EGCRProp Instructions Manual

R. P. Jr. Costa* and M. A. Leigui de Oliveira
Federal University of ABC (UFABC),
09210-580, Santo André, SP, Brazil

1. Abstract

EGCRProp [a] is a Monte Carlo code written in C ++ for the propagation of Ultra-High Energy Cosmic Rays (UHECRs) through Extragalactic Magnetic Fields (EMFs). In the simulation, it is calculated the three-dimensional trajectory of nuclei (from proton to iron) through unitary cells of coherent magnetic fields, as well as the particle's dynamic parameters: the trajectory radius or the traveled distance, the energy, and the deflection angle, are recorded after each event to be further analyzed. To take into account the magnetic field discontinuities, we have implemented smooth transitions in the region between the neighboring cells. We take into account the energy losses due to the interactions between the UHECRs and the Extragalactic Background Light (EBL). The energy losses are approximated as a Continuous Energy Loss (CEL) parameterizing the mean energy loss per unit path length by the energy loss length. The code takes advantage of GNU Multiple Precision Floating-Point Reliably C++ (MPFRC++) library [1], a high-performance C++ interface for Multiple Precision Floating-Point Reliably (MPFR) library [2], which is based on the GNU Multiple Precision (GMP) arithmetic library [3] and allows one to use arbitrarily precise numbers instead standard double precision numbers, and of GNU Scientific Library (GSL)[4], which provides a wide range of mathematical routines.

Keywords: Ultra-High Energy Cosmic Rays Propagation, Extragalactic Magnetic Fields, Magnetic Deflections.

[a] Please, acknowledge the use of the **EGCRProp** code by quoting this site `http://pesquisa.ufabc.edu.br/egcrprop` and citing R. P. Costa Junior, and M. A. Leigui de Oliveira. "A Numerical Model for the Propagation of Ultra-High Energy Cosmic Rays through Extragalactic Magnetic Fields", Proc. of the 35th ICRC (ICRC2017), PoS(ICRC2017)477.

* Corresponding author: rubens.costa@ufabc.edu.br

I. THE CODE STRUCTURE

EGCRProp package[1]: is composed of two object-oriented codes[2] both written in C++: the propagator itself and a tensorial magnetic field generator. The propagator can be run with several input parameters (see Sec. II) and it generates several output files (see Sec. III). The spatial coordinates of different charged nuclei are generated after each iteration to be further displayed in a three-dimensional viewer[3] (see Fig. 1), as well as their dynamic parameters (trajectory radius or traveled distance, particle's energy and deflection angle) are recorded after each event to be to be further analyzed. The tensorial magnetic field generator must be running at least once before the propagator, it produces random orientations for the magnetic fields which are modeled by assuming a cellular structure of coherent fields [6–9].

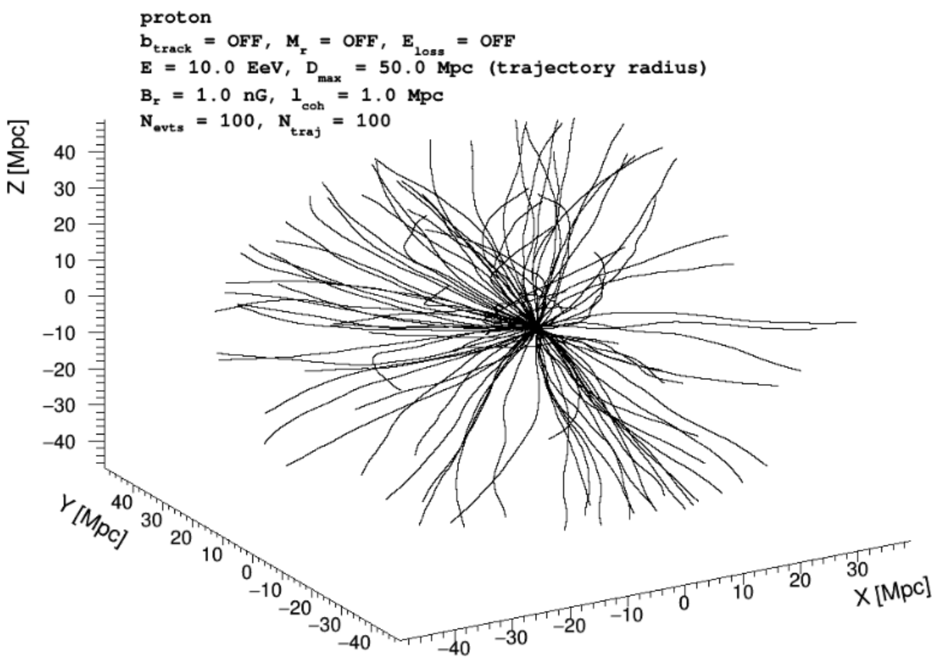

FIG. 1: Trajectories of 100 protons with $E = 10.0$ EeV in EGMF from **EGCRProp** code. We assumed cells of $l_{\rm coh} = 1.0$ Mpc with $\vec{B}$ with random orientations, but constant intensities of 1.0 nG. The trajectories were limited within a radius of 50.0 Mpc and energy losses neglected in these plots.

EGCRProp code follows a structure of classes and methods. In Fig. 2, an illustration of such structure is shown. Light blue rectangles indicate the propagator and the tensorial generator. The Controller class (represented by the red arrows) is responsible by communication between the auxiliary classes (green and gray balls) and between these with the main one (big central ball in light gray). Dark blue rectangles represent the methods that perform calculations, whereas gray boxes indicate those where the adopted models are implemented and red rectangles the processes of checking and setting. The orange tablets represent the reading methods and the printing one. In Yellow are indicated the ROOT MACRO and the plots created with it.

[1] The file *README.md* contains the instructions for the installation and the compilation required for an **EGCRProp** run.
[2] The main files are *EGCRProp.cc* and *tensors_generator.cc*.
[3] The file *ROOT_MACRO.cpp*, which makes use of a few features from the ROOT [10] framework.

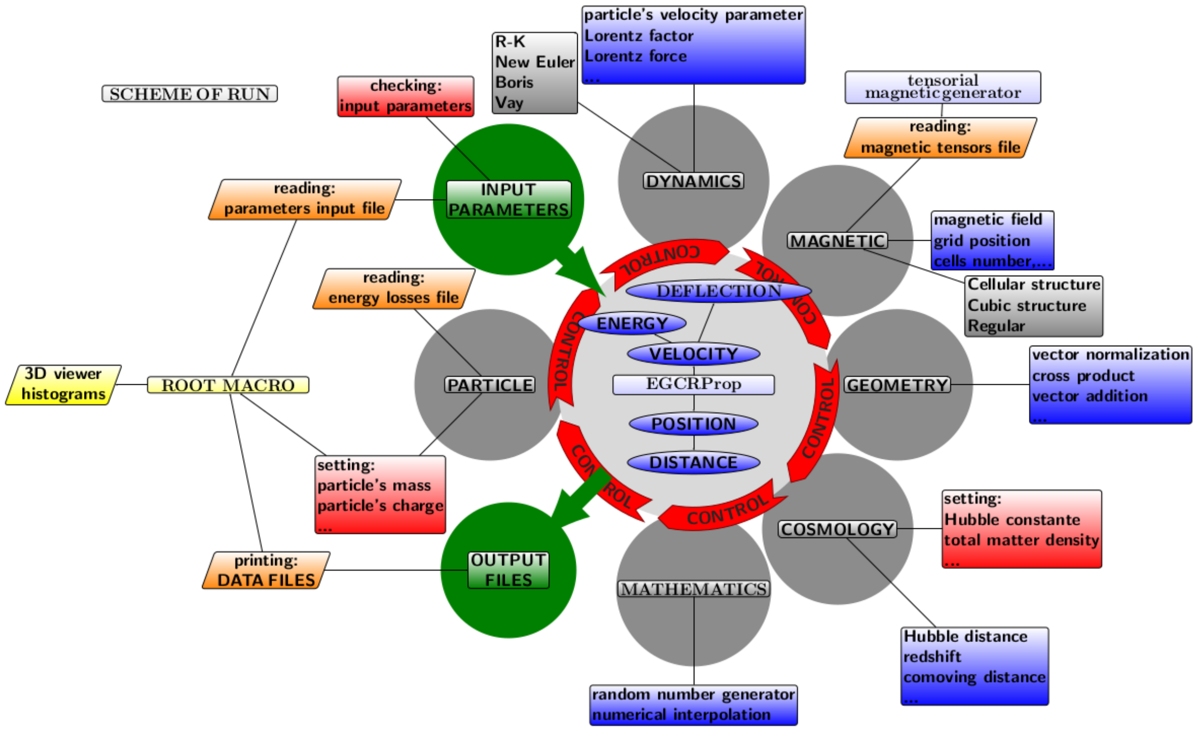

FIG. 2: An illustration of **EGCRProp** classes and methods structure.

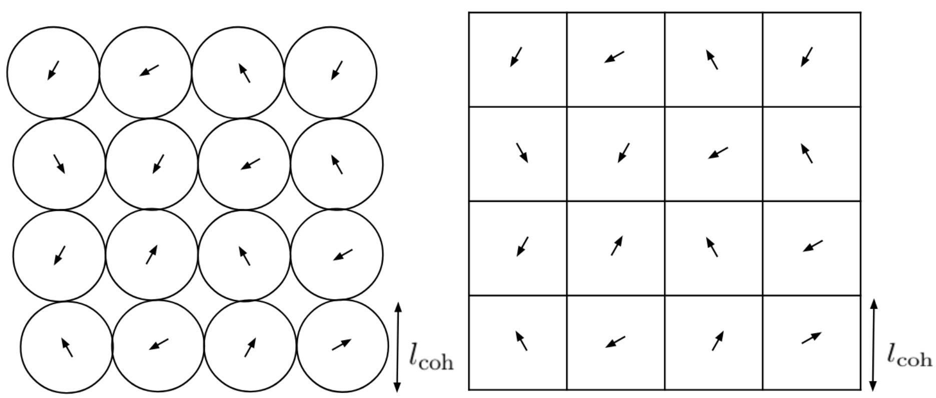

FIG. 3: The sketches of the magnetic field cellular structures, spherical (left panel) and cubic (right panel), valid for cells in a supercluster of galaxies, or cells inside a cluster of galaxies.

A. Magnetic Field Models

Our magnetized Universe is modelled as a cube of volume $(170\ \mathrm{l_{coh}})^3$, within which unitary (spherical [7–9] or cubic [6]) cells of fixed lattice parameter equal to $l_{\rm coh}$ and constant magnetic fields of strength $B_{\rm r}$ and random orientations (see Fig. 3). Moreover, to take into account the magnetic field discontinuities, in the case of spherical cells, a coherence region is defined by distance from the center of the cell as $(1 - s_{\rm depth})\, l_{\rm coh}/2$, where $s_{\rm depth}$ is a skin depth (dashed lines in Fig. 4). Within such region, the magnetic field orientation (θ and ϕ) is the same as that of the center of the cell. Beyond the coherence region, the magnetic field orientation is weighted by:

$$\theta = \left(\frac{\theta_1}{d_1} + \frac{\theta_2}{d_2} + \cdots + \frac{\theta_{n_{\text{cells}}}}{d_{n_{\text{cells}}}}\right)\left(\frac{1}{d_1} + \frac{1}{d_2} + \cdots + \frac{1}{d_{n_{\text{cells}}}}\right)^{-1}, \tag{1}$$

$$\phi = \left(\frac{\phi_1}{d_1} + \frac{\phi_2}{d_2} + \cdots + \frac{\phi_{n_{\text{cells}}}}{d_{n_{\text{cells}}}}\right)\left(\frac{1}{d_1} + \frac{1}{d_2} + \cdots + \frac{1}{d_{n_{\text{cells}}}}\right)^{-1}, \tag{2}$$

where n_{cells} is the number of neighboring cells to be considered in the calculations and d_i the distance of the particle to the center of the cell i, with $d_1 < d_2 < ... < d_{n_{\text{cells}}}$. Up to three layers of neighboring cells can be considered in the calculations ($2 \leq n_{\text{cells}} \leq 27$). The magnetic field $\vec{B}(\theta, \phi)$ is given by:

$$\begin{aligned} B_x &= B_{\text{r}} \sin\theta \cos\phi, \\ B_y &= B_{\text{r}} \sin\theta \sin\phi, \\ B_z &= B_{\text{r}} \cos\theta. \end{aligned} \tag{3}$$

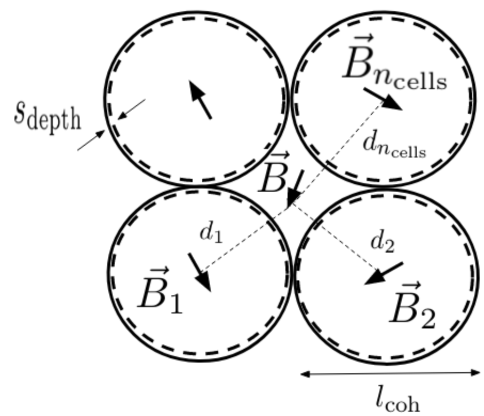

FIG. 4: A sketch of the region of transition between the cells of constant magnetic fields as modeled in **EGCRProp** .

B. Comoving Distance

An effect of the expanding Universe is the constants changes in the distance between two comoving objects. In cosmology, there are many ways to calculate the distances in an expanding Universe [12]. The mathematical expression for Hubble's law is as follows:

$$v = H_0 D, \tag{4}$$

where v is the speed of the receding galaxies, H_0 the Hubble's constant which corresponds to the value of H in the local Universe (at $z = 0$) and D the proper distance which can change over time. In general, H is a function of the redshift, $H(z) = H_0 E(z)$[4], with

$$E(z) \equiv \sqrt{(1+z)^3\Omega_m + (1+z)^2\Omega_k + \Omega_\Lambda} \tag{5}$$

a dimensionless function, where Ω_Λ is the dark energy density, Ω_m the total matter density and $\Omega_k = 1 - (\Omega_m + \Omega_\Lambda)$ represents the "curvature of space". For flat space ($\Omega_k = 0$) the density parameter Ω follows the relation $\Omega = \Omega_m + \Omega_\Lambda = 1$.

The Hubble's time t_{H} is defined as follows:

$$t_{\text{H}} \equiv \frac{1}{H_0}, \tag{6}$$

[4] The values for the cosmological parameters used in **EGCRProp** are $H_0 = 70.0$ (km/s)/Mpc, $\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$ and $\Omega_k = 0$ (flat space).

and the Hubble's distance $D_{\rm H}$ as the speed of light c divided by the Hubble's constant:

$$D_{\rm H} \equiv \frac{c}{H_0}. \tag{7}$$

In the expanding Universe, for a small redshift ($z \ll 1$), it is possible to approximate [13]:

$$z \approx \frac{D}{D_{\rm H}}. \tag{8}$$

If two objects are moving with the Hubble's flow, the comoving distance

$$D_{\rm C} = D_{\rm H} \int_0^z \frac{dz'}{E(z')} \tag{9}$$

remains constant with the epoch (at $z = 0$). The **EGCRProp** calculates the distance from the observer to the source by Eq. (9), with redshift given by Eq. (8).

C. Energy Losses Model

Due to the energy dependence for the scattering of UHECRs on EGMFs, $\theta \propto E^{-1}$, the energy losses have to be considered when describing the intergalactic propagation. We approximated the energy loss as Continuous Energy Loss (CEL) processes parameterizing the mean energy loss per unit path length by the energy loss length $\chi_{\rm loss}$ (see Fig. 5), which contains the contributions due to photo-pion production $\chi^{\pi}_{\rm loss}$, pair production $\chi^{\rm pair}_{\rm loss}$, photodisintegration of nuclei $\chi^{\rm dis}_{\rm loss}$, and adiabatic losses due to cosmic expansion $\chi^{\rm exp}_{\rm loss}$.

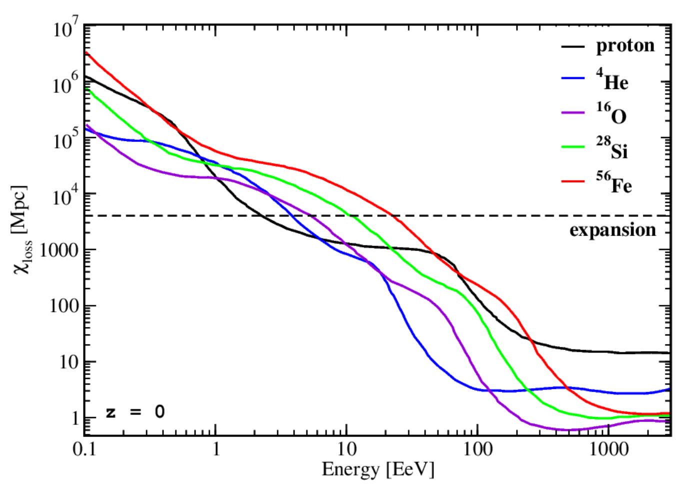

FIG. 5: The total energy loss length, $\chi_{\rm loss}$, as a function of energy, for several nuclei (protons, helium: ^{4}H, oxygen: ^{16}O, silicon: ^{28}Si and iron: ^{56}Fe). The horizontal dashed line indicates the effect of the adiabatic expansion of the Universe. Adapted from [14].

The effect of propagation of nuclei, except for protons, cannot be calculated precisely from the energy loss length shown in Fig. 5, because an accelerated nucleus can change its mass through photodisintegration interactions. The precise calculation for nuclei propagation should be done with the cross sections for all nuclei and isotopes lighter than the injected nucleus. In addition to the cross sections for losing one, two and more nucleus, the calculation should evaluate the decaying probability for unstable nuclei that may be generated in the propagation. However, somehow the calculation of energy losses through Fig. 5 can be useful when the interest is for a maximal spreading angle. In general terms, this approximation gives us information on the differences in energy evolution for the propagation of protons and heavier nuclei.

For great sources distances, cosmological effects must be taken into account. Due to the higher density CMB photons at a previous epoch, the density of photons and the temperature at a distance corresponding to a redshift z

are, respectively, $n_\gamma \propto (1+z)^3$ and $T_{\rm CMB} \propto (1+z)$. As a consequence, the energy loss length at the redshift z can be obtained from the value in the local Universe by using the following scaling law [7]:

$$\chi_{\rm loss}(E,z) = \frac{\chi_{\rm loss}[(1+z)E, z=0]}{(1+z)^3}. \tag{10}$$

EGCRProp takes into account the energy losses as are shown in Fig. 5 by correcting the energy loss length with redshift by Eq. (10). The energy loss length due to cosmic expansion scales as $\chi^{\rm exp}_{\rm loss} = \chi^{\rm exp}_{{\rm loss},z=0} \times (1+z)^{-3/2}$.

D. Calculation of the Deflection Angle

On typical length scales of UHECRs propagation, the size of the Earth as an observer vanishes. Hence, in a simulation, a point-like observer should be assumed. However, it is very inefficient to simulate a target like this, since, in practice, no event will reach the observer. On the other hand, the finite size of the observer can introduce spurious effects in the measurements of the anisotropy of UHECRs and must be treated very carefully. In an **EGCRProp** run, the deflection angle α of particle's trajectory is calculated by the scalar product between the particle's arrival (as measured at the higher Earth's atmosphere) momentum $\vec{p}_{\rm a}$ and the particle's injection (at the source position) momentum $\vec{p}_{\rm i}$:

$$\cos\alpha = \frac{\vec{p}_{\rm i} \cdot \vec{p}_{\rm a}}{|\vec{p}_{\rm i}||\vec{p}_{\rm a}|}. \tag{11}$$

E. The Propagation Procedure

Before the simulations, the tensorial magnetic field generator must be run to produce the random orientations[5] of the magnetic field cellular structure. Each pair of the tensor coordinates generated is associated with the center of each cell. The center of each cell is placed in a grid with a lattice parameter equal to the coherence length $l_{\rm coh}$. An event starts as a particle (or antiparticle)[6] placed in the Universe's center. The particle's initial speed is given by its initial energy. In the beginning of an event ($t = 0$), a particle is kicked from the Universe's center with momentum $\vec{p}(\theta, \phi)$ given by:

$$\begin{aligned} p_x(0) &= p \sin\theta \cos\phi, \\ p_y(0) &= p \sin\theta \sin\phi, \\ p_z(0) &= p \cos\theta, \end{aligned} \tag{12}$$

where θ and ϕ are, respectively, distributed within the intervals $[0, \pi]$ and $[0, 2\pi]$ for a set of many events. Subsequently, the particle is propagated through the extragalactic medium up to a predetermined distance. In each step of the simulation, the dynamics and energy losses of the particle are simulated. The particle's energy changes are given through interpolation of the energy loss length as shown Fig. 5 and the effects of the magnetic deflections are calculated as described in Sec. I. At the end of the simulation, the deflection angle α of the particle's trajectory and the final particle's energy are calculated.

II. INPUT PARAMETERS

Tab. I shows the input parameters[7] for an **EGCRProp** run with their respective descriptions and default values.

---

[5] The file *magnetic_tensors.dat*, which contains a pair of tensor coordinates (zenith and azimuth angles, respectively, uniformly distributed within the intervals $[0, \pi]$ and $[0, 2\pi]$) for each cell.

[6] We use backtracking and forward-tracking procedure, hereafter we will refer to forward-tracking method only. Note that in the backtracking method, the particle's energy increases rather than decreases as in the standard propagation.

[7] The inuput parameters need to be written in the file *input_parameters.dat*.

Parameter	Decription	Default
P_{spec}	particle specie: **1** proton; **2** helium: ^{4}He; **3** oxygen: ^{16}O; **4** silicon: ^{28}Si; **5** iron: ^{56}Fe	**1**
E_{EeV}	energy in EeV: ranging from 0.1 EeV (at $z = 0$) up to 30.0 ZeV (at the source position)	10.0
D_{Mpc}	maximum distance in Mpc	50.0
E_{loss} [8]	energy losses: **0** off; **1** on	**0**
MF_{model}	magnetic field model: **1** Spherical Structure; **2** Cubic Structure; **3** Uniform Magnetic Field	**1**
B_{nG}	magnetic field strength in nG	1.0
l_{coh} [9]	coherence length in Mpc	1.0
s_{depth} [10]	skin depth in % of $l_{coh}/2$ (cell radius)	5.0
n_{cells}	number of nearby cells to be considered: ranging from 2 up to 27 cells	2
b_{track} [11]	backtracking mode: **0** off; **1** on	**0**
d_{stop} [12]	stopping distance mode: **1** for a total traveled distance of D_{Mpc}; **2** for a trajectory of linear radius of D_{Mpc}	**2**
M_r [13]	magnetic rigidity mode: **0** off; **1** on	**0**
N_{evts}	number of particles to be launched	1000
N_{traj}	number of plotted trajectories	1
i_{method}	integration method of the equation of motion: **1** Runge-Kutta 4th; **2** Boris; **3** Vay; **4** New Euler	**1**
t_{scale}	time scale (integration step of the equation of motion)	0.0001
r_{dist} [14]	random distribution: **1** uniform; **2** gaussian (with $\sigma = 1$)	**1**
r_{seed}	random seed: **0** based on time; **1** fixed (123 as default - variable mySeed, line 17 in the file MPFRGSLvariables.h)	**0**

TABLE I: Input parameters for a **EGCRProp** run.

III. OUTPUT FILES

The output files of **EGCRProp** encodes the command options used (see Tab. I), and several data files are generated. For instance, when the default parameters are used, one gets[15]:

- For the tensor coordinates:

  magnetic_tensors_SEED123.dat;

- If the tensorial magnetic field generator worked correctly at the end of its operation, it is generated:

  TENSORSGENERATOR − SUCCESSFULLYCOMPLETED_SEED123.dat;

- For the particle's position:

  EGCRProp − traj − 100_Eloss0_A1_B1.0_lcoh1.0_E1.0_D50.0_Nevts1_1.dat;

- For the dynamic parameters:

  EGCRProp − D0 − defl − Enrg − 020_Eloss0_A1_B1.0_lcoh1.0_E10.0_D50.0_Nevts1.dat;

- For the summary of the simulations:

  EGCRProp − summary − 020_Eloss0_A1_B1.0_lcoh1.0_Nevts1.dat;

- If the propagator worked correctly at the end of its operation, it is generated:

  EGCRProp − SUCCESSFULLYCOMPLETED − 020_Eloss0_A1_B1.0_lcoh1.0_Nevts1.dat;

---

8 The energy losses are approximated as a Continuous Energy Loss (CEL).
9 It works only for $MF_{model} = \mathbf{1}$ and $MF_{model} = \mathbf{2}$.
10 It works only for $MF_{model} = \mathbf{1}$.
11 If the backtracking mode is **on**, the Universe's center is placed at $z = 0$. If the backtracking mode is **off**, the Universe's center is placed at $z = D_{Mpc}/D_H$.
12 Stopping distance **1** works only if the backtracking mode is **on**.
13 If the magnetic rigidity mode is **on**, in the calculations the particle's initial energy will be multiplied by the particle's atomic number Z ($E_0 = E_{EeV} \times Z$), and the output file will be containing the particle's magnetic rigidity ($R = E_{EeV}/Z$).
14 **EGCRProp** makes use of the "Mersenne Twister" generator of Makoto Matsumoto and Takuji Nishimura [11] through the GSL library [4].
15 The three first numbers in the output file name denote the command's options for backtracking, stopping distance, and magnetic rigidity, respectively. The others numbers denote the command's options for energy losses (E_{loss}), particle's atomic number (A), magnetic field strength (B), coherence length (l_{coh}), particle's initial energy (or magnetic rigidity, if $M_r = \mathbf{1}$) (E_{EeV}), maximum distance (D_{Mpc}), and events number (Nevts), respectively.

IV. ACKNOWLEDGMENTS

The authors are very thankful to UFABC (Universidade Federal do ABC) and CAPES (Coordenação de Aperfei çoamento de Pessoal de Níivel Superior) for the financial and computational supports that made possible the execution of this work.

[1] MPFR C++ library, http://www.holoborodko.com/pavel/mpfr. [Accessed August 24, 2018].
[2] MPFR library, http://www.MPFR.org/. [Accessed August 24, 2018].
[3] GNU MP library, https://gmplib.org/. [Accessed August 24, 2018].
[4] GSL library. https://www.gnu.org/software/gsl/. [Accessed August 24,2018]
[5] ExtraGalagactic Cosmic-Ray Propagator (EGCRProp), 2018. http://pesquisa.ufabc.edu.br/egcrprop/. [Accessed August 24, 2018]
[6] T. Wibig. Propagation of Ultra-High Energy Cosmic Rays in Extragalactic Magnetic Fields. Central European Journal of Physics, 2(2):277-299, 2004. https://doi.org/10.2478/BF02475633
[7] A. Achterberg et al. Intergalactic Propagation of UHE Cosmic Rays. 1999. http://adsabs.harvard.edu/abs/1999astro.ph..7060A.
[8] K. Kotera and M. Lemoine. Inhomogeneous Extragalactic Magnetic Fields and the Second Knee in the Cosmic Ray Spectrum. Physics Review D, 77:023005, 2008. https://doi.org/10.1103/PhysRevD.77.023005.
[9] A. De Angelis et al. Contraints on Large-Scale Magnetic Fields from the Auger Results. Modern Physics Letters, A23:315-317, 2008. https://doi.org/10.1142/S0217732308026431.
[10] I. Antcheva et al., ROOT - A C++ Framework for Petabyte data Storage, Statistical Analysis and Visualization. Computer Physics Communications, 180(12):2499-2512, 2009 https://doi.org/10.1016/j.cpc.2009.08.005.
[11] Matsumoto M & Nishimura T., ACM Transactions on Modeling and Computer Simulation, 8 (1) (1998) 3-3.
[12] D. W. Hogg. Distance Measures in Cosmology. arXiv e-prints, 1999. https://ui.adsabs.harvard.edu/#abs/1999astro.ph..5116H.
[13] E. Harrison. The Redshift-distance and Velocity-distance Laws. The Astrophysical Journal, 403(1):28-31, 1993. https://doi.org/10.1086/172179.
[14] Allard D. Extragalactic Propagation of Ultrahigh Energy Cosmic-Rays. Astroparticle Physics, 39-40:33-43, 2012.https://doi.org/10.1016/j.astropartphys.2011.10.011.