CRPropa - A Toolbox for Cosmic Ray Simulations

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Abstract. The astrophysical interpretation of recent experimental observations of cosmic rays relies increasingly on Monte Carlo simulations of cosmic ray propagation and acceleration. Depending on the energy range of interest, several different propagation effects inside the Milky Way as well as in extragalactic space have to be taken into account when interpreting the data. With the CRPropa framework we aim to provide a toolbox for according simulations. In recent versions of CRPropa, the ballistic single particle propagation mode aiming primarily at extragalactic cosmic rays has been complemented by a solver for the differential transport equation to address propagation of galactic cosmic rays. Additionally, modules have been developed to address cosmic ray acceleration and many improvements have been added for simulations of electromagnetic secondaries. In this contribution we will give an overview of the CRPropa simulation framework with a focus on the latest improvements and highlight selected features by example applications.

1. Introduction

Current and future detectors for ultra-high energy cosmic rays (UHECR), neutrinos, and gamma-rays provide us with an increasing amount of precision data. The Pierre Auger Observatory [1] and Telescope Array [2] measured the spectrum [3, 4] and composition [5, 4] of the UHECR flux at the highest energies, and also observed anisotropy in the arrival direction of UHECR [6, 7]. The IceCube neutrino detector measured a flux of extraterrestrial neutrinos [8], and, recently, observed a first coincident event with a flaring gamma ray blazar [9].

However, understanding this wealth of data is no easy task. The place and mechanism of acceleration of cosmic rays remains unknown and the newest data challenges the so far prevailing
models. Accounting for propagation effects, the observations point to a surprisingly hard spectral index and heavy composition at the accelerators [10], requiring at least extensions to the simplest models for the acceleration process. Observation of mass composition at the ankle [11] indicate a surprisingly light composition that is at odds with simple models for the transition between galactic and extragalactic cosmic rays, and even at the lowest energies the observed particle spectra challenge simple models for acceleration in supernovas [12]. To develop - and test - the increasingly complex models required to understand our data, detailed simulations of the propagation and acceleration mechanisms are needed.

2. The CRPropa Software
The CRPropa software in its third major version [13] has been developed as a versatile simulation tool to efficiently develop predictions from astrophysical models. The code includes a variety of components to set up simulations for the propagation of particles, including models for energy losses in interactions and creation of secondary particles. In particular, particles can be propagated through arbitrary three-dimensional magnetic fields and be subjected to energy losses due to interactions in photon fields by pair-production, photo-meson production, photodisintegration, due to nuclear decay, and due to the adiabatic expansion of the universe. The full propagation can be performed including the combination of both, cosmological effects and three-dimensional propagation. The simulation of the physical processes is limited to the highly relativistic propagation regime where the rest-mass of the particles can be neglected. In addition to modules subjecting the propagated particles to physical effects, a large collection of tools to inject particles with desired properties into the simulation respectively record the requested output are included. Execution of the simulation utilizes shared-memory parallel architectures using OpenMP. Parallelization on distributed-memory architectures can be implemented by users e.g. using MPI.

The individual components are independent and can be combined by the user to a customized simulation. Additional components not yet included in CRPropa can be written by the users in Python or C++ and included in the simulations, usually without requiring a new compilation of the CRPropa code. We strive to collect the contributions of users to the code and either include them into CRPropa or facilitate sharing of code amongst user by referencing them on the CRPropa webpage.

Code development follows an open procedure. All changes to the code are tracked using a public git repository. Discussions on bugs and future enhancements as well as support questions are transparent in an online issue tracker. Contributions to the code by users as well as any larger modification is subjected to peer review before inclusion to not only minimize wrong computations, but also enforce technical standards and code quality to ensure the future maintainability of the project. Guidelines for contributions, and thus also for the review, are public and distributed alongside the CRPropa code. In particular, unit-tests, inline documentation, and also usage examples published on the CRPropa website are required. CRPropa is licensed under the GPLv3 [14].

3. Recent Developments and Example Applications
3.1. Galactic Cosmic Rays
CRPropa has been recently extended to simulate propagation of galactic cosmic rays [15]. For low energy cosmic rays the calculation of individual particle trajectories is not feasible, as integrating the equation of motion becomes too computational intensive. Instead, cosmic ray propagation is described stochastically via the modified Parker transport equation

$$\frac{\partial n}{\partial t} + \vec{u} \cdot \nabla n = \nabla \cdot (\kappa \nabla n) + \frac{1}{p^2} \frac{\partial}{\partial p} \left( p^2 \kappa_{pp} \frac{\partial n}{\partial p} \right) + \frac{1}{3} (\nabla \vec{u}) \frac{\partial n}{\partial \ln p} + S(\vec{x}, p, t)$$

(1)
Figure 1. Time evolution of the density of cosmic rays in the Galactic plane resulting from homogeneous injection of cosmic rays in a JF 12 galactic magnetic field model for several choices of the diffusion parameter $\epsilon$ (From [15]).

which relates the particle density $n$ at point $\vec{x}$, momentum $p$, and time $t$ of a system with the local spatial diffusion tensor $\hat{\kappa}$, momentum diffusion coefficient $\kappa_{pp}$, advection speed $\vec{u}$ and particle sources $S(\vec{x}, p, t)$. Additional terms can be added to eq. 1 to account for particle interactions and decays.

The stochastic description can be reconciled with the single particle description in CRPropa
by treating the corresponding stochastic partial-differential equation instead of eq. 1. Here, individual ‘pseudo’ particles make in every step of the simulation effective steps in space and momentum according to the diffusion coefficients. In the limit of many particles the resulting distributions of the particles are identical to the direct solution of eq. 1, respectively the simulation of ensembles of individual trajectories.

While this has the advantage that the propagation of ensembles of low energy particles can be calculated very efficiently and interactions can be accounted for at the same time with the regular CRPropa modules, additional assumptions on the diffusion coefficients have to be made in the simulations. As an example application, in figure 1 the time evolution of the cosmic ray density in the Galactic disc is displayed for several choices of the diffusion coefficient. In case of large ratios between parallel and perpendicular diffusion $\kappa_\perp/\kappa_\parallel = \epsilon$, particles leak quickly out of the galaxy; For small $\epsilon$ particles are bound to the galactic field and follow the structure of the magnetic field models as expected.

3.2. Particle Acceleration

In the majority of models for cosmic ray sources, particles are believed to be accelerated in shocked plasmas via the first-order Fermi mechanism (e.g. [17]) which predicts a power-law emission spectrum $dN/dE \propto E^\gamma$ with $\gamma \leq -2$. However, evaluation of the data of the Pierre Auger Observatory indicates [10, 18, 19] harder injection spectra that require new or at least modified acceleration models (e.g. [20, 16]).

To simulate the processes in the sources, we created modules to calculate particle acceleration via scatter processes, e.g. by plasma waves. Input to the simulation is a user defined step length corresponding to the frequency of scatter events of the particles. With appropriate choices of these parameters, the simulation of first-order Fermi acceleration [21] and second-order Fermi acceleration is possible. Using this new feature it was demonstrated that acceleration via the second-order Fermi mechanism after pre-acceleration, geometrical effects of the acceleration region can modify the spectrum from a power-law to a peaking distribution as shown in figure 2. With the modified spectrum, the observations of the Pierre Auger Observatory can be explained without implying an unexpected high abundance of heavy elements at the sources [16].

![Figure 2. Acceleration spectra from second order Fermi acceleration with a fixed minimum step length after injection in center of spherical acceleration region with radius R (From [16]).](image-url)
3.3. Photon Propagation and Production

Photon propagation in CRPropa relied so far on external codes such as DINT [22] or EleCa [23]. Consequently, the simulations were not easily extendable and full consistency between both components were hard to achieve, as for example some photon models were not available in the independent codes and effects of the local magnetic field were not easy to account for.

To increase the precision of photon propagation as important secondary messenger, new photon propagation modules have been created inside the CRPropa core structure that allow a consistent simulations setup. For this, modules for all energy loss processes present in DINT and ELeCa, have been implemented, and also additional photon production channels are now considered [24]. In particular, photon creation during photo-disintegration of nuclei, elastic scattering and radiative decay have been included and the simulation accounts for deflections in the local magnetic field. To also speed up the computation, which, in some circumstances, can be otherwise prohibitively time consuming, a new thinning procedure is currently under development.

4. Conclusion

The wealth of data in astroparticle physics provides new detailed insights in the highest energetic processes of the universe. The CRPropa software framework provides the necessary means to develop our understanding and compare the predictions of the models with data. The latest development efforts extend the scope of the project from propagation of the highest energetic particles only to include also lower energy and acceleration processes, thus enabling a consistent view on high energy astroparticle physics.

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