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Impact of background radiation on the ultra-high-energy cosmic-ray composition

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Abstract. This paper examines how ultra-high-energy cosmic rays (UHECRs) interact with the intergalactic medium and spread through cosmic background radiation. We investigate the relationships between particle interactions and cosmic ray composition using CRPropa3 software simulations. Our results provide insight into the behavior of these particles with respect to different cosmic background radiations by revealing a robust link between interaction levels and cosmic ray composition. The goal of this work is to further our understanding of UHECR sources and how they behave in the Universe at ultra-high energy.

Resumo. Este estudo investiga a propagação de raios cósmicos ultra-energéticos (UHECRs) através da radiação cósmica de fundo e suas interações no meio intergaláctico. Utilizando o software CRPropa, exploramos as correlações entre as interações de partículas e a composição dos raios cósmicos. Nossos resultados revelam uma forte correlação entre os níveis de interação e a composição dos raios cósmicos, fornecendo insights sobre o comportamento dessas partículas em relação a diversas radiações cósmicas de fundo. Esta pesquisa tem como objetivo contribuir para uma compreensão mais profunda das fontes de UHECRs e seu comportamento em energias ultra-altas no Universo.

Keywords. Astroparticle physics – Cosmic Rays – Infrared: diffuse background

1. Introduction

As crucial messengers, ultra-high-energy cosmic rays (UHECRs) provide deep insights into the extreme astrophysical phenomena dispersed throughout our Universe. This study attempts to examine and contrast Xmax (1) (distribution of the depth of maximum) simulations run by CRPropa3 (2), providing insight into the various interactions and energy losses that these high-energy particles experience during their interstellar journey (3).

Cosmic rays are emitted from sources such as supernovae, pulsars, active galactic nuclei, and starburst galaxies (4). During their epic journey, they interact with various components of cosmic background radiation and are deflected by extragalactic and Galactic magnetic fields (6). There are several different types of this background radiation, including: Cosmic Microwave Background (CMB): Remnant radiation from the early universe, providing insights into the universe's early stages; Extragalactic Background Light (EBL): A range of wavelengths from infrared to ultraviolet emitted by stars, galaxies, and active galactic nuclei, crucial in understanding cosmic evolution; Galactic Background Radiation: Emissions from within our Milky Way include synchrotron radiation and infrared radiation from interstellar dust; Radio (URB), Infrared (IRB), Ultraviolet, and X-ray Background: These radiations span different energy spectra and come from various astrophysical sources, contributing to our understanding of cosmic phenomena (8; 9).

Along this arduous path, cosmic rays endure energy dissipation mechanisms, including photodisintegration, pair production, and pion production, engendering the emergence of neutrinos and gamma rays and instigating particle cascades spanning a spectrum of energy regimes (7). The culmination of this voyage culminates in the arrival of these particles at Earth, where the Xmax parameter serves as a pivotal tool for discerning their composition. Xmax represents the depth in the atmosphere at which an extensive air shower initiated by a cosmic ray reaches its maximum number of secondary particles. Employing CRPropa3, our investigation comprehensively analyzes the resulting Xmax simulations. This allow us to get enhanced insights into the intricate interactions and consequential energy losses experienced by ultra-high-energy cosmic rays.

Essentially, this comparative study advances our understanding of the makeup and behavior of UHECRs and substantially contributes to the current search for their cosmic sources. As the effect of the Radio Background Light (URB) is the least understood, our work focuses on analyzing its effects as well as the impact of larger distances on the composition, which is directly related to the amount of background radiation to which the cosmic ray is exposed prior to reaching Earth. Because we use simulations to study the UHERCS, we also need to consider carefully the models we choose to run the simulations. To better understand the effects of this decision on the final composition, we also compared the IRB models that researchers typically use for these kinds of simulations.

2. Results

For this work, we simulated 10^7 particles leaving the source, with different compositions to examine the regions where our targeted impacts were more significant. We used the composition found by Auger (1): P - 0.59; He - 0.053; N - 0.32 e Fe - 0.038. The hadronic model utilized was the EPOS-LHC, as it usually gives the best results (5). We also included the lines for the other two primary models for comparison.

2.1. Radio Background Light effect

Based on our analysis, the mixed composition (1) and intermediate compositions (2) exhibited the most compositional shifts, less present on heavier compositions (3). Another intriguing finding was that, despite URB having a lower energy radiation,

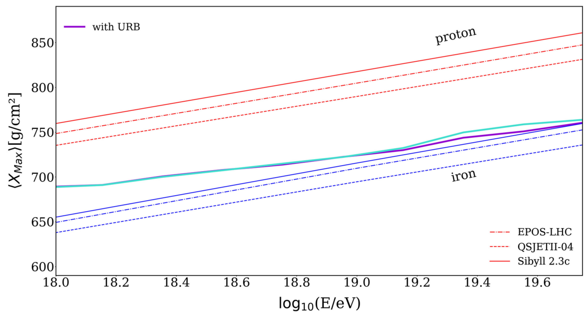

Figure 1. The URB effect with Pierre Auger Composition

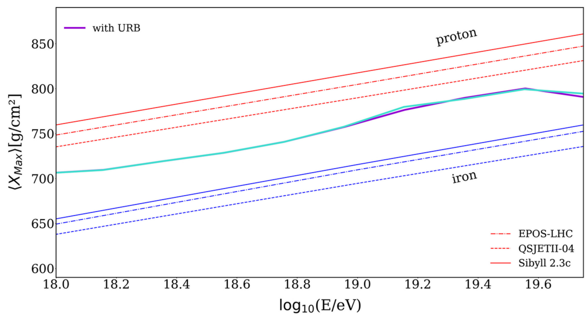

Figure 2. The URB effect with Nitrogen composition

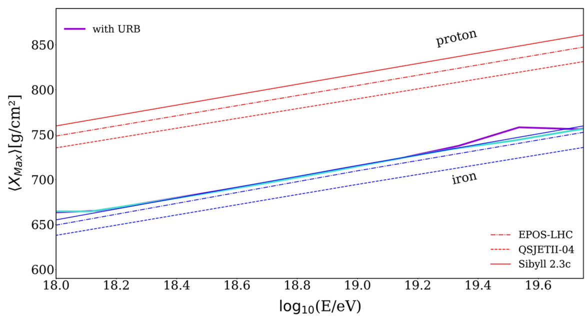

Figure 3. The URB effect with iron composition

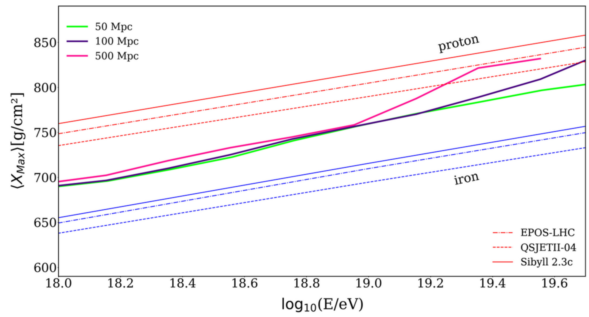

Figure 4. The URB effect on only N leaving the source

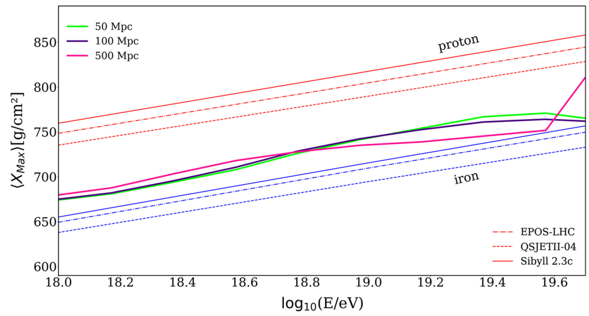

Figure 5. The URB effect on only Fe leaving the source

the effect was more pronounced on particles with greater energies.

2.2. Distance effect

Analogous results to the previous analysis were obtained for the various distances, indicating larger impacts at higher energies and on the compositions of medium mass (e.g., N) (4), and less on the heavier compositions (5). As expected, the further the cosmic ray has to travel, the bigger the effect of the EBL on the composition, which is explained by the many possible mechanisms of interaction discussed before. The next step is to quantify this effect, to further understand the presence of this different radiations and it's interactions with the UHERCS.

2.3. Infrared Background models

The infrared background model is constructed with various approaches, including phenomenological, semi-analytical, empirical (Dominguez), and more (**?**). To learn more about the impact of this decision on the Xmax, we looked into the compositional result utilizing two models constructed using various techniques. The impact of the selected model is shown in the composition, especially for intermediate-weight (N) cosmic rays, where it becomes significant around 10^{19} eV energy threshold.(7), same effect also seen in the mixed composition (6). This highlights the importance of carefully choosing the Infrared Background (IRB) model when doing propagation models. Furthermore, a future study will measure the magnitude of this impact on the composition. Such an analysis is consistent with our goal of comprehending the complex relationship between the selected IRB model and cosmic-ray composition, an essential first step in determining the percentage contribution of this parameter to cosmic-ray behavior and composition.

3. Conclusions

Our study made it possible to quantify in detail the impact of the Extragalactic Background Light (EBL) on Ultra-High-Energy Cosmic Rays (UHECRs) that are heavier/intermediate elements. The observed differences between the produced findings, which are especially noticeable in the higher energy regimes, highlight how crucial it is to carefully choose a suitable EBL model when running simulations at these higher energy levels. These results underline the urgent need for a thorough investigation to foster a more profound comprehension of the influence of the Radio Background (URB) on the behavior and trajectories of cosmic rays. This kind of investigation becomes crucial for clarifying

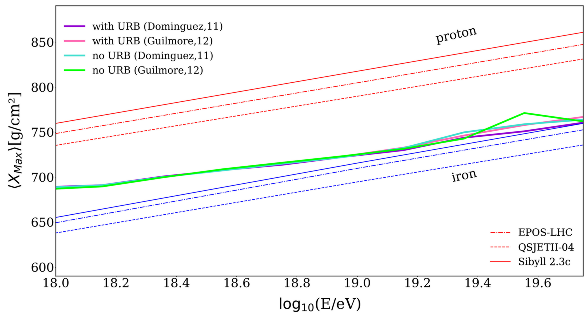

Figure 6. The effect of the IRB models on the Pierre Auger composition

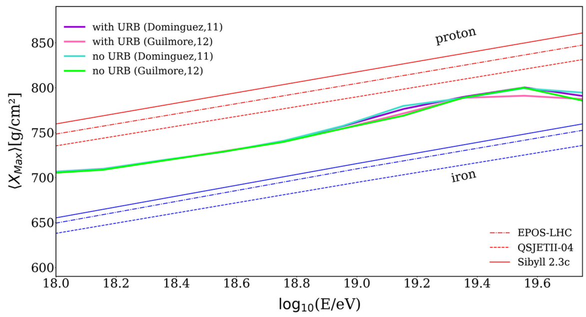

Figure 7. The effect of the IRB model on only N leaving the source

the complicated connections between the Radio Background and cosmic ray propagation mechanisms. It also provides important information about the intricacies of cosmic ray interactions in urban settings and their wider astrophysical consequences.

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