Propagation of Very High Energy Radiation in the Universe

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The sources of cosmic rays, in particular ultra-high energy cosmic rays with macroscopic energies above $\sim 10^{18}$ eV, have still not been identified. This is partly caused by the fact that the sky observed in these cosmic rays is surprisingly isotropic and that deflection in galactic and extragalactic magnetic fields may still be substantial. The main goal of project C8 of the SFB 676 was to further develop a general software tool, known as CRPropa, which allows to propagate ultra-high energy cosmic rays from the sources to the observer and make predictions for spectrum, mass composition and sky distribution with a given astrophysical scenario for distribution and injection spectra and composition of the sources and the structure of cosmic magnetic fields.

1 Introduction

Recent years have seen interesting results on spectrum [1,2], composition [3,4], and anisotropy [5, 6] of ultra-high energy cosmic rays above 10^{17} eV, both from the Pierre Auger Observatory and other experiments such as the Telescope Array and the High Resolution Fly's Eye (HiRes). This continued after the end of project C8. As an example we highlight the recent first unambiguous detection of an anisotropy of ultra-high energy cosmic ray (UHECR) arrival directions around 8×10^{18} eV [7]. In order to interpret these data in the context of concrete astrophysical scenarios for the distribution of the sources, their injection characteristics such as spectrum, maximal energy and mass composition, as well as for the distribution of large scale cosmic magnetic fields requires a comprehensive numerical tool that can simulate the deflection of UHECRs over several orders of magnitude in energy and length scales, ranging from hundreds of megaparsecs down to galactic scales of the order of kiloparsecs, including their interactions such as photo-disintegration, pion production and pair production.

In particular, the distribution of structured cosmic magnetic field plays a central role in the interpretation of sky distribution, spectrum and mass composition of ultra-high energy cosmic rays (UHECR) above 10^{18} eV, as has been shown in Ref. [9]. Motivated by this, the main goal of the project C8 was the development of a general software tool that allows simulating the propagation of extragalactic cosmic ray nuclei and protons, including secondary electromagnetic cascades and neutrinos, within a magnetic field model that can be specified in a general way, taking into account all relevant interactions such as pion-production, photo-disintegration and pair production. This goal was achieved with the public release of the code CRPropa 2.0 [8] which can be accessed at `https://crpropa.desy.de/Main_Page`. This code was developed in close collaboration with Nils Nierstenhöfer from the University of Wuppertal who visited

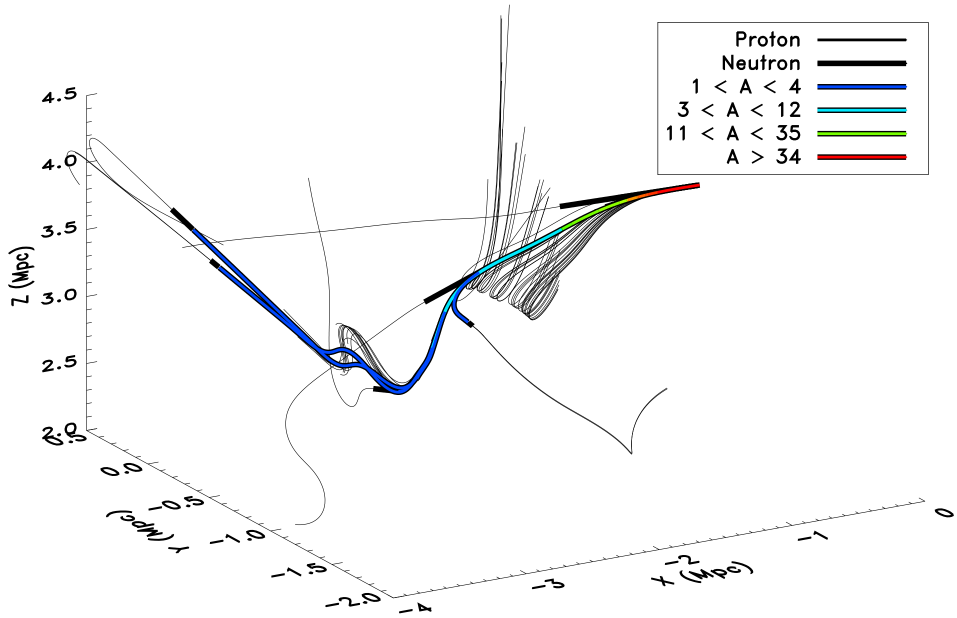

Figure 1: 3D trajectory of an iron nucleus and its hadronic secondaries in the minimum of the photodisintegration mean free path (at energy $E \sim 1.2 \times 10^{21}$ eV) in a high magnetic field region of a structured magnetic field (10^{-9} G $< B < 10^{-7}$ G). Color coded is the mass number of the secondary particles. Notice that after photo-disintegration the heavy nucleus and its secondary particles have the same Lorentz factor $\Gamma \sim E/A$ and therefore secondary protons are stronger deflected than heavier nuclei due to their higher charge-to-mass ratio. Reprinted from Ref. [8], with permission from Elsevier.

Hamburg for several months and was partly funded by the SFB fellowship program. As an illustration, Figure 1 shows the simulated development of a nuclear cascade in a structured magnetic field. The code CRPropa has been extensively applied to various astrophysical scenarios for the origin of ultra-high energy cosmic rays above 10^{18} eV within the Pierre Auger Observatory. It is currently being applied systematically to fitting the spectrum and mass composition of the UHECR flux measured by the Pierre Auger experiment in order to extract the properties of the sources such as maximal energy and injected mass composition. In fact, from March 2012 to spring 2014 the PI G. Sigl acted as one of the leaders of a newly created task within the Pierre Auger experiment whose goal is to perform detailed Monte Carlo simulations of all relevant astrophysical scenarios whose predictions are to be compared with the data. The code CRPropa 2.0 developed within project C8 played a central role in this task.

During the more systematic application of CRPropa 2.0 to various astrophysical scenarios it became obvious that such a general simulation tool should be highly modular, since constraining the origin of UHECRs requires simulations predicting spectra, compositions and anisotropies for a large number of astrophysical scenarios, and comparison with experimental data. To this end, CRPropa was upgraded to version 3.0 in close collaboration with the Universities of Aachen and Wuppertal. All relevant interactions, the solver for trajectory integration and the production of secondary $\gamma-$rays and neutrinos have been inherited from CRPropa 2.0 [8]. In addition, two new features have been implemented:

2 Cosmology in 3D

Cosmological effects such as the redshift evolution of the photon backgrounds and the adiabatic expansion of the universe are important when simulating the propagation of UHECRs. These effects can notably modify the UHECR spectra which is important in particular when comparing predictions with measured spectra at energies below a few 10^{18} eV where experimental statistics is large. Spectral changes can easily be taken into account in 1D simulations. However, in 3D, when deflections due to the pervasive cosmic magnetic fields are considered, it is not possible to know *a priori* the effective propagation length, and therefore the redshift, of the simulated particles. To approximately correct for these effects, one can re-simulate each 3D trajectory in 1D for a propagation time equal to the one of the 3D trajectory. One can then correct the final state of the 3D trajectory by randomly choosing from the final state products and energies of the 1D simulation [10].

3 Galactic propagation

The Galactic magnetic field (GMF) is expected to significantly contribute to the total deflections of charged extragalactic UHECRs. Therefore, the functionality of CRPropa 3.0 was extended to allow forward- and backtracking of UHECRs through different models of the GMF available in the software. Arbitrary field models can be defined using one of the grid techniques, described in the next section. Additionally, several models in analytical form are available, including the JF12 model with both regular and random component [11, 12].
A different, highly efficient, way to model galactic propagation is the lensing technique described and implemented in the PARSEC software [13]. In this approach UHECR interactions with photons and interstellar matter are neglected due to the short distance inside the Galaxy compared to extragalactic distances. The lensing technique uses a set of transformation matrices for different energies to map the directions of UHECRs at the border of the galaxy to directions observed at Earth. CRPropa 3.0 provides an interface to PARSEC to apply the lensing technique on UHECRs that were propagated from an extragalactic source to the border of the Galaxy. This combination allows to simulate the propagation of UHECRs through both the extragalactic and galactic magnetic field, which would be computationally unfeasible with pure forward tracking.

4 Applications

CRPropa 2.0 and 3.0 are now extensively being used to simulate predictions for observable spectra, mass composition and anisotropies in so-called *benchmark scenarios* for the distribution of the UHECR sources, the injected mass composition and maximal energies, as well as for the distribution of cosmic magnetic fields. Figure 2 shows an example where simulated spectra and their mass composition in a scenario in which sources inject a mixed mass composition are

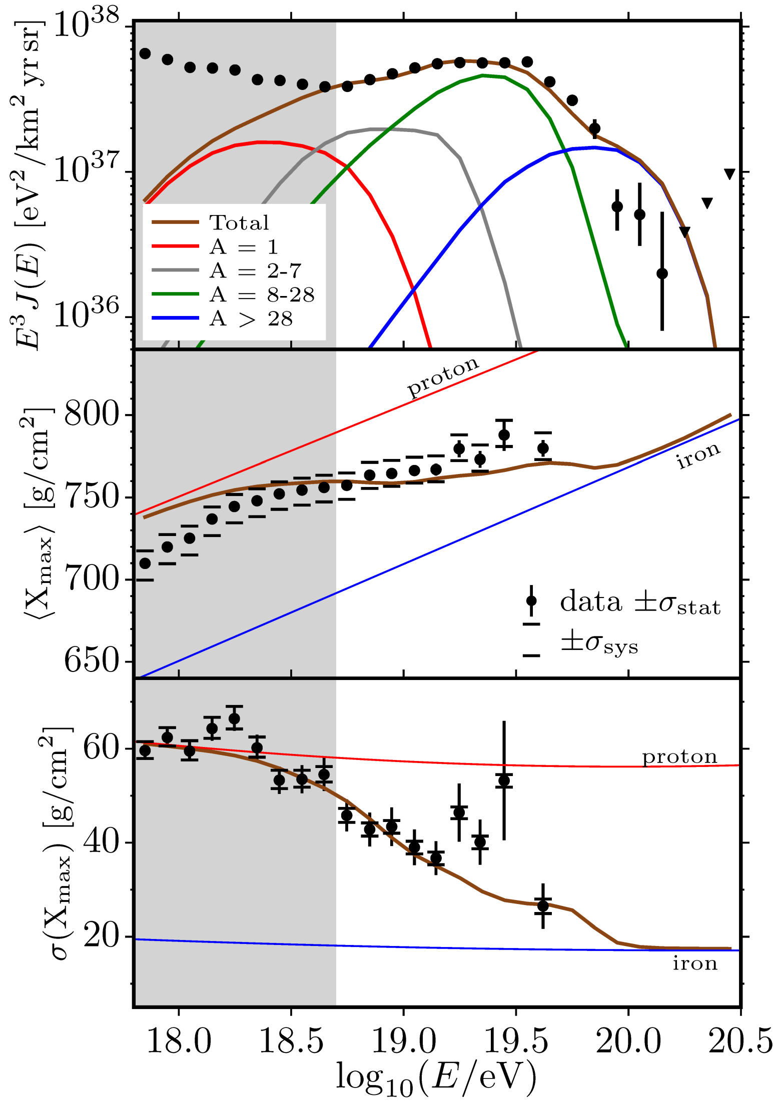

Figure 2: Comparison of simulated predictions and measurements by the Pierre Auger experiment of various observables in a scenario where uniformly distributed sources inject a mixed composition of elements. Upper panel: All-particle spectrum and spectra of the mass groups indicated compared to the measured spectrum. Middle panel: The average depth of shower maximum $X_{\max}$ is sensitive to the average mass composition. Lower panel: The variance of $X_{\max}$ is sensitive to the width of the arriving mass distribution. The best fit values here correspond to an injection spectrum $\propto E^{-0.62}$ up to a maximum energy per charge $E/Z \leq 3.6 \times 10^{18}\,$eV, dominated by nitrogen. Figure adopted from Ref. [14].

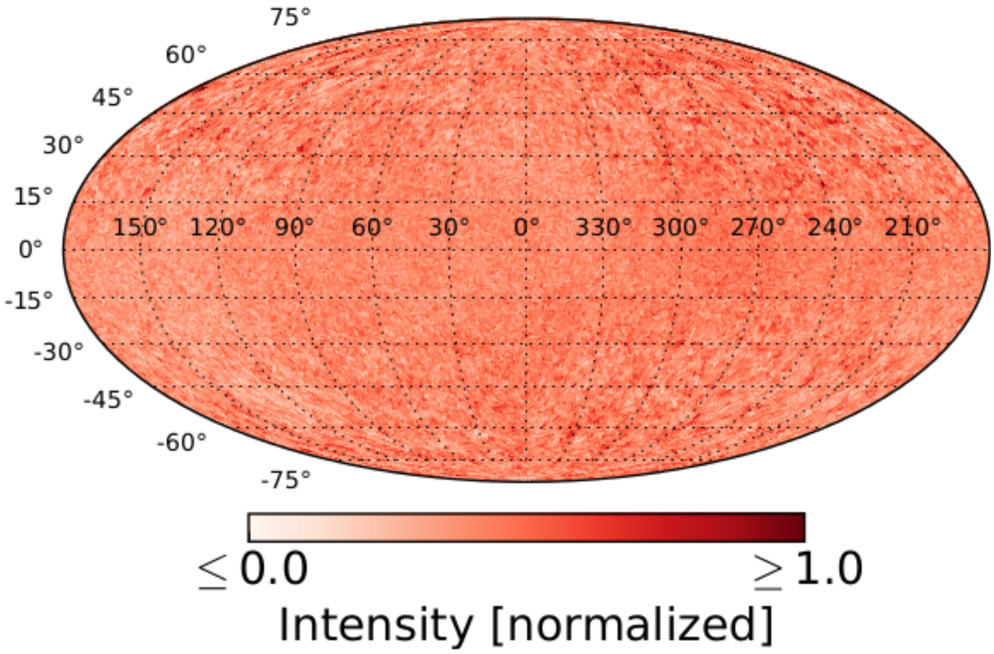

Figure 3: Simulated distribution of arrival directions of UHECRs above 10^{18} eV injected from a discrete set of sources of average density $10^{-3}\,\mathrm{Mpc}^{-3}$, randomly selected with a probability proportional to the baryon density following the local large scale structure. The UHECRs are deflected in an extragalactic magnetic field whose distribution was taken from a model following Ref. [9] and a galactic magnetic field modelled as in Refs. [11,12]. Figure adopted from Ref. [14].

compared to the data. Figure 3 shows an example for the simulated arrival direction distribution at the border of our Galaxy of protons injected in discrete sources. Such kind of simulations have also been used to develop the science case for the continuation of the Pierre Auger project beyond 2015. Furthermore, CRPropa has been extensively used within the first full Pierre Auger collaboration paper on global fits of the data to astrophysical scenarios parametrised by the injected mass distribution and spectra [15]. As an interesting and somewhat unexpected result it was found that very hard injection spectra with relatively low maximal energy were favoured by the fits. This also led to the important conclusion that the suppression of the UHECR flux observed above a few 10^{19} eV may have more to do with the maximal energy to which particles are accelerated within the sources than with energy loss processes, mostly pion production, known as the Greisen–Zatsepin–Kuzmin (GZK) effect, during propagation. In addition, the fits also favour injection of predominantly Helium and Nitrogen.

Our code CRPropa has also been applied to simulate secondary $\gamma-$ray and neutrino fluxes: Recently the IceCube experiments reported the detection of two neutrinos at PeV energies whose origin is likely extragalactic [16]. In Ref. [17] we investigated whether so-called *cosmogenic neutrinos*, i.e. neutrinos that are produced by the interactions of primary UHECRs with the cosmic microwave and infrared backgrounds, could explain the observed events. We found that the predicted neutrino fluxes fall short by a factor of about ten unless extreme, unlikely assumptions are made about the evolution of the UHECR sources and/or the maximal energy to which protons are accelerated within their sources. It is thus much more likely that the IceCube events are produced within discrete sources such as active galaxies or γ-ray bursts.

The particular role of the Galactic magnetic field, for example, in UHECR lensing and for UHECR anisotropies has been investigated in some details in Refs. [18,19] in collaboration with Gwenael Giacinti who was partially funded by the SFB fellowship program as a visitor. For example, in Ref. [19] through UHECR trajectory simulations in the Galactic magnetic field we found that if the mass composition is light at energies $\sim 10^{18}$ eV around the ankle, the sources very likely have to be extragalactic, otherwise the predicted flux would be too anisotropic, inconsistent with the Pierre Auger observations. This finding also led to a full author paper of the whole Pierre Auger collaboration [20].

Finally, physics beyond the Standard Model in the form of Lorentz symmetry violations have been extensively constrained by applying UHECR observations. In particular, the non-observation of ultra-high energy photons by the Pierre Auger Observatory [21] implies that such photons have to undergo pair production on the cosmic microwave background. This strongly constrains tiny deviations of photon and electron dispersion relations from their Lorentz invariant form which otherwise would strongly modify the kinematics of the pair production reaction [22].

Our results on UHECR propagation have been presented in various conference proceedings, see Refs. [10, 23–26], as well as on summer schools, e.g. Ref. [27]. The also resulted in two PhD theses [28, 29].

5 Summary and Outlook

The development of a general tool for the propagation of UHECRs and their secondary products including $\gamma-$rays and neutrinos has been essentially achieved during project C8 and the focus is now shifting towards applications to various scenarios for the UHECR origin including the sources and their magnetic environment. For this reason, the initial project C8 was not continued. Instead, the numerical tools developed within C8 have been and still are applied to scenarios for the distribution of cosmic magnetic fields developed, in part, within project C9.

At the same time, project C8 set the stage to further develop and generalize CRPropa. For example, at low energies charged particles essentially diffuse, in particular in the Galactic Magnetic field and the simulation of a large number of trajectories becomes computationally inefficient. In this situation it is more efficient to solve a diffusion equation or a stochastic differential equation. To this end, in version 3.1 CRPropa has been extended by a module that allows to simulate Galactic cosmic rays by solving the relevant transport equation using stochastic differential equations which also takes into account anisotropic diffusion with different rates along and perpendicular to the coherent magnetic field component [30]. Furthermore, CRPropa is currently adapted and applied to model high energy cosmic ray sources by groups at DESY/Zeuthen and Bochum.

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