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Radio-galaxies as ultra-high energy cosmic rays sources

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Abstract. Ultrahigh-energy cosmic rays (above 1 EeV) are an astrophysical phenomenon whose source is unknown. Near Earth radio galaxies (< 50 Mpc distance), in particular Centaurus A, M87 and Fornax A, are considered to be one of the main sources of ultrahigh energy cosmic rays, as demonstrated by the Pierre Auger Collaboration. Cosmic rays are deflected in the intergalactic and intragalactic medium by interaction with electromagnetic fields and/or other particles. In this work, we study in detail radio galaxies and describe the influence of their properties as plausible sources of cosmic rays using the CRPropa3 software. We compare our results with data from the Pierre Auger Observatory to understand the mechanisms involved in the acceleration of particles and the impact of the interactions between particles from these sources on their propagation in the Universe.

Resumo. Raios cósmicos de altíssimas energias (acima de 1 EeV) são fenômenos astrofísicos sem uma origem definida. Considera-se as radiogaláxias próximas à Terra (< 50 Mpc de distância), especialmente Centaurus A, M87 e Fornax A, como um dos grupos das principais fontes de raios cósmicos ultra-energéticos, resultado este mostrado pela Colaboração Pierre Auger. Raios cósmicos sofrem desvios no ambiente intergaláctico e intragaláctico, ocasionados por interações com campos magnéticos e/ou outras partículas. Neste trabalho estudamos com detalhes radiogaláxias e descrevemos a influência de suas características como possíveis fontes de raios cósmicos utilizando o programa CRPropa3. Nossos resultados são comparados com os dados do Observatório Pierre Auger para melhor compreensão de quais mecanismos estão envolvidos na aceleração de partículas e quais os efeitos das interações das partículas provenientes destas fontes durante sua propagação pelo Universo.

Keywords. particle acceleration – 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 diagram Hillas, (1984), 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.

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 intergalactic medium until they arrive on Earth and are detected. This propagation does not occur in a straight line because of a number of factors. One of the main causes of this non-straight line propagation is the presence of magnetic fields inside and outside our galaxy, which deflect charged particles (cosmic rays) from their trajectory due to the Lorentz force. These magnetic fields were not considered in our simulations at first.

Another reason why the trajectory of cosmic rays is not straight is the interactions of these particles with background photons, such as the cosmic microwave background (CMB) and the cosmic infrared background (IRB), creating secondary particles such as neutrinos, muons, pions, and electrons. These interactions not only change the trajectory of the particles but also lead to energy losses. For this reason, we take them into account in our simulations.

3. Simulation setup

For our simulations, we use the open-source CRPropa3 (Batista 2016) software. This software uses the Monte Carlo method to simulate the propagation of particles through the universe, and allows some individual inputs. For example, it is possible to change the data of the particles (nuclei, photons, neutrinos), the distance to the source, the maximum particle energy, the energy losses, and the composition of the cosmic rays. For our first source, we have chosen Centaurus A (NGC 5128), one of the nearest radio galaxies (~ 3.6 Mpc) about which there is extensive literature, apart from the existence of a hotspot of particles coming from the direction of Centaurus A (Matthews 2018).

First, we determine which particles to store. We created two observers: one detected incoming nuclei, the other incoming gamma rays. These cosmic rays were simulated with different compositions: H, He, N, Si, Fe, and Auger composition (76.9% H, 15.4% He, 4.6% N, 2.3% Si, 0.76% Fe) (Oliveira, 2021).

The maximum energy that each source can provide is calculated by considering three factors: gac, g_{cr}, and L_ν. The factor g_{ac} is related to the efficiency with which the particles accelerate within their sources. In other words, the ratio between the energy that a particle can use and the energy that a source can emit. the g_{cr} factor, on the other hand, indicates the efficiency with which accelerated particles become cosmic rays that propagate in the universe. L_ν indicates the luminosity of the source at a frequency ν. Since we are simulating radio galaxies, the frequency chosen is 1.1 GHz, as found in radio spectra. All these factors are used to obtain the equation 1 (Oliveira, 2021), which is used to calculate R_{max}, a new parameter that represents the stiffness of the

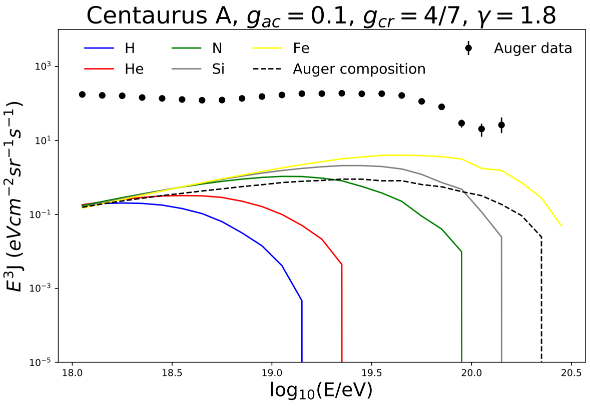

Figure 1. Graphic comparing different compositions spectra, with $g_{ac} = 0.1, g_{cr} = 4/7$ and $\gamma = 1.8$. E$_{max} = 10^{20.15}$eV.

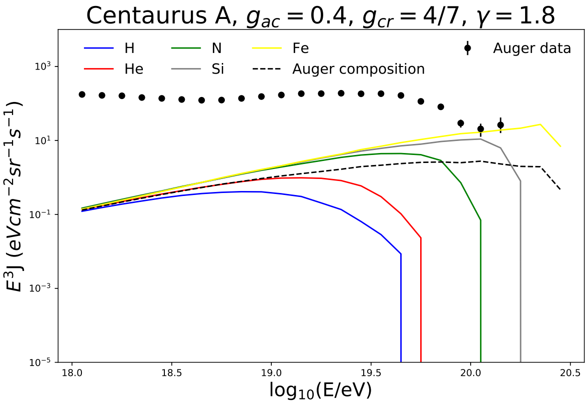

Figure 2. Graphic comparing different compositions spectra, with $g_{ac} = 0.4, g_{cr} = 4/7$ and $\gamma = 1.8$. $E_{max} = 10^{20.55}$eV.

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.

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

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 $g_{cr} \in [0.1, 0.9]$, where $g_{cr} = 4/7$ is the ideal value due to the energy equipartition (Eichmann, 2018). The luminosity of $L_{1.1}$ (GHz) was measured 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 term ω_s is the relative exposure of the source, the "percentage" of time that the Observatory can observe a given direction. This value depends on its right ascension α and the zenith of the Observatory, $\theta_{\max}$.

4. Results and analysis

We can apply weighting and plot the flux of detected particles against the energy. Figures 1, 2, and 3 show how the variation g_{ac} changes the spectrum in the source. The more efficient a source is at accelerating particles, the higher energy levels can be achieved by cosmic rays. Figures 1, 4, and 5 show us how the varying spectral index γ shapes the spectrum. 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. Changes to g_{cr}, on the other hand, have little effect on the spectrum, with the largest contribution being the flux values (the number of particles detected).

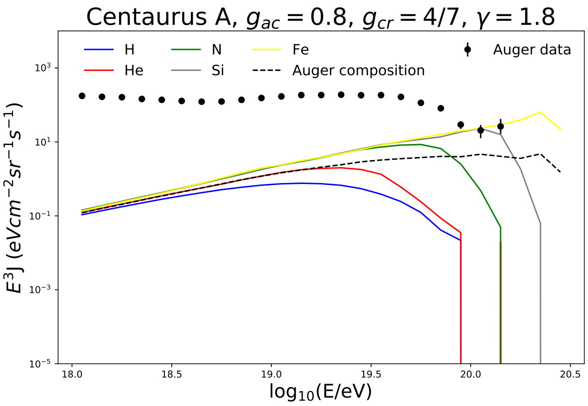

Figure 3. Graphic comparing different compositions spectra, with $g_{ac} = 0.8, g_{cr} = 4/7$ and $\gamma = 1.8$. $E_{max} = 10^{21.05}$eV.

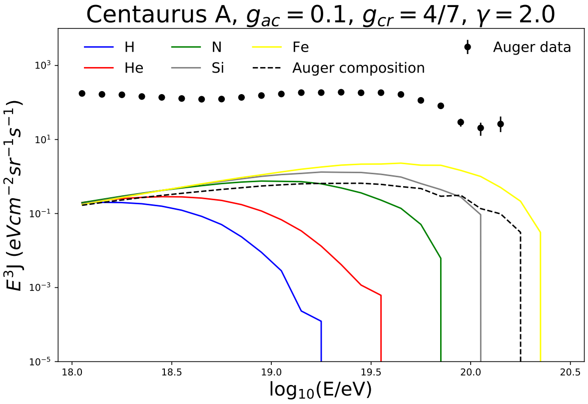

Figure 4. Graphic comparing different compositions spectra, with $g_{ac} = 0.1, g_{cr} = 4/7$ and $\gamma = 2.0$. $E_{max} = 10^{21.05}$eV.

Changes in the spectral index γ make the loops smoother, especially at the end of the spectrum. Lower indices are best for displaying spectra with higher energy.

5. Conclusions

It is noteworthy that radio galaxies are strong candidates for sources of cosmic rays and, moreover, their acceleration mechanisms agree well with the spectrum detected by the Auger

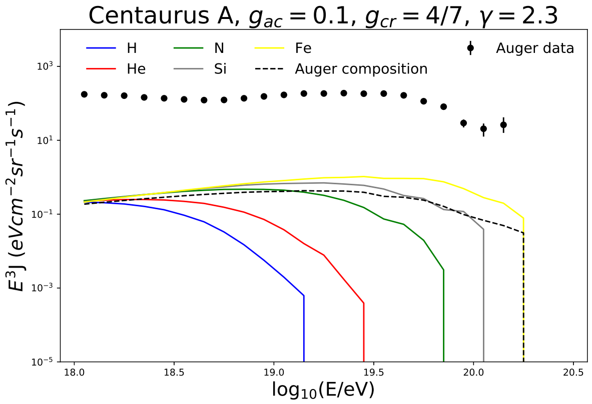

Figure 5. Graphic comparing different compositions spectra, with $g_{ac} = 0.1$, $g_{cr} = 4/7$ and $\gamma = 2.3$. $E_{max} = 10^{21.05}$eV.

Observatory. These favorable results obtained with Centaurus A prompt us to check and simulate other radio galaxies to see if they also show good agreement with the data. The study of secondary particles may also help us better characterize the acceleration mechanisms of radio galaxies. Another possible analysis can be done with observed gamma rays, which has not yet been done but is planned as we study more radio galaxies and collect more data.

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