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Propagation of Ultra-High Energy Cosmic Rays through Extragalactic Magnetic Fields: An Exploratory Study of the Distance Amplification from Rectilinear Propagation

Authors : Rubens P. Costa, Marcelo A. Leigui de Oliveira

Abstract : The comprehension of features on the energy spectra, the chemical compositions, and the origins of Ultra-High Energy Cosmic Rays (UHECRs) - mainly atomic nuclei with energies above ~1.0 EeV (exa-electron volts) - are intrinsically linked to the problem of determining the magnitude of their deflections in cosmic magnetic fields on cosmological scales. In addition, as they propagate from the source to the observer, modifications are expected in their original energy spectra, anisotropy, and the chemical compositions due to interactions with low energy photons and matter. This means that any consistent interpretation of the nature and origin of UHECRs has to include the detailed knowledge of their propagation in a three-dimensional environment, taking into account the magnetic deflections and energy losses. The parameter space range for the magnetic fields in the universe is very large because the field strength and especially their orientation have big uncertainties. Particularly, the strength and morphology of the Extragalactic Magnetic Fields (EGMFs) remain largely unknown, because of the intrinsic difficulty of observing them. Monte Carlo simulations of charged particles traveling through a simulated magnetized universe is the straightforward way to study the influence of extragalactic magnetic fields on UHECRs propagation. However, this brings two major difficulties: an accurate numerical modeling of charged particles diffusion in magnetic fields, and an accurate numerical modeling of the magnetized Universe. Since magnetic fields do not cause energy losses, it is important to impose that the particle tracking method conserve the particle’s total energy and that the energy changes are results of the interactions with background photons only. Hence, special attention should be paid to computational effects. Additionally, because of the number of particles necessary to obtain a relevant statistical sample, the particle tracking method must be computationally efficient. In this work, we present an analysis of the propagation of ultra-high energy charged particles in the intergalactic medium. The EGMFs are considered to be coherent within cells of 1 Mpc (mega parsec) diameter, wherein they have uniform intensities of 1 nG (nano Gauss). Moreover, each cell has its field orientation randomly chosen, and a border region is defined such that at distances beyond 95% of the cell radius from the cell center smooth transitions have been applied in order to avoid discontinuities. The smooth transitions are simulated by weighting the magnetic field orientation by the particle's distance to the two nearby cells. The energy losses have been treated in the continuous approximation parameterizing the mean energy loss per unit path length by the energy loss length. We have shown, for a particle with the typical energy of interest the integration method performance in the relative error of Larmor radius, without energy losses and the relative error of energy. Additionally, we plotted the distance amplification from rectilinear propagation as a function of the traveled distance, particle's magnetic rigidity, without energy losses, and particle's energy, with energy losses, to study the influence of particle's species on these calculations. The results clearly show when it is necessary to use a full three-dimensional simulation.

Keywords : cosmic rays propagation, extragalactic magnetic fields, magnetic deflections, ultra-high energy
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