A Hybrid Monte Carlo Generator for Ultra-High Energy Cosmic Rays from their Sources to the Observer

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Abstract.
To understand in detail cosmic magnetic fields and sources of Ultra-High Energy Cosmic Rays (UHECRs) we have developed a Monte Carlo simulation for galactic and extragalactic propagation. In our approach we identify three different propagation regimes for UHECRs, the Milky Way, the local universe out to 110 Mpc, and the distant universe. For deflections caused by the galactic magnetic field a lensing technique based on matrices is applied which are created from backtracking of antiparticles through galactic field models. Propagation in the local universe uses forward tracking through structured magnetic fields extracted from simulations of the large scale structure of the universe. UHECRs from distant sources are simulated using parameterized models. In this contribution we present the combination of all three simulation techniques by means of probability maps. The combined probability maps are used to generate a large number of UHECRs, and to create distributions from approximately realistic universe scenarios. Comparisons with physics analyses of UHECR measurements enable the development of new analysis techniques and help to constrain parameters of the underlying physics models like the source density and the magnetic field strength in the universe.

1. Introduction
Several large scale observatories measure the arrival of cosmic rays with energies in the multi EeV regime, so-called ultra-high energy cosmic rays (UHECRs). The fundamental questions addressed to these data concern e.g. the origin of UHECRs, their chemical composition, and the cosmic magnetic fields they traversed.

A step forward in exploring the physics potential of these data is expected from comparisons of the measured distributions with UHECRs from simulated universe scenarios. The technical challenges in producing the required number of simulated UHECRs so far prevented the exploitation of these technique to full extend, as the number of parameters to describe a universe scenario is large, and propagation of UHECRs from a source to the observer suffers from a low hit probability.

In this contribution we elaborate on the technical realization of a Monte Carlo generator, enabling mass production of simulated UHECRs for multiple universe scenarios.
Simulations indicate that for sources far away the observed arrival directions of isotropically emitted cosmic rays show less structure compared to those from nearby sources. Consequently we divide the extragalactic propagation into the distant universe (> 110 Mpc) where a parameterized Monte Carlo is used and the local universe (< 110 Mpc) where forward tracking is performed. Inside the galaxy stochastic processes are negligible, enabling the utilisation of an efficient backtracking algorithm.

In the following sections we introduce the propagation methods for each regime in detail and finally present a simulated UHECR energy spectrum compared to data from experiments.

2. Parameterized Simulation in the Distant Universe

For high statistic simulations the parameterized propagation of cosmic rays has been implemented in the PARSEC software [2]. The probability distribution to observe a particle from a direction at the edge of the Milky Way is calculated as set of maps for individual energy ranges. In this calculation energy losses from electron pair production and photo-pion production as well as from the expansion of the universe are modeled as continuous energy loss, which on average agrees with the results from forward propagation codes (cf. fig. 1)

To describe the deflection in a turbulent magnetic field the arrival probability is smeared around the direction of the source using a Fisher distribution (cf. fig 2). It is the normal distribution on the surface of a sphere and its width $\sigma$ is proportional to

$$\sigma \propto \sqrt{D\Lambda B E}.$$ 

$D$ is the distance of the source, $\Lambda$ the coherence length and $B$ the strength of the magnetic field, $E$ denotes the energy of the cosmic ray.

The resulting probability maps of the individual sources are superimposed for each energy range and normalized to an integrated probability of one.

![Figure 1. Comparison of the continuous energy loss approximation in PARSEC [2] with CRPropa [3].](image1)

![Figure 2. Fisher distribution for different values of $\sigma$, and the distribution of isotropic arrival directions.](image2)

3. Forward Tracking in the Local Universe

In contrast to the parameterized simulation, forward tracking features stochastic interactions and structured magnetic fields. The CRPropa [3] software package provides the latest physics
Figure 3. Mass density isosurfaces in a slice of the large scale structure [4] with a diameter of 220 Mpc.

models for cosmic ray propagation, including nuclear decay and various interactions with the extragalactic background light. Structured magnetic fields can be created as turbulent fields or they can be extracted from large scale structure simulations, cf. Fig 3. One unique feature of the presented simulations performed by Dolag et al. [4] is the inclusion of constraints on the position of prominent observed clusters, e.g. the Virgo Cluster.

Based on these two components we have developed a simulation code for individual tracking of cosmic rays optimized for mass production.

Advanced approximations reduce the amount of trajectories which are not observed. Dynamic observer sizes depending on the source distance increase the amount of hits, and geometric distortions are corrected for correspondingly. By limiting the total propagation time and confining the particles to an ellipsoid, with the source and the observer in the focal points, we significantly reduce the computation time.

Regarding the smallest structures found in the large scale structure simulation, a resolution of the magnetic field of about 100 kpc or less is desirable. A regular grid with this sampling has a size of 150 GB. To support the utilisation of all available computing systems like local computing clusters, HPC (SMP and MPI) clusters or the LHC Grid, we implemented different algorithms to handle this large amount of data.

For a single trajectory only a small subset of the magnetic field data is accessed. Keeping only the most recently accessed parts in memory (paging) drastically reduces the required main memory. This algorithm is suited for shared memory processing on nodes with many cores, but increases the disc and memory load. To overcome these limiting factors we implemented a spatial partitioning algorithm, which is especially suited for a many node computing cluster setup. In this scenario each node processes all cosmic rays within a small simulation volume. Cosmic rays passing the boundaries of this volume are transferred to another node processing
4. Galactic Lensing
The relatively small distance propagated in the galaxy, compared to the extragalactic regimes, allows for neglecting energy losses. Without any stochastic processes the far more effective backtracking technique can be used instead of computationally intensive forward tracking. In this algorithm antiprotons are emitted isotropically at the position of Earth and are tracked to the border of the galaxy using the CRT software package [5].

From simulations with sufficient coverage of directions and energies deflection matrices are generated. For each energy bin, the start and end directions of the trajectories are binned by solid angle and summarized in a matrix. By normalizing the matrix to the maximum of sums of columns, the elements of the matrix \((i, j)\) can be interpreted as probability that a particle entering the galaxy from direction \(i\) is observed from direction \(j\). To achieve an angular accuracy of about 1 degree, matrices with 50k x 50k elements are needed, which are, however, typically sparsely populated. The resulting transformation matrices, lenses, can be applied to individual particles or to probability maps.

The good performance allows to easily analyse the effect of different galactic magnetic field models on cosmic ray propagation. Figures 4 and 5 illustrate the effect of galactic deflection on probability maps using the lensing technique.

5. Combined Simulation and Comparison to the Measured Energy Spectrum
In order to generate a complete scenario for UHECR propagation the three simulation regimes are combined.

The probability maps of the two extragalactic simulations are merged and transformed using the galactic lensing technique. To avoid discontinuities between the local and the distant universe, the mean deflection and the flux of the two regimes need to be compatible. This is achieved by tuning the magnetic field strength for the parameterized simulation to match the mean deflection in the forward tracking simulation. In figure 6 the parameterized mean deflection is compared to the forward tracking simulations. The relative fluxes of the distant and local universes are matched by weighting the maps such that the total contribution of the local universe in the lowest energy bin matches the expected contribution from continuous sources in the same volume.

From the resulting probability maps UHECRs are generated, which we compare to measured distributions. In figure 7 we compare our simulation of UHECRs with the energy spectrum as measured with the HiRes experiment [6] and the Pierre Auger Observatory [1]. The fluxes of the local and the distant universe have been scaled to fit the total measured flux of the Pierre...
Figure 6. Mean deflection of the extragalactic propagation regimes. The parameters for the distant universe have been chosen such that the mean deflection matches the one found in the local universe.

Figure 7. Cosmic ray flux, measured by the HiRes experiment [6] and Pierre Auger Observatory [1], compared to the scaled spectra of the simulation.

Auger Observatory at 10 EeV. While the contribution of each regime alone can not reproduce the measurements, the combination of the two gives a reasonable description of the data distribution.

6. Conclusion

To enable mass production of ultra-high energy cosmic rays we have divided the universe into three simulation regimes. For each regime a simulation technique optimized for the given circumstances has been chosen to improve the overall performance. The inclusion of detailed structured magnetic fields in the simulation is well suited for studies of anisotropy and cosmic magnetic fields in the universe.

References

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