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Cosmic-ray ensembles resulting from synchrotron radiation: status and prospects of simulations

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Cosmic rays should obviously generate cascades of product particles while propagating in space as a result of interactions with fields, radiation and matter. Such phenomena, referred to cosmic-ray ensembles (CRE), are expected to differ in shapes, sizes and constituents, and thus became a key point of the Cosmic-Ray Extremely Distributed Observatory (CREDO) Collaboration scientific program. The research dedicated to comprehensive studies of CRE requires an alternative approach to the detection of cosmic rays, taking into account their spatial and/or temporal correlations on the global scale. However, a potential observation of at least parts of CRE at Earth could make a valuable contribution to the up-to-date cosmic ray astrophysics, even though it poses a technical challenge. One of the most common scenarios of CRE formation is the synchrotron radiation of charged particles propagating in omnipresent magnetic fields. We present the updated results of CRE simulations for this case, discussing the physics conditions favourable for the observation of such particle cascades, as well as practical perspectives of this research direction.

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1. Introduction

The enigmatic nature of ultra-high energy cosmic rays (UHECR), characterized by energies exceeding $\geq 10^{18}$ eV, continues to intrigue the field of astrophysics. Despite extensive research, there is still no consensus on the sources and mechanisms responsible for their production. Theoretical models can be broadly categorized into two approaches: the "bottom-up" perspective, which explores the acceleration of charged particles to ultra-high energies at astrophysical objects like active galactic nuclei (AGN) [link], gamma-ray bursts (GRB)[link], and radio galaxy jets[link], and the "top-down" scenario, which considers the decay or annihilation of supermassive particles as the origin of UHECR [link]. Both models allow for the existence of UHE photons, albeit with varying estimates of their fraction within the UHECR flux.

Notably, the presence of UHE photons has profound implications for our understanding of fundamental physics. For instance, the study of UHE photons can serve as a testing ground for new physics scenarios, including Lorentz invariance violation (LIV) [link]. LIV predicts an increase in the mean free path of photons, resulting in an amplified photon flux. However, despite the theoretical expectations, the unambiguous detection of UHE photons has remained elusive, imposing constraints on certain top-down models. This discrepancy between the predictions of theoretical models and experimental observations makes the search for UHE photons a compelling and ambitious endeavor.

It is important to acknowledge that interpreting UHECR data is a complex task due to the inherent uncertainties in extrapolating interaction models from lower energies to the UHE range. As a consequence, the absence of registered UHECR photons may be imprecisely attributed to their limited chances of reaching Earth, as a result of interactions with fields, radiation, and matter during propagation. Such interactions inevitably give rise to particle cascades known as cosmic-ray ensembles (CRE). Understanding the characteristics, composition, and spatial extent of these CRE is of great significance for advancing our knowledge of UHECR astrophysics.

While traditional cosmic ray experiments primarily focus on the detection and analysis of individual cosmic rays, progress in studying globally correlated cosmic particles on a large scale has been slower, mainly due to the challenges associated with hardware requirements. To overcome this limitation, the Cosmic-Ray Extremely Distributed Observatory (CREDO) Collaboration [link] has embarked on an innovative research program aimed at investigating CRE phenomena. By harnessing existing detector arrays and individual devices, regardless of their size or type, the collaboration seeks to create a widespread network for joint data analysis, providing a unique perspective on cosmic-ray astrophysics.

In this paper, we present an extension of a method for simplifying the processing of CRE simulation results, specifically focusing on the possible shapes and distributions of the constituents of a CRE. Our simulations consider synchrotron radiation, a universal process occurring in every astrophysical environment. By simulating the formation of particle cascades, we focus on UHE electrons as the primary particles, assuming their acceleration or production through pair production by UHE photons.

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2. Simulation tools

The research conducted by the CREDO collaboration is driven by an ambitious objective of enabling a comprehensive global study of cosmic ray data, encompassing a diverse range of astrophysical scenarios to be explored in the future. Therefore, the selection of software for simulating the propagation of particles in space is motivated by the need to account for an expanding array of astrophysical processes and phenomena. CRPropa 3 [link!], a fundamental option for simulating the propagation of cosmic ray particles and the subsequent formation of cosmic-ray ensembles (CRE), stands out as a widely utilized Monte Carlo code in the field. This state-of-the-art software facilitates the simulation of various particle types, including photons, leptons, and nuclei, within astrophysical environments. It takes into account interactions with background radiation, fields, matter, and cosmological effects. CRPropa 3 follows modular code standards, where essential simulation aspects, such as sources, observers, interactions, magnetic fields, and breaking conditions, are implemented as separate modules, allowing for customization and flexibility.

CRPropa 3 proves to be a valuable and versatile tool for addressing a broad range of high-energy astrophysics problems. Its official website [link!] serves as a comprehensive resource, providing users with updates, usage examples, and tutorials, ensuring efficient utilization of the software's capabilities. Whether modifying existing modules or developing new ones in C++ or Python, users can seamlessly combine and sequence these modules to suit their specific research objectives.

In addition to CRPropa simulations, another crucial software tool used for post-processing purposes was the CRE-Pro script, which is extensively discussed in [reference]. The preliminary results obtained using this script have been demonstrated in [link]. These cited articles focus on conducting a detailed study of synchrotron radiation emitted by charged particles in motion. Such investigations aim to highlight synchrotron radiation as one of the most common and inevitable energy loss mechanisms occurring in regions permeated by electromagnetic fields, which is essentially everywhere. To ensure universality, our simulations encompass the motion of primary ultra-high energy electrons, considering that these particles can be either accelerated to their energies or produced as a result of energy loss processes from more energetic particles.

The number of synchrotron photons generated in a simulation run depends on several input parameters, including the energy range between the starting energy of the parent electron, denoted as E, and the energies of the emitted photons. To avoid computational resource limitations, the lower limit of the emitted photon energies is set to prevent an excessive demand on computational resources. As a result, typical simulation runs may involve the generation of billions of synchrotron photons. By omitting the linear propagation of these photons, memory and time can be saved during the simulation process.

However, such a simplification has drawbacks, one of which is the loss of information on the precise coordinates of synchrotron photons after they are generated by the code, since it makes sense to store only their emission points. Fortunately, simple geometrical considerations (Figure 1) allow to estimate the size of the area on the observer surface where the photons should be confined.

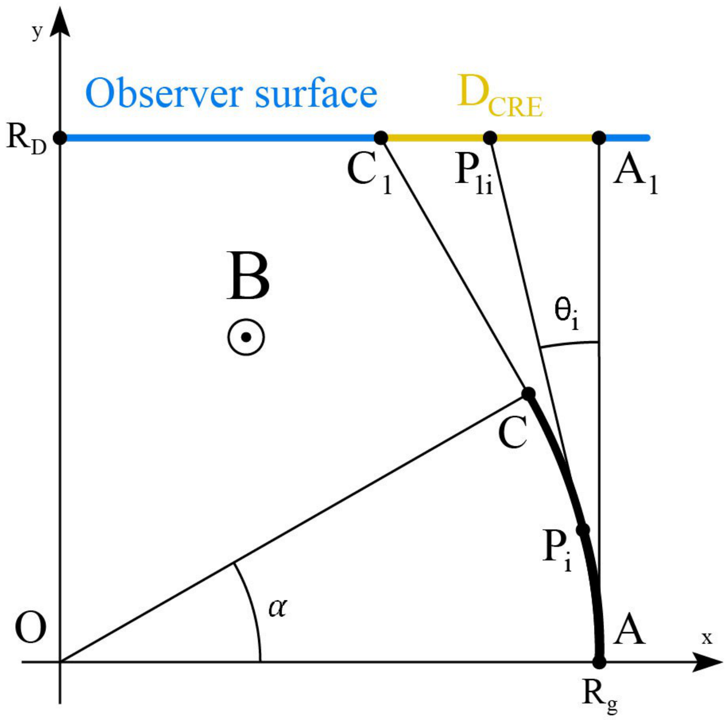

Figure 1: Post-processing of synchrotron photons with the CRE-Pro script. An electron propagates in a transverse magnetic field B along the arc AC of initial gyroradius R_g and angular size α, starting at a distance R_D from the observer surface. Emitted photons are spread within A_1C_1 region of D_{CRE}.

Omitting specific details, which can be found in the cited papers, we present here only the final expression for the size of the CRE:

$$D_{CRE} = R_g + R_D \tan\alpha - \frac{R_g}{\cos\alpha}, \quad (1)$$

where $R_g = E/ceB$ represents the gyroradius of the electron trajectory at its starting point, $\alpha \sim D_{step}/R_g$ corresponds to the angular size of the arc. In the majority of cases relevant to our simulations, the value of α is negligibly small since the arc can always be chosen small enough ensuring conservative treatment of physics parameters such as the magnetic field and the energy of the primary electron. This approach allows for the estimation of a maximal value for the CRE size, although it is informal in nature. What holds real importance is the precise knowledge of the distribution of synchrotron photons along the CRE. This information is crucial for studying the simplest CRE observation scenario - the 2 photon CRE, as previously explored in our papers. As we have omitted the propagation of photons within CRPropa, we have lost this information and must reintroduce it based on a reasonable model.

In this paper, we propose a more accurate method for estimating the distribution of photons across the observer plane. It is important to note that while the proportional distribution of photons has shown promise in our previous studies, it is not without limitations and may not be universally applicable. One has to realize that the angle between the start of the arc (at distance R_D from the plane) and the end of the arc (on the plane) is not α, because the path of the arc is not perpendicular to the plane.

We can find the angle of inclination of the arc with respect to the plane θ:

$$\theta = \arctan(\frac{R_D}{R_g * \alpha}). \tag{2}$$

Given that the angle is θ, the length of the arc projected onto the plane will be smaller than the original length of the arc. Specifically, the length of the projection can be calculated as $R_g * \alpha * \cos\theta$, where $\cos(\theta)$ accounts for the reduction in the apparent size of the arc due to its inclination relative to the plane.

As a result, the density of projected points is altered due to variations in the apparent length of different segments of the arc when projected onto the plane. To account for this density change, we need to "stretch" the projected arc by a factor of $1/\cos(\theta)$ to restore its actual length. Consequently, the density of points on the projected arc is increased by a factor of $1/\cos(\theta)$ compared to the density of points on the original arc. Furthermore, it's important to note that θ is not constant along the arc, except in cases where the arc is part of a helix. Therefore, the scaling factor for density will vary along the length of the arc in general. However, in situations where the arc is negligibly small, which is typically the case in the astrophysical conditions we study, this refinement becomes practically indistinguishable from the proportional approach and can be safely omitted.

The other improvement of calculating the distribution of photons along the observer surface, is related to introducing the so-called synchrotron cone, within which the intensity of synchrotron radiation is believed to be confined [link]. While the opening angle of the synchrotron cone is negligibly small (proportional to reciprocal of the electron's Lorentz factor) for ultra-high energies, it still induces changes at significant observer distances. Consequently, instead of a linear arrangement of photons along A_1C_1 as shown in Figure 1, we anticipate a transformation where each point is replaced by an ellipse. This modified two-dimensional pattern, characterized by ellipsoidal footprints, more accurately reflects the observed shape of particle cascades on the ground, leading to improved results.

3. Results

to be added during editing

4. Summary

to be added during editing

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References

[1] .... to be added during editing