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Cherenkov radio emission from showers in dense media at EeV energies

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Abstract: The properties of extremely energetic neutrino- and cosmic ray-induced showers depend on the shower energy, on the type of particle initiating the shower, and on the medium. Studying these dependences is important both for understanding cascade phenomenology, and for estimating the efficiency of experiments using the radio technique. In this contribution we study the feasibility of applying 'thinning techniques' to the simulation of extremely energetic electromagnetic showers. We show that thinning is a powerful tool that allows a considerable reduction in computing time while keeping a good level of accuracy in the relevant shower and radio observables produced in the simulations. We apply thinning techniques to the simulation of EeV electromagnetic showers in ice and the lunar regolith, including the Landau-Pomeranchuk-Migdal effect that is relevant for shower development at very high energies. This study is essential in determining the sensitivity to extremely energetic neutrinos and cosmic rays of experiments looking for radiopulses in ice such as RICE and ANITA, and in the Lunar regolith such as LUNASKA, the Westerbork radiotelescope array and LOFAR.

Introduction

The search for coherent Cherenkov radio pulses in the MHz-GHz frequency range emitted by the excess of negative charge generated in neutrino-induced showers in dense media, is a very promising technique for the detection of UHE astrophysical neutrinos [1]. This search is currently being performed in experiments using Antarctic ice or the lunar regolith as targets for ν interactions. A good understanding of the dependences of extremely energetic ν- and cosmic ray-induced showers is crucial for interpreting the data collected by these experiments. Typically the radio technique is expected to be most effective for νs above $\sim 10^{15}$ eV, with fluxes expected up to at least the EeV (10^{18} eV) range and above. Modeling ν-induced showers calls for detailed Monte Carlo simulations of their development in dense media – at these energies, full simulations become infeasible, due to the prohibitively large CPU time. A possible solution is to apply 'thinning techniques' in which only a representative sample of particles in the shower is tracked, which are given a weight to compensate for the rejected secondaries. In this contribution we explore the feasibility of applying thinning to the simulation of EeV electromagnetic (EM) showers in dense media with the aim of calculating their associated Cherenkov emission in the radio frequency range. In the past, longitudinal profiles of EeV EM showers were obtained in a fast and approximate one-dimensional (1D) Monte Carlo simulation. The associated electric field was computed performing the Fourier transform of the 1D longitudinal profile [2]. In this work, for the first time, the electric field is obtained directly in a three-dimensional simulation.

Thinning of showers in dense media for radio applications

Though thinning techniques have been applied extensively to extensive air showers, these implementations are not necessarily suited to modeling coherent Cherenkov emission from EeV EM showers. Cherenkov radiation is produced by charged particles at all stages in the development of the shower, and the emission can be understood as the diffraction pattern emitted by a finite source of charge spreading in the longitudinal and lateral dimensions. At the Cherenkov angle the lateral spread of the shower determines the maximum in the frequency spectrum, while away from the Cherenkov angle the spectral maximum is correlated with the spread of the shower along its axis. For coherent Cherenkov radiation in the radio regime, the spectrum is determined by the distribution of excess negative charge, which is produced mainly by sub-MeV particles, while the Landau-Pomeranchuk-Migdal effect stretches the showers in the longitudinal dimension because of $>$PeV particles.

The peculiar characteristics of coherent Cherenkov radio emission thus call for a thinning method tailored to accurately track the highest and lowest energy particles in the shower, in both the lateral and longitudinal dimensions. We have implemented a thinning algorithm based on the Hillas method [3] in the ZHS code [4], the main modification being that we introduce two thinning energies $E_{\max}$ and $E_{\min}$, equivalent to a weight limitation [5]. Since all EM interactions can be characterised as $A \rightarrow B + C$ (e.g. for pair production $\gamma \rightarrow e^{+} + e^{-}$), if all three particles A, B, and C have energies above $E_{\max}$ or below $E_{\min}$ we always track them. If E_A, E_B, & $E_C \in (E_{\min}, E_{\max})$, either B or C is accepted with a probability p_i proportional to its energy. A weight $w_i = {p_i}^{-1}$ is assigned to the accepted particle to guarantee energy conservation. When only one or two of E_A, E_B, E_C fall in the interval $(E_{\min}, E_{\max})$, we proceed as per [5] for interactions straddling the maximum thinning threshold, and use analogous methods for those interactions straddling either the lower or both thinning thresholds.

The set of relevant parameters in our thinning algorithm is given by $\{E_{\min}, E_{\max}\}$. We consequently define $f_{\rm L} = E_{\max}/E_{\min}$. These parameters need to be optimized so that one obtains the most accurate description of the shower minimizing the number of tracked particles and hence the computing time $t_{\rm CPU}$. To do this, we use two different methods to compare thinned with full shower simulations for energies up to 10^{16}eV, for all possible combinations of thinning parameters.

One method involves generating sets of showers with the same thinning parameters, and comparing the variation in observables between these showers with the natural variation between fully simulated showers. We aim to maximise the quality parameter $Q(E_{\min}, E_{\max})$, defined in [5] as $Q = (\sigma_0^2 \; t^0_{\rm CPU})/(\sigma^2 \; t_{\rm CPU})$ where σ_0^2 (σ^2) is the measured variance of a particular observable over the set of fully simulated showers (set of thinned showers), and $t^0_{\rm CPU}$ ($t_{\rm CPU}$) is the average CPU time of the full (thinned) simulations.

A second method consists of performing a full simulation of a single shower while *simultaneously* performing thinned simulations of *the same shower* for all possible combinations of thinning parameters. This procedure allows a precise measure of the artificial fluctuations introduced by thinning, which in the first method are obscured by shower-to-shower fluctuations. Then the relative accuracy of the shower observables obtained in each of the thinned simulations is calculated by comparing to those obtained in the full simulation. We define an acceptable accuracy for observable estimates to be those within 10% (at the level of agreement between different simulations of UHE showers in dense media) of their fully simulated values, and choose from the $(E_{\min}, E_{\max})$ combinations satisfying this criteria, those minimizing $t_{\rm CPU}$.

Both methods give similar results. $t_{\rm CPU}$ is found to scale with shower energy E_0 and with $f_{\rm L}^{-1}$ as expected, though a rise in $t_{\rm CPU}$ is observed for $E_{\min} \lesssim 100$ MeV, as the thinning algorithm operates less efficiently when ionisation losses are significant. The relative accuracy with which an observable is determined in a thinned simulation scales as $f_{\rm L}^{-0.5}$. Also, for a fixed $f_{\rm L}$, the relative accuracy scales approximately as $E_{\min}^{-0.5}$ and $t_{\rm CPU}$ depends very weakly on $E_{\min}$. The thinning parameters maximizing Q and giving a relative accuracy smaller than 10% while minimizing CPU time are $f_{\rm L} \sim 10^3 - 10^4$ and $E_{\min} \sim$ 10 MeV - 1000 MeV. This is not surprising since most of the excess charge of the shower is produced in the sub-MeV range. Our simulations suggest that the optimal value of $f_{\rm L}$ increases slowly with E_0. This is extremely important given the fact that $t_{\rm CPU}$ decreases as $f_{\rm L}^{-1}$. Our results also indicate that $E_0/E_{\max} > 10^3$ in order to achieve a good description of the high energy interactions in the shower.

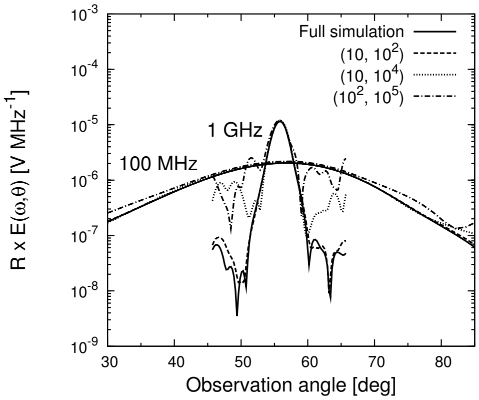

Figure 1: Angular distribution of the electric field at the Cherenkov angle in a $E_0 = 100$ TeV electromagnetic shower in ice. A fully simulated shower (solid line) is shown along with the exact same shower simulated for various combinations of $(E_{\rm min}, E_{\rm max})$ with $E_{\rm min}$ and $E_{\rm max}$ in MeV: dashes $(10, 10^2)$, dots $(10, 10^4)$, dots-dashes $(10^2, 10^5)$.

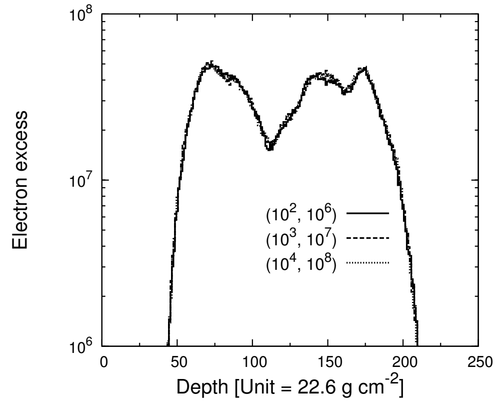

Figure 2: Longitudinal distribution of the electron excess in a single E_0 = 1 EeV electromagnetic shower in the regolith of the Moon (using the parameters in [6]), *simultaneously* simulated with three different combinations of $(E_{\rm min}, E_{\rm max})$: solid $(10^2, 10^6)$, dashes $(10^3, 10^7)$, dots $(10^4, 10^8)$.

In Fig. 1 we show the angular distribution of the Cherenkov electric field in a fully simulated E_0=100 TeV electromagnetic shower in ice along with *exactly* the same shower simulated simultaneously for various combinations of thinning parameters. At high frequencies ($\sim$ GHz), and away from the Cherenkov angle, the observation wavelength is small enough so that the fine details of the shower, even at the single particle level, are relevant for radio emission, and only combinations of thinning parameters such as $(E_{\rm min}, E_{\rm max}) = (10, 10^2)$ for which the reduction in $t_{\rm CPU}$ is not very significant (only by a factor ~ 3) can reproduce the angular distribution. On the other hand, one can see that the optimal combinations of thinning parameters, found in the previous paragraph, reproduce with a 10% accuracy the most important features of the radio emission, such as $\Delta\theta$, the full width of the Cherenkov cone at half maximum, with large reductions in CPU time of the order of ~ 1000.

EeV electromagnetic showers in ice and the regolith of the Moon

The full simulation of a single E_0 =1 EeV electromagnetic shower in ice or in the lunar regolith, tracking all particles down to typically a few hundred keV kinetic energy as required by radio applications, would take of the order of 4 years in a single 3 GHz processor. Using our typical optimal thinning parameters $(E_{\rm min}, E_{\rm max}) = (10^3, 10^7)$, $t_{\rm CPU}$ is reduced by a factor $\sim 10^4$ so that the same shower can be simulated in 3.5 hours while keeping the relative accuracy of the relevant shower and radio observables within 10%.

In Fig. 2 we show the longitudinal profile of the electron excess for a single E_0=1 EeV electromagnetic shower in the lunar regolith, for several optimal combinations of thinning parameters. This primary energy is well above the energy at which the LPM effect starts to become important for shower development ($E_{\rm LPM} \sim 7.7 \times 10^8$ MeV in the regolith). This effect reduces the cross section for pair-production and bremsstrahlung that decrease as $E^{-0.5}$ instead of being constant or increase logarithmically with energy respectively. As a consequence the interaction length for these processes increases as $E^{0.5}$ and the showers get stretched in

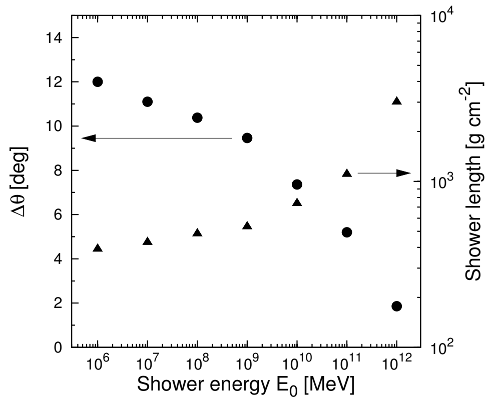

Figure 3: Full width at half maximum $\Delta\theta$ of the angular distribution of the electric field around the Cherenkov angle in the regolith of the Moon (circles) vs E_0. We also plot the width of the longitudinal profile where the excess charge falls below 0.1 its value at maximum (triangles).

the longitudinal dimension. It is remarkable how the multi-peaked longitudinal profile characteristic of showers with E_0 above $E_{\rm LPM}$ [2] is well reproduced in the simulations with different optimal thinning levels. The ability to reproduce the structure of such high energy showers is also necessary for any future work on the effect of large-scale surface roughness of the lunar regolith on the coherence of transmitted Cherenkov signals.

Our thinned simulations confirm the trend observed in [2]: Showers with $E_0 > E_{\rm LPM}$ fluctuate much more than lower energy showers. Also the width of the Cherenkov cone $\Delta\theta$ defined as the full width at half maximum, decreases as E_0 and hence the width of the longitudinal profile of the shower increases. We have simulated 20 EM showers of primary energies E_0 = 10 TeV to 1 EeV in the regolith of the Moon. In Fig. 3 we plot the average $\Delta\theta$ as a function of E_0. Below $E_{\rm LPM}$, $\Delta\theta$ decreases logarithmically with E_0, however at an energy typically 10 $E_{\rm LPM}$, $\Delta\theta \sim E_0^{-0.30\pm0.08}$ confirming for the first time in a 3D MC simulation the scaling relation obtained in [2].

Conclusions

We have successfully demonstrated that thin sampling can be adapted to Monte Carlo simulations of EeV electromagnetic showers for the purpose of calculating coherent Cherenkov radiation. The time saved allows more precise 3D calculations of the spectrum to be performed at higher energies and in a variety of media. We have confirmed the scaling relationships derived from 1D simulations in ice, and their applicability to the lunar regolith.

Acknowledgements

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