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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" [1] perspective, which explores the acceleration of charged particles to ultra-high energies at astrophysical objects like active galactic nuclei, gamma-ray bursts, and radio galaxy jets, and the "top-down" scenario, which considers the decay or annihilation of supermassive particles as the origin of UHECR [2]. Both models allow for the existence of ultra-high energy (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) [3]. 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 [4] 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 [5], 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 proves to be a versatile tool for addressing a broad range of high-energy astrophysics problems. Its official website [6] serves as a comprehensive resource, providing users with updates, usage examples, and tutorials, ensuring efficient utilization of the software's capabilities.

In addition to CRPropa simulations, another crucial software tool used for post-processing purposes was the CRE-Pro script, which is extensively discussed in [7]. The preliminary results obtained using this script have been demonstrated in [8]. 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 (Fig. 1) allow to estimate the size of the area on the observer surface where the photons should be confined.

Omitting specific details, which can be found in [7], we present here only the final expression for the size of the CRE:

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

where $R_g = E/ceB$ represents the gyroradius of the electron trajectory at the starting point of the arc D_{step} long, $\alpha \sim D_{step}/R_g$ 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 two-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.

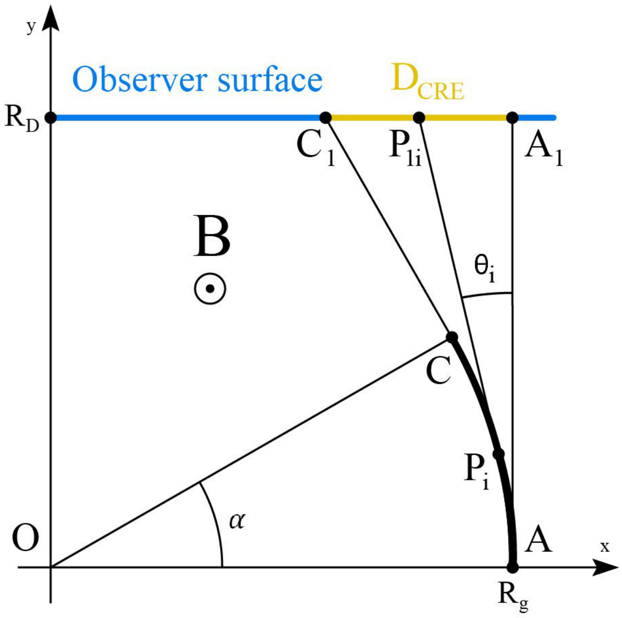

Figure 1: Post-processing of synchrotron photons with the CRE-Pro script. An electron propagates in a transverse magnetic field B along the arc AC of initial gyroradius R_g, size D_{step} and angular size α, starting at a distance R_D from the observer surface. Emitted photons are spread within A_1C_1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

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:

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

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 $R_g \cdot \alpha \cdot \cos\theta$, 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.

Another 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 [9]. 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 Fig. 1, we anticipate a transformation where each point is replaced by an ellipse. This modified two-dimensional pattern, characterized by elliptical footprints, more accurately reflects the observed shape of particle cascades on the ground, leading to improved results.

In our approach, we have also considered the decrease in electron energy during its propagation using a simple method. Since the generated synchrotron photons generally have energies of the same order of magnitude, we assume a gradual energy loss by the electron, leading to corresponding changes in its Lorentz factor. Implementing these proposed enhancements involves calculating the inclination angle θ_i for each photon emitted at point P_i along the arc. This is followed by computing the opening angle of the associated cone, considering the linear decrease in the Lorentz factor along the arc. Furthermore, we incorporate a Gaussian angular distribution for the photons within their cones, while the azimuthal angle is randomly selected.

3. Results

Using the enhancements of the CRE-Pro script described above to additionally analyze the outputs of CRPropa simulations (with the primary electrons ejected from the Galactic centre towards the Solar system and the Galactic magnetic field described by JF12 model [10]), we conducted a series of tests to demonstrate the new capabilities and emphasize the differences. The most significant difference between the current script features and the previously used version is, as already pointed out, the formation of a two-dimensional footprint of a CRE arriving at the observer plane (Fig. 2).

Electromagnetic cascades, originating from UHE photons in geomagnetic or Solar magnetic fields (e.g., [11, 12] respectively), fall into a particular scenario of CRE origination. They are expected to produce elongated footprints on the top of the Earth's atmosphere as well as on the ground. We simulated such CRE for several values of the primary electron energy at specific observer distances. As one can see from Tab. 1, the photon distribution can indeed be extrapolated to an extremely oblate ellipse, which is consistent with expectations. However, since its shorter axis has a non-negligible length, additional studies of the photons distribution within it are possible.

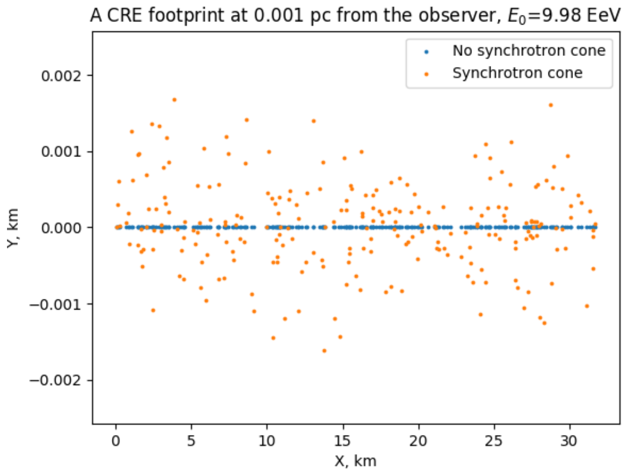

Figure 2: Example footprint of a CRE with and without the synchrotron cone option.

L	$\log(E_0/eV)$							
	16.5	16.8	17.0	17.5	17.8	18.0	18.5	18.8
-3	$7.9 \cdot 10^{-6}$	$1.0 \cdot 10^{-7}$	$1.93 \cdot 10^{-7}$	$2.6 \cdot 10^{-7}$	$2.0 \cdot 10^{-7}$	$1.2 \cdot 10^{-6}$	0.17	0.14
-2	$7.5 \cdot 10^{-7}$	$4.7 \cdot 10^{-7}$	$5.6 \cdot 10^{-7}$	$8.9 \cdot 10^{-7}$	$1.5 \cdot 10^{-6}$	$3.8 \cdot 10^{-6}$	$1.6 \cdot 10^{-6}$	$2.9 \cdot 10^{-6}$
-1	$1.5 \cdot 10^{-7}$	$2.7 \cdot 10^{-7}$	$2.1 \cdot 10^{-7}$	$2.4 \cdot 10^{-7}$	$2.7 \cdot 10^{-7}$	$4.4 \cdot 10^{-7}$	$7.5 \cdot 10^{-6}$	$6.6 \cdot 10^{-6}$
0	$8.7 \cdot 10^{-8}$	$1.3 \cdot 10^{-7}$	$1.1 \cdot 10^{-7}$	$1.3 \cdot 10^{-7}$	$1.4 \cdot 10^{-7}$	$3.1 \cdot 10^{-7}$	$9.5 \cdot 10^{-7}$	$2.4 \cdot 10^{-6}$
1	$7.0 \cdot 10^{-8}$	$1.2 \cdot 10^{-7}$	$6.4 \cdot 10^{-8}$	$7.4 \cdot 10^{-8}$	$6.2 \cdot 10^{-7}$	$1.5 \cdot 10^{-7}$	$9.4 \cdot 10^{-7}$	$2.3 \cdot 10^{-6}$
2	$3.2 \cdot 10^{-8}$	$4.5 \cdot 10^{-8}$	$5.2 \cdot 10^{-8}$	$6.9 \cdot 10^{-8}$	$9.1 \cdot 10^{-8}$	$1.8 \cdot 10^{-7}$	$3.9 \cdot 10^{-7}$	$2.8 \cdot 10^{-6}$
3	$1.2 \cdot 10^{-8}$	$2.2 \cdot 10^{-8}$	$3.8 \cdot 10^{-8}$	$4.3 \cdot 10^{-8}$	$3.1 \cdot 10^{-8}$	$1.4 \cdot 10^{-7}$	$3.4 \cdot 10^{-7}$	$6.2 \cdot 10^{-7}$
4	$1.2 \cdot 10^{-8}$	$1.3 \cdot 10^{-8}$	$1.3 \cdot 10^{-8}$	$1.3 \cdot 10^{-8}$	$2.4 \cdot 10^{-8}$	$3.7 \cdot 10^{-8}$	$1.8 \cdot 10^{-7}$	$4.0 \cdot 10^{-7}$

Table 1: Fractions of ellipse axes for CRE footprints initiated by primary electrons with specific energies at certain observer distances; $L = \log(R_D/pc)$.

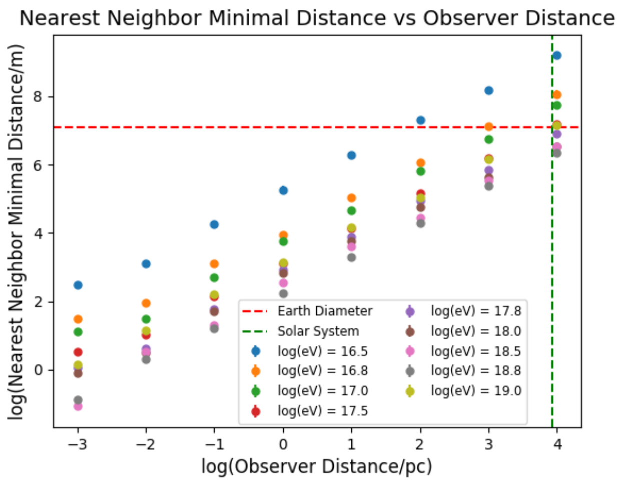

Figure 3: The minimal distance between two neighbour photons in the CRE footprint vs observer distance from the point of CRE initiation.

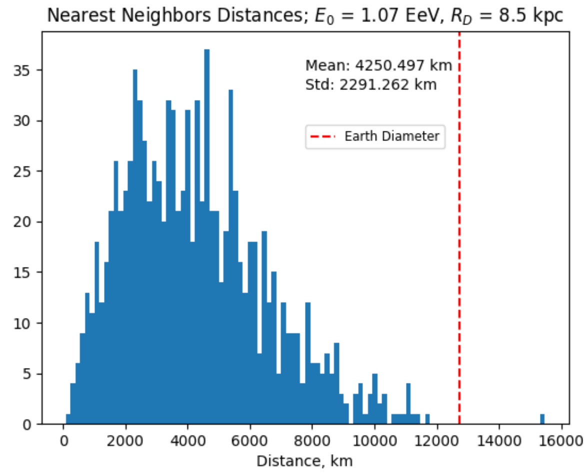

Figure 4: Minimal nearest neighbor distances between the photons in the CRE footprint. Out of 1024 entries, 1023 have values less than the Earth's diameter.

An illustrative example of the 2D photons distribution study is the calculation of the nearest neighbour distance, aiming to estimate the chances of a two photon CRE reaching the observer at a certain distance from the CRE origination point. Using the same set of input parameters (primary electron energies and observer distances), as displayed in Tab. 1, we can roughly estimate the "parameter space" favourable for two photons constituting the same CRE not to be separated with a distance exceeding the Earth's diameter (Fig. 3). For every pair of the input parameters, the simulation was repeated 10 times, but the standard error of the mean was too low to be noticeable in the plot for every value obtained. One may notice that, for the highest energies of the primary electron, there is a high chance of at least one two-photon CRE matching within the area of the Earth's size when propagating from the Galactic center region, even at distances comparable to the distance to the Solar system. To verify this conclusion, we repeated the simulation of the footprint of a CRE resulting from the propagation of a 1 EeV primary electron at a distance of 8500 pc from the Galactic center (roughly matching the Solar system distance). Only in 1 of 1024 cases the minimal nearest neighbor photon distance exceeded the size of the Earth. This estimation supports the overall assumption that two-photon CREs, originated by synchrotron emission of high-energy electrons, are not only possible on the area of the Earth's size but should also be a common occurrence.

4. Summary

When ultra-high energy electrons traverse through the Universe, they undergo various processes, with one of the most prominent being energy loss through synchrotron emission. This phenomenon arises due to the omnipresence of magnetic fields throughout the cosmos. Emitted synchrotron photons present a potential scenario for CRE, which is a focal point of interest within the scientific program of CREDO. This paper builds upon our previous study, aimed to estimate the conditions favorable for detecting a two-photon CRE within an area equivalent to the size of the Earth.

We discuss the improvements made to our algorithm aimed at increasing the reliability of the model used for simulating the distribution of product photons over the observer surface. The most significant enhancement involves the introduction of the synchrotron cone, which transforms the previously analyzed linear footprints of a CRE into two-dimensional patterns. The latter resemble those observed in experiments in the field of high-energy astrophysics and align with predictions within related scenarios. We provide examples of the photon distributions within these footprints and evaluate their shapes, offering potentially valuable insights for future investigations. The highlight of our current study is the demonstration of a significant probability of two-photon CREs, initiated by high-energy electrons, reaching the size of the Earth at observer distances of at least kpc scales. We plan to further extend our studies to account for different scenarios of CRE formation and anticipate that the use of the enhanced tool presented in this paper will be helpful in our research.

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