Extragalactic sources and propagation, including constraints on extragalactic magnetic fields

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UHECR2016

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Image: ASPERA
Measurements on UHECRs

**SPECTRUM**

- Energy spectrum of UHECRs
  - Data from Telescope Array and Auger, Astrop. J. 794 (2014) 2, 172

**ARRIVAL DIRECTION**

- Arrival directions of UHECRs
  - Data from Telescope Array and Auger, PoS (ICRC2015) 035

**COMPOSITION**

- Average and Standard Deviation of $X_{\text{max}}$
  - Data from Auger, PoS (ICRC2015) 271 (proton), 320 (iron), 420 (proton, iron)

13/10/16

AvV - EG sources and propagation
UHECR secondaries

ASTROPHYSICAL

NEUTRINO FLUX

ISOTROPIC DIFFUSE

γ-RAY BACKGROUND

IceCube, PoS (ICRC2015) 1081

Extragalactic environment

- Source distribution following the Large-Scale Structure (LSS)
- Deflection in the extragalactic magnetic (EGMF)
- Example based on LSS formation simulations by Miniati et al. 2004:
Energy-loss interactions

- Pair production
- Photopion production on CMB and EBL
- Photodisintegration
- Nuclear decay
- Redshift losses
- Electromagnetic cascade propagation

Galactic propagation

- Deflections in the galactic magnetic field
- Example: GMF model by Jansson and Farrar 2012
  - Large-scale regular field
  - Large-scale random (striated) field
  - Small-scale random (turbulent) field
CRPropa 3


• A public astrophysical simulation framework for propagating extraterrestrial ultra-high energy particles

• Initial release was on 23/03/2016

• Available from crpropa.desy.de

• Online installation on VISPA

• Modular redesign of the code structure
Example simulation

- Source distribution: following LSS from Dolag et al. 2005
- Source density: $10^{-3}$ Mpc$^{-3}$
- EGMF structure: Dolag et al. 2005
- EGMF strength: Miniati et al. 2004
- GMF model: Jansson and Farrar 2012
- EBL model: Gilmore et al. 2012
- Injection spectrum:
  \[
  \frac{dN}{dE} \propto \begin{cases} 
  (E / E_0)^{-\alpha}, & E < E_{\text{cut}} \\
  (E / E_0)^{-\alpha} \exp(1 - E / E_{\text{cut}}), & E > E_{\text{cut}}
  \end{cases}
  \]
- Cutoff energy: $E_{\text{cut}} = 780$ EeV
- Injection index: $\alpha = 1.5$
Arrival directions

$E > 10^{18}$ eV

**Before GMF**

- $p$
- Fe

Intensity [normalized]

$\leq 0.3$  $\geq 0.7$

**After GMF**

- $p$
- Fe

Intensity [normalized]

$\leq 0.3$  $\geq 0.7$
Angular power spectra

• Measure for the anisotropy
• Dipole amplitude: \(~0.06\)
• 99% CL isotropy lines for full sky coverage

$$C_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2$$
Spectrum and composition

- 4D includes cosmological effects and adiabatic energy losses due to expansion of the universe
- Spectrum: only small differences
- Composition for $E<10$ EeV:
  - 1D heavier than 4D; increased path length due to EGMF
  - 4D heavier than 3D; adiabatic energy losses

$\alpha=1.5, E_{\text{cut}}=780$ EeV

\[ \langle \ln(A) \rangle \]

\[ \begin{align*}
\text{iron, 4D} & \quad \text{iron, 3D} & \quad \text{iron, 1D (universal)} \\
\text{protons, 4D} & \quad \text{protons, 3D} & \quad \text{protons, 1D (universal)}
\end{align*} \]
Highly magnetized voids

- MHD simulations of structure formation
- Large differences between EGMF models
Average deflections

- Strong magnetic fields in voids
- Deflections of 100 EeV protons closer than ~10 Mpc relatively small (≤ 5°), depending on source distribution and magnetic seed power spectrum
- Deflections of iron nuclei would be very large (≥ 30°) even for nearby sources

R. Alves Batista et al., in preparation
Full spectrum + composition

- Extragalactic combined fit model + galactic cosmic rays from supernova remnants and Wolf-Rayet star explosions

Secondary photons and neutrinos

- Source evolution: GRBs, AGNs, SFR
- $\nu$'s and $\gamma$'s affected strongly
- At tension with Fermi LAT and IceCube results
Summary

• CRPropa 3 up and running, available at crpropa.desy.de
• Allows for spectrum, composition and arrival direction predictions for UHECRs as well as for secondary neutrinos and photons
• 3D/4D effects can affect the expected composition
• Expected average deflection at 100 EeV small for protons, but can be large for iron nuclei
Backup slides
1D, 3D and 4D

- **1D:**
  - Redshift effects included
  - Magnetic field deflections not included
  - 1D source evolution
  - Particle (almost) always hits observer

- **3D:**
  - Redshift effects not included
  - Magnetic field deflections included
  - 3D source distribution
  - Particle can miss observer in space

- **4D:**
  - Redshift effects included
  - Magnetic field deflections included
  - 3D source distribution + evolution
  - Particle can miss observer in space and time
Reference scenario

• Homogeneous distribution of identical sources

• Injection spectrum: \( \frac{dN}{dE} \propto E^{-\alpha} \exp(-E / ZR_{\text{cut}}) \)

• Maximum energy: \( R_{\text{cut}} = Z \times 200 \text{ EV} \)

• Injection index: \( \alpha = 2.5 \)

• Source evolution: comoving

• Initial CR type: protons
Reference scenario

- Already some tension with Fermi LAT isotropic diffuse γ-ray background
Maximum energy dependence

- $50 \leq R_{\text{cut}} \leq 800$ EV
- $\nu$'s only affected for $E > 10$ EeV
- $\gamma$'s only slightly affected
Spectral index dependence

- $2.0 \leq \alpha \leq 2.9$
- ν's affected similarly as CRs
- γ's only slightly affected
Source evolution dependence

- Multiplied by \((1+z)^m\), for \(-6 \leq m \leq 6\)
- \(m = 0\): BL Lacs
- \(m = -6\): HSP BL Lacs
- \(\nu's\) and \(\gamma's\) affected strongly
- Only \(m \approx -6\) allowed by Fermi LAT
Source evolution models

- GRBs, AGNs, SFR
- \(\nu\)'s and \(\gamma\)'s affected strongly
- None allowed by Fermi LAT
CR mass dependence

• Initial CR: protons vs iron
• Heavier primaries reduces neutrino and photon flux
1D: Combined fit

\[
\frac{dN}{dE} \propto \begin{cases} 
  p_i E^{-\gamma}, & E / Z_i < R_{\text{cut}} \\
  p_i E^{-\gamma} \exp(1 - E / Z_i R_{\text{cut}}), & E / Z_i > R_{\text{cut}} 
\end{cases}
\]

\[
\gamma = 0.94^{+0.09}_{-0.10}
\]

\[
\log_{10} (R_{\text{cut}} / V) = 18.67 \pm 0.03
\]

\[
p_H = 0.0^{+29.9\%}_{-}\]

\[
p_{\text{He}} = 62.0^{+3.5\%}_{-22.2\%}
\]

\[
p_N = 37.2^{+4.2\%}_{-12.6\%}
\]

\[
p_{\text{Fe}} = 0.8^{+0.2\%}_{-0.3\%}
\]
Mixed composition combined fit

- Comoving source evolution
- $\gamma = 0.73$
- $R_{\text{max}} = 3.8$ EV
- 98.69% Nitrogen, 1.31% Iron
Pair production

\[ ^A N + \gamma \rightarrow ^A N + e^+ + e^- \]

- Energy loss per interaction \( \sim 2m_e/m_p \approx 0.1\% \)
  \( \rightarrow \) continuous energy loss

- Most important reaction for creation of secondary photons in the TeV range
Photopion production

\[ ^A N + \gamma \rightarrow ^{A-1} N' + p + \pi^0 \rightarrow ^{A-1} N' + p + \gamma \gamma \]
\[ \rightarrow ^{A-1} N' + n + \pi^+ \]

• Event generation, mean free path and energy loss from SOPHIA
• “Simulates the interactions of nucleons with photons over a wide range in energy”
• “The simulation of the final state includes all interaction processes which are relevant to astrophysical applications”
• “Includes resonance excitation and decay, direct single pion production and diffractive and non–diffractive multiparticle production”
Photodisintegration and decay

\[ ^A N + \gamma \rightarrow ^{A'} N' + X (n, p, ...) \]

- PD cross sections for 183 isotopes from TALYS + extensions for A<12, 2200 excl. channels
- All isotopes with lifetime >2s, A≤56 and Z≤26
- Nuclear decay for 434 isotopes from NuDat2 + alterations to correctly account for electron capture
Photon backgrounds

- CMB
- EBL, 6 different models
Galactic propagation

• Cosmic ray propagation through magnetic fields can be modelled on any scale

• From the CRPropa 3 paper:

<table>
<thead>
<tr>
<th>General magnetic fields</th>
<th>Galactic magnetic fields</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Uniform</strong></td>
<td>Toroidal halo field model adopted from [24, 25].</td>
</tr>
<tr>
<td>Magnetic field is a position independent single</td>
<td></td>
</tr>
<tr>
<td>vector magnetic field.</td>
<td>Halo</td>
</tr>
<tr>
<td><strong>Grid</strong></td>
<td>Magnetic field model of axisymmetric (ASS) or bisymmetric (BSS) logarithmic spiral shape.</td>
</tr>
<tr>
<td>Provides a periodic magnetic field grid with</td>
<td>Pshirkov et al. magnetic field model, consisting of a large-scale regular (disk and halo) field [16].</td>
</tr>
<tr>
<td>trilinear interpolation, equal spacing, and</td>
<td>The axisymmetric (ASS) and the bisymmetric (BSS) disk model can be chosen.</td>
</tr>
<tr>
<td>different sizes along each axis.</td>
<td></td>
</tr>
<tr>
<td><strong>Modulated</strong></td>
<td>Implementation of the Jansson &amp; Farrar magnetic field model, consisting of a large-scale regular and random ( striated) field and a small-scale random (turbulent) field [10, 15].</td>
</tr>
<tr>
<td>Grid</td>
<td></td>
</tr>
<tr>
<td>Provides a periodic small scale scalar field.</td>
<td></td>
</tr>
<tr>
<td><strong>Turbulent</strong></td>
<td></td>
</tr>
<tr>
<td>A random magnetic field with a turbulent</td>
<td></td>
</tr>
<tr>
<td>spectrum [23].</td>
<td></td>
</tr>
</tbody>
</table>
3D: Lensing method

• Lenses obtained through backtracking
• Stored in matrices dependent on rigidity $E/Z$
• Map discrete directions outside the galaxy to discrete observed directions on Earth
Galactic lensing method

- Map discrete directions outside the galaxy to discrete observed directions on Earth

\[ V_E = (p_1, \ldots, p_N) \quad \times \quad M \quad = \quad O_E = (p_1, \ldots, p_N) \]
Galactic deflection matrix

- Backtrack $\sim 10^6$ UHECRs per rigidity, 100 rigidity bins

$$\hat{M}_E = \begin{pmatrix} 1 & 1 & 1 \\ 2 & 1 & 0 \\ 0 & 2 & 1 \end{pmatrix}$$

Sum of columns: 3, 4, 2

$$\hat{M}_E' = \begin{pmatrix} 1 \\ \frac{1}{2} \\ 0 \\ \frac{1}{4} \\ \frac{1}{4} \\ \frac{1}{4} \\ \frac{1}{4} \\ \frac{1}{4} \\ \frac{1}{4} \end{pmatrix}$$
Galactic deflection matrix

2/3 of flux enter galaxy in pixel 1
1/3 of flux enter galaxy in pixel 2

\[ \vec{\nu} = \begin{pmatrix} \frac{2}{3} \\ \frac{1}{3} \\ 0 \end{pmatrix} \]

\[ M_E = \begin{pmatrix} \frac{1}{4} & \frac{1}{4} & \frac{1}{4} \\ \frac{1}{4} & \frac{1}{4} & \frac{1}{4} \\ 0 & \frac{1}{4} & \frac{1}{4} \end{pmatrix} \]

\( m_{ij} \) is probability that particle which enters galaxy in pixel \( j \) is observed on earth in pixel \( i \)

Get observed distribution by matrix multiplication

\[ M_E \cdot \vec{\nu} = \vec{O} \]

\[ \begin{pmatrix} \frac{1}{4} & \frac{1}{4} & \frac{1}{4} \\ \frac{1}{4} & \frac{1}{4} & \frac{1}{4} \\ 0 & \frac{1}{4} & \frac{1}{4} \end{pmatrix} \cdot \begin{pmatrix} \frac{2}{3} \\ \frac{1}{3} \\ 0 \end{pmatrix} = \begin{pmatrix} \frac{3}{12} \\ \frac{5}{12} \\ \frac{2}{12} \end{pmatrix} \]
Figure 8. Comparison of PSB and TALYS photodisintegration models for hard nitrogen injection.
EGMF constrains

G. Sigl, “Astroparticle Physics: Theory and Phenomenology”

Fig. 4.8 Summary of observational constraints on cosmological fields in the plane of comoving coherence length and r.m.s. field strength are presented as shaded areas. At lengths below the resistive length scale given by Eq. (4.130) magnetic fields would be damped within a Hubble time, the CMB constraint is from Ref. [181], the Faraday rotation limits are from Ref. [178, 179], the horizontal upper limit is from the contribution to radiation, see Eq. (4.194), and the Zeeman effect on spectral lines, and the coherence length can not be larger than today’s Hubble scale. A possible lower limit of the form of Eq. (8.79) [182] (Fermi GeV blazars) will be discussed in Sect. 8.1.8, but is not generally agreed upon. Magnetic fields in galaxies and galaxy clusters are shown as white shades. The relation Eq. (4.141) for MHD turbulence is shown as red band. Dashed and solid blue lines show the evolution of maximally helical and non-helical fields following Eq. (4.146) and (4.148), respectively, with initial comoving strength $3 \times 10^{-6}$ G and coherence length given by the comoving Hubble scale at the electroweak and QCD phase transition, see Eq. (4.121), shown as arrows. The dotted blue line is for initial magnetic helicity $H_t = 10^{-10} H_{\text{max}}$ starting at the electroweak scale, motivated by certain baryogenesis scenarios discussed in Sect. 4.7 below. Since helicity is conserved, see Eq. (3.272), it follows the non-helical scaling until $B^2_{31 c,0}$ has decreased by a factor $H_t/H_{\text{max}}$ after which the field is maximally helical and follows the scaling Eq. (4.146). Parts of figure based on Ref. [182].
FIG. 1. Power spectrum of the initial magnetic field at $z \simeq 53$ (left) and $z \simeq 0$ (right panel), in comoving units, as a function of the comoving wave number $h^{-1}k$. 

Alves Batista et al., in preparation
The propagation was done using the CRPropa 3 code [51]. Particles are injected by sources with energies between 1 EeV and 1000 EeV, with the following spectrum:

\[
\frac{dN}{dE} \propto \begin{cases} 
E^{-\alpha} & \text{if } E_{\text{max}} > E \\
E^{-\alpha} \exp \left(1 - \frac{E}{E_{\text{max}}} \right) & \text{if } E_{\text{max}} \leq E 
\end{cases}
\]  

(1)

where \(\alpha_{\text{Fe}} = 1\) and \(\alpha_p = 2\) are the spectral indices for the injected iron and proton scenarios, respectively. Here \(E_{\text{max}}\) is the maximal energy. In this work we use \(E_{\text{max}, p} = 500\ \text{EeV}\) for protons and \(E_{\text{max}, \text{Fe}} = 156\ \text{EeV}\) for iron primaries. One should note that these choices are arbitrary.

Spectra of EGMF paper
<table>
<thead>
<tr>
<th>nucleus E [EeV]</th>
<th>D [Mpc]</th>
<th>sources</th>
<th>run F</th>
<th>run L</th>
<th>run S</th>
<th>run O</th>
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<td>p</td>
<td>10</td>
<td>0-10</td>
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<td>21.4° ± 11.5°</td>
<td>31.7° ± 19.6°</td>
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<td>lss</td>
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<td>92.4° ± 17.7°</td>
<td>76.5° ± 19.0°</td>
<td>75.7° ± 16.5°</td>
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</table>
Full spectrum & composition

SNRs
Full spectrum & composition

SNRs combined
Full spectrum & composition

- 2\textsuperscript{nd} Galactic component
- Reacceleration by Galactic wind termination shocks
- Wolf-Rayet star explosions
Full spectrum & composition

• Combined
• SNRs + WR-CRs + 3 different extragalactic models