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SimProp : Monte Carlo code for UHECR propagation

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SimProp v2r4: Monte Carlo simulation code for UHECR propagation, R. Aloisio, D. Boncioli, A. di Matteo, A.F. Grillo, S. Petrera, F. Salamida, JCAP11(2017)009

Introduction

SimProp is a Monte Carlo code for simulating the propagation of Ultra-High-Energy Cosmic Rays through intergalactic space

SimProp run :

- N events are simulated → N primary particles with mass number A_{inj}
- The initial energy E_{inj} is sampled from a power-law distribution from E_{min} and E_{max} with spectral index $-\gamma$
- The source redshift z_{inj} is sampled from a uniform distribution between z_{min} and z_{max}
- The propagation of particles (primary and secondary) is followed

Magnetic field are neglected → 1-dimensional propagation

Introduction

Processes taken into account:

- **Redshift energy loss** $\left(-\frac{1}{E}\frac{\mathrm{d}E}{\mathrm{d}t}\right)_{\mathrm{ad}} = H(t) = H_0\sqrt{(1+z)^3\Omega_{\mathrm{m}} + \Omega_\Lambda}$
- **Interactions with background photons** :
  - Electron-positron pair production
  - Photodisintegration of nuclei
  - Pion photoproduction (approximated as single pion production)
- **Decays of neutrons and unstable nuclei** (instantaneous decay is always assumed)

Phenomenological models are used in UHECR studies

→ Several **photo disintegration models** are available in SimProp (command-line -M)

PSB with Stecker-Salamon thresholds is the default one

Introduction

Photon background taken into account:

- **CMB photons** (well known)
- **EBL photons** (not directly measured)

Phenomenological models are used for the **EBL spectrum and its evolution with redshift**

→ Several **EBL models** are available in SimProp (command-line -L)

No.	model
0	none (CMB only)
1	Stecker et al. 2006 **(default)**
2	power-law approximation
3	Kneiske et al. 2004
4	Domínguez et al. 2011 best fit
5	Domínguez et al. 2011 lower limit
6	Domínguez et al. 2011 upper limit
7	Gilmore et al. 2012 fiducial

- Compile the software: **`make`**
- Run SimProp with default options: **`./SimProp | grep Event`**

```
** Events to be generated: 100
** Event 0 ****************************************
** Event 1 ****************************************
** Event 2 ****************************************
** Event 3 ****************************************
** Event 4 ****************************************
…
```

Input parameters

- **Compile the software:** `make`
- **Run SimProp with default options:** `./SimProp | grep Event`

`./SimProp -h`

```
SimProp -N [number of events, D=100]  -s [random seed, D=65539]
         -A [A (0 for all), D=56]  -e [min energy log10(Emin/eV), D=17.]
         -E [max energy log10(Emax/eV), D=21.]
         -g [injection spectral index, D=1.]
         -z [min redshift, D=0.] -Z [max redshift, D=1.]
         -r [source relative distance (Mpc), D=0.]
         -L [EBL, 0=none, 1=Stecker+ '06, 2=power law, 3=Kneiske+ '04,
             4=Dominguez+ '11 (best), 5=Dominguez (lower), 6=Dominguez (upper),
             7=Gilmore+ '12 (fiducial), D=1]
         -M [nuclear model type, 0=Stecker-Salamon, 1=arb. Gaussians,
             2=arb. Breit-Wigner, 3=arb. Breit-Wigner with alpha,
             4=arb. Gausssians with alpha, D=0]
         -n [scales nucleon photodis. cross sections (only with M>=3), D=1.]
         -a [scales alpha photodis. cross sections (only with M>=3), D=1.]
         -D [beta decay, 0=none, 1=istantaneous, D=1]
         -S [pion photoproduction, -1=continuous for protons only,
             0=continuous for all nuclei, 1=stochastic on CMB only,
             2=stochastic on CMB+EBL, D=1]
         -p [e+e-, 0=neglected, 1=individually written to output (WARNING: very
             large files!), 2=binned in z, 3=only total energy written, D=0]
         -o [output types, 0=all branches, 1=summary tree, 2=both, D=0]
```

Input parameters

`-s`	seed of the random number generator	65539
`-N`	number of events to be generated	100
`-A`	mass number of primary nuclei, A_{inj} (chosen at random for each event with `-A 0`)	56
`-e`	$\log_{10}(E_{\text{min}}/\text{eV})$, where E_{min} is the minimum injection energy	17
`-E`	$\log_{10}(E_{\text{max}}/\text{eV})$, where E_{max} is the maximum injection energy	21
`-g`	injection spectral index, γ	1
`-z`	minimum source redshift, z_{min}	0
`-Z`	maximum source redshift, z_{max}	1
`-r`	distance between sources, L_{s},[5] in Mpc	0
`-L`	EBL model	1
`-M`	photodisintegration model	0
`-n`	nucleon ejection scaling factor (only with `-M 3` and `-M 4`)	1
`-a`	alpha-particle ejection scaling factor (only with `-M 3` and `-M 4`)	1
`-D`	beta decay: `0` disabled, all nuclei treated as their respective beta-decay stable isobars; `1` enabled, treated as instantaneous	1

Input parameters

`-S`	treatment of pion production: `-1` continuous energy loss approximation for protons, neglected for other nuclei (as in *SimProp* v2r0); `0` continuous energy loss for both protons and other nuclei; `1` stochastic, on the CMB only; `2` stochastic, on both the CMB and the EBL	1
`-p`	electrons and positrons: `0` disregarded, `1` individually written to output file (warning: results in very large output files), `2` binned according to production redshift (by default $[10^{-4.0}, 10^{-3.8}), \ldots, [10^{+0.8}, 10^{+1.0})$, but can be changed in the file `src/Output.h` before compiling), `3` only total energy written	0
`-o`	output type (see below): `0` old (`nuc` and `ev` trees); `1` new (`summary` tree); `2` both	0

Simulate one event

```
./SimProp -N 1 -A 56 -e 18. -E 18. -g 1. -z 1 -Z 1 -o 1
```

```
          >>  SimProp v2r4  <<

-------------------------------------------------------------------------------
  Authors: D. Boncioli, A. di Matteo, A.F. Grillo, S. Petrera and F. Salamida
-------------------------------------------------------------------------------
  events              : 1
  random seed         : 65539
  A                   : 56
  Emin                : 1e+18 eV
  Emax                : 1e+18 eV
  inj. spectr. index  : 1
  zmin                : 1
  zmax                : 1
  dist. btw. sources  : 0
  EBL model           : 1
  nuclear model       : 0
  nucleon ej. scaling: 1
  alpha ej. scaling   : 1
  beta decay          : 1
  pion photoprod.     : 1
  pair photoprod.     : 0
  output type         : 1

=====================================================================
SimProp v2r4
** Initial nucleus is: 56
** Losses are:  CMB + EBL (Stecker et al. 2006)
** Limits on redshift are: 1 1
** Limits on energy   are: 1e+18 eV 1e+18 eV
** Output files is: SimProp-v2r4_N1_A56_e18.0_E18.0_g1.00_z1.00_Z1.00_r0.00_L1_M0_n1.00_a1.00_D1_S1_p0_o1_s65539.root
```

Simulate one event

./SimProp -N 1 -A 56 -e 18. -E 18. -g 1. -z 1 -Z 1 -o 1

```
** Events to be generated: 1
** Event 0 ****************************************
==> Primary nucleus (A,Z,E,z): 56 26 1e+18 1
... propagating nucleus (56, 26)  Ecurr 1e+18 from z 1
....... stacking 1 p + 0 n, z=0.938395, E=1.73071e+16
...... int. type 1 (56, 26) -> (55, 25) zfin=0.938395 Efin=9.69197e+17
... propagating nucleus (55, 25)  Ecurr 9.5189e+17 from z 0.938395
....... stacking 2 p + 2 n, z=0.908095, E=1.70366e+16
...... int. type 4 (55, 25) -> (51, 23) zfin=0.908095 Efin=9.37011e+17
... propagating proton (1, 1)  Ecurr 1.73071e+16 from z 0.938395
........... proton (1, 1) reaches Earth with E = 8.92857e+15
... propagating nucleus (51, 23)  Ecurr 8.68865e+17 from z 0.908095
....... stacking 0 p + 1 n, z=0.479724, E=1.32118e+16
...... int. type 1 (51, 23) -> (50, 23) zfin=0.479724 Efin=6.73803e+17
... propagating proton (1, 1)  Ecurr 1.70366e+16 from z 0.908095
........... proton (1, 1) reaches Earth with E = 8.92857e+15
... propagating proton (1, 1)  Ecurr 1.70366e+16 from z 0.908095
........... proton (1, 1) reaches Earth with E = 8.92857e+15
... propagating neutron (1, 0)  Ecurr 1.70366e+16 from z 0.908095
nucleus 1.69991e+16; electron 2.90856e+13; neutrino 8.33471e+12
........ neutron decays into 3 particles at z=0.908095
... propagating neutron (1, 0)  Ecurr 1.70366e+16 from z 0.908095
nucleus 1.70034e+16; electron 2.00091e+13; neutrino 1.31574e+13
........ neutron decays into 3 particles at z=0.908095
... propagating nucleus (50, 23)  Ecurr 6.60591e+17 from z 0.479724
nucleus 6.60571e+17; electron 1.33551e+13; neutrino 6.99588e+12
........ nucleus decays into 3 particles at z=0.479724
... propagating neutron (1, 0)  Ecurr 1.32118e+16 from z 0.479724
nucleus 1.31878e+16; electron 1.86877e+13; neutrino 5.31909e+12
........ neutron decays into 3 particles at z=0.479724
... propagating proton (1, 1)  Ecurr 1.69991e+16 from z 0.908095
........... proton (1, 1) reaches Earth with E = 8.90896e+15
... propagating electron antineutrino (0, 0)  Ecurr 8.33471e+12 from z 0.908095
........... electron antineutrino (0, 0) reaches Earth with E = 4.36808e+12
... propagating electron (0, -1)  Ecurr 2.90856e+13 from z 0.908095
........ electron produced with E=2.90856e+13 at z=0.908095
... propagating proton (1, 1)  Ecurr 1.70034e+16 from z 0.908095
........... proton (1, 1) reaches Earth with E = 8.91119e+15
... propagating electron antineutrino (0, 0)  Ecurr 1.31574e+13 from z 0.908095
........... electron antineutrino (0, 0) reaches Earth with E = 6.89557e+12
... propagating electron (0, -1)  Ecurr 2.00091e+13 from z 0.908095
........ electron produced with E=2.00091e+13 at z=0.908095
... propagating nucleus (50, 24)  Ecurr 6.60571e+17 from z 0.479724
....... stacking 1 p + 0 n, z=0.402886, E=1.25254e+16
...... int. type 1 (50, 24) -> (49, 23) zfin=0.402886 Efin=6.26269e+17
... propagating electron antineutrino (0, 0)  Ecurr 6.99588e+12 from z 0.479724
........... electron antineutrino (0, 0) reaches Earth with E = 4.72783e+12
... propagating electron (0, -1)  Ecurr 1.33551e+13 from z 0.479724
........ electron produced with E=1.33551e+13 at z=0.479724
... propagating proton (1, 1)  Ecurr 1.31878e+16 from z 0.479724
........... proton (1, 1) reaches Earth with E = 8.91235e+15
... propagating electron antineutrino (0, 0)  Ecurr 5.31909e+12 from z 0.479724
........... electron antineutrino (0, 0) reaches Earth with E = 3.59465e+12
... propagating electron (0, -1)  Ecurr 1.86877e+13 from z 0.479724
........ electron produced with E=1.86877e+13 at z=0.479724
... propagating nucleus (49, 23)  Ecurr 6.13744e+17 from z 0.402886
nucleus 6.13722e+17; electron 1.38019e+13; neutrino 8.12668e+12
........ nucleus decays into 3 particles at z=0.402886
... propagating proton (1, 1)  Ecurr 1.25254e+16 from z 0.402886
........... proton (1, 1) reaches Earth with E = 8.9283e+15
... propagating nucleus (49, 22)  Ecurr 6.13722e+17 from z 0.402886
....... stacking 0 p + 1 n, z=0.0294584, E=9.19098e+15
...... int. type 1 (49, 22) -> (48, 22) zfin=0.0294584 Efin=4.50358e+17
... propagating electron neutrino (0, 0)  Ecurr 8.12668e+12 from z 0.402886
........... electron neutrino (0, 0) reaches Earth with E = 5.79283e+12
... propagating positron (0, 1)  Ecurr 1.38019e+13 from z 0.402886
........ positron produced with E=1.38019e+13 at z=0.402886
... propagating nucleus (48, 22)  Ecurr 4.41167e+17 from z 0.0294584
........... nucleus (48, 22) reaches Earth with E = 4.28543e+17
... propagating neutron (1, 0)  Ecurr 9.19098e+15 from z 0.0294584
nucleus 9.18154e+15; electron 7.37907e+12; neutrino 2.06049e+12
........ neutron decays into 3 particles at z=0.0294584
... propagating proton (1, 1)  Ecurr 9.18154e+15 from z 0.0294584
........... proton (1, 1) reaches Earth with E = 8.91881e+15
... propagating electron antineutrino (0, 0)  Ecurr 2.06049e+12 from z 0.0294584
........... electron antineutrino (0, 0) reaches Earth with E = 2.00153e+12
... propagating electron (0, -1)  Ecurr 7.37907e+12 from z 0.0294584
........ electron produced with E=7.37907e+12 at z=0.0294584
** event ended - elapsed time (s) 0.06129
```

Simulate one event

```
./SimProp -N 1 -A 56 -e 18. -E 18. -g 1. -z 1 -Z 1 -o 1
```

```
 ++++  Succesfully processed 1 events ++++
--------------------------------------------------
      Nucleus Type   Number reaching Earth
--------------------------------------------------
            1                  8
           48                  1
--------------------------------------------------
        Total                  9

--------------------------------------------------
photons from pi0 decay:              0
electrons produced:                  5
positrons produced:                  1
--------------------------------------------------
      Neutrino Type     Number reaching Earth
--------------------------------------------------
electron neutrinos:                  1
electron antineutrinos:              5
muon neutrinos:                      0
muon antineutrinos:                  0
--------------------------------------------------
        Total                        6
```

Simulate 5000 events

```
./SimProp -N 5000 -A 56 -e 18. -E 22. -g 1. -z 0.1 -Z 0.1 -o 1 | grep Event
```

```
root SimProp-v2r4_N5000_A56_e18.0_E22.0_g1.00_z0.10_Z0.10_r0.00_L1_M0_n1.00_a1.00_D1_S1_p0_o1_s65539.root
root [0] summary->Print()
root [0] summary->Draw(“nucEnergy")
```

Summary tree
(one entry for each event)