect the makeup of light (H), medium (N), and heavy (Si) cosmic rays in comparison to what the Pierre Auger Observatory detects (Mixed). (Aloisio, Berezinsky and Blasi, 2014).

Composition	H %	He %	N %	Si %	Fe %
H	100	0	0	0	0
N	0	0	100	0	0
Si	0	0	0	100	0
Mixed	76.9	15.4	4.6	2.3	0.8

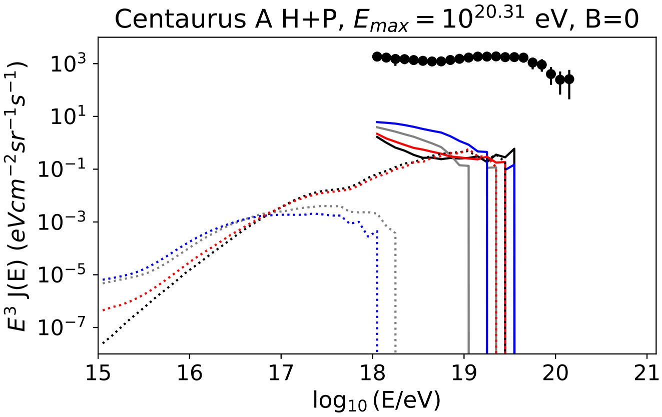

Figure 2. Flux by energy of various compositions of injected cosmic rays, $g_{ac} = 0.1, g_{cr} = 0.1$. Dotted lines represent secondary photons, and solid lines represent hadrons. Pure H compositions are represented by black lines, pure N compositions by grey lines, pure Si compositions by blue lines, and mixed compositions by red lines. Scattered points refers to Pierre Auger Observatory data (Pierre Auger Collaboration, 2021).

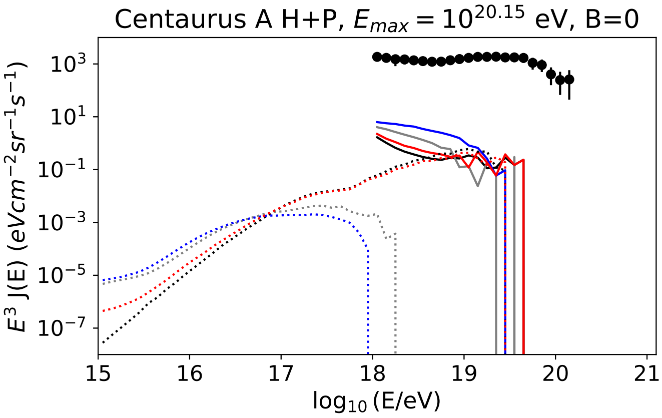

Figure 3. Energy flux of various injected cosmic ray compositions with $g_{ac} = 0.1, g_{cr} = 4/7$.

Figures 2, 3, and 4 illustrate how the spectrum detected ($g_{ac} = 0.1$ is fixed) is affected by variation in the parameter g_{cr}, whereas figures 3, 5, and 6 illustrate the effects of parameter g_{ac} on the spectrum ($g_{cr} = 4/7$ is fixed). Cosmic rays can reach higher energy levels the more effective a source is at accelerating particles, and the more energy wasted in the process of forming cosmic rays, the less energy available for the acceleration environment.

For hadrons, it can be seen that changes in g_{ac} strongly affect the spectrum, suggesting that this parameter has a significant effect on the acceleration of the nuclei, which was already expected.

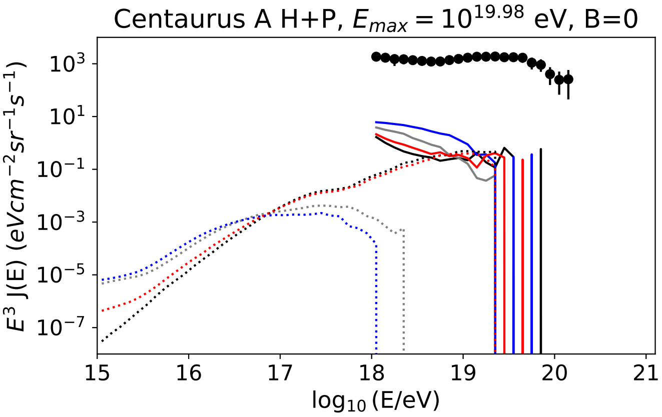

FIGURE 4. Energy flux of various injected cosmic ray compositions with $g_{ac} = 0.1, g_{cr} = 0.8$.

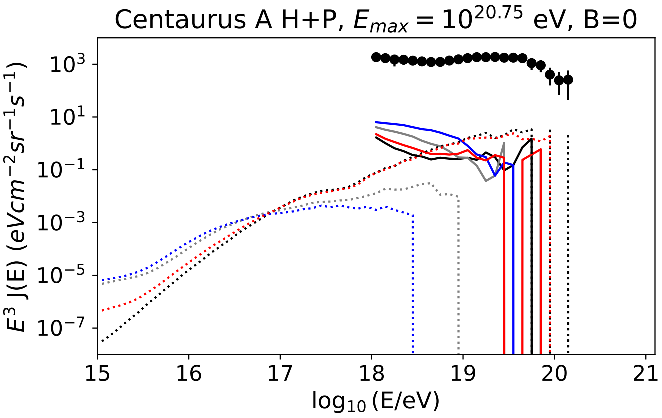

FIGURE 5. Energy flux of various injected cosmic ray compositions with $g_{ac} = 0.4, g_{cr} = 4/7$.

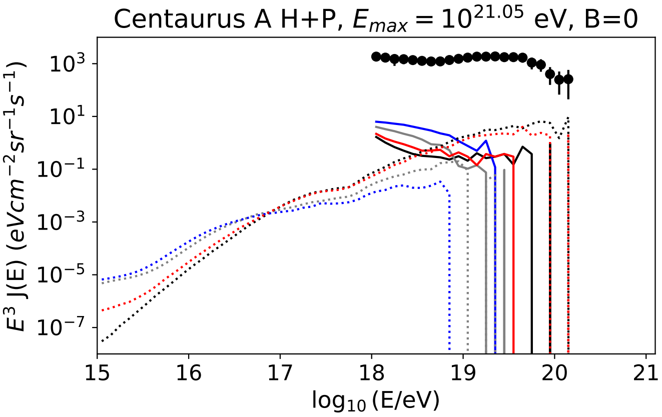

FIGURE 6. Energy flux of various injected cosmic ray compositions with $g_{ac} = 0.8, g_{cr} = 4/7$.

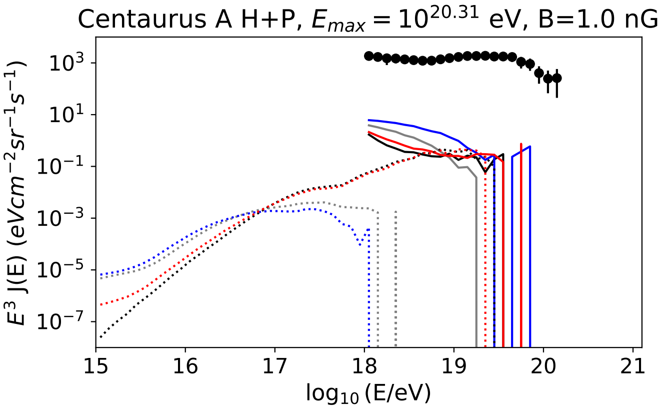

FIGURE 7. Energy flux of various injected cosmic ray compositions with $g_{ac} = 0.1, g_{cr} = 0.1$ and magnetic field.

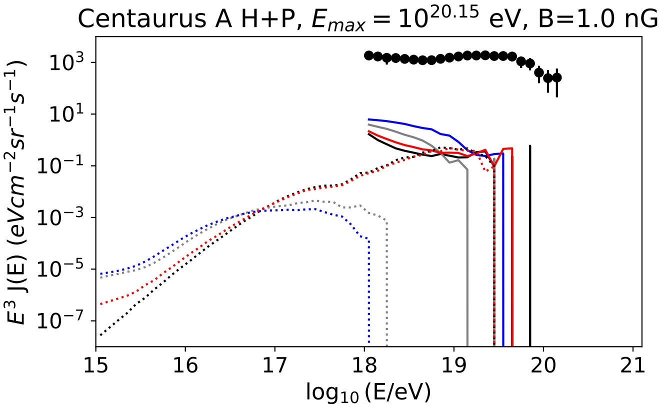

FIGURE 8. Energy flux of various injected cosmic ray compositions with $g_{ac} = 0.1, g_{cr} = 4/7$ and magnetic field.

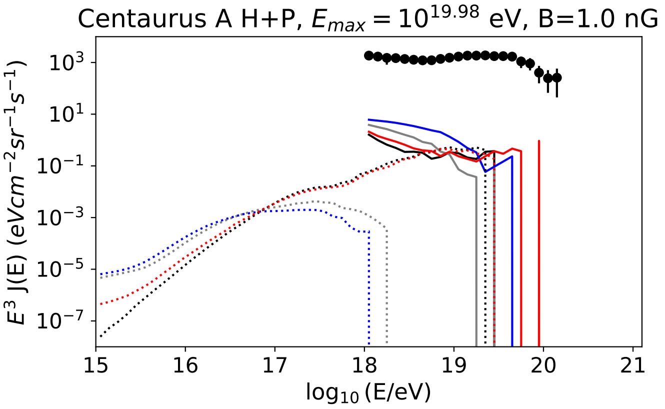

FIGURE 9. Energy flux of various injected cosmic ray compositions with $g_{ac} = 0.1, g_{cr} = 0.8$ and magnetic field.

On the other hand, changes to g_{cr} have minimal impact on the spectrum; flux values (the quantity of particles observed) make up the major contribution. These effects may also be confirmed for secondary photons; g_{ac} variation has a significant influence on maximum energy, whereas g_{cr} variation has little effect on spectra.

The variations in the spectra are displayed in Figures 7, 8, and 9 when $g_{ac} = 0.1$ is held constant and an extragalactic medium-permeating magnetic field with an intensity of 1.0 nG is assumed. Despite Centaurus A's proximity to Earth cosmologically, it is anticipated that its spectra would differ significantly depending on whether the magnetic field is present or absent. The observed simulated phenomenon lacks a logical physical explanation, and its observation can be ascribed to an oversimplified magnetic field model that might not accurately reflect reality.

It is conceivable to confirm that, at higher energies ($E > 10^{17}$ eV), lighter compositions result in a larger flow of secondary photons, while heavier compositions are associated with a higher flux of hadrons when both hadrons and photons are studied. This can be explained by the energy lost during propagation, but to put it briefly, heavier nuclei can interact and divide into more nuclei, whereas lighter nuclei have a lower energy threshold for photodesintegration, producing more secondaries. The differences in spectral properties of hadrons and photons are critical for determining what type of astronomical object may be the source of ultra-high energy cosmic rays, which will be more feasible with a detected spectrum for gamma rays.

5. Conclusions

It is worth noting that radio galaxies are strong candidates for cosmic ray sources, and their acceleration mechanisms match the spectrum found by the Auger Observatory. These encouraging results with Centaurus A compel us to investigate and simulate other radio galaxies to see if they, too, exhibit strong agreement with the facts. Secondary particle analysis will also aid in better characterizing the acceleration mechanisms of radio galaxies. On the same page, a better understanding of how the extragalactic magnetic field is spread, which leads to more accurate models being built and incorporated into software, is critical to the development of knowledge about likely origins of cosmic rays.

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