Propagation of ultra-high energy cosmic rays

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During propagation from their sources to the Earth UHECRs are subject to:

- energy redshift due to the expansion of the universe

- interactions with radiation backgrounds (CMB and IR/visible/UV extragalactic background light) → energy losses, composition changes

- deflections in the intergalactic/Galactic magnetic fields

These processes change the spectrum, mass composition and arrival direction of the particles observed at Earth with respect to those of the particles emitted by the sources observed at Earth are shaped by source properties + propagation
Interactions with radiation backgrounds: studied in detail since Greisen, Zatsepin & Kuz'min (1966)

- $e^-e^+$ pair production ($A+\gamma \rightarrow A+e^-+e^+$)
- disintegration of nuclei ($(A+i)+\gamma \rightarrow A+ i N$)
- photopion production ($p+\gamma \rightarrow p+\pi^0$, $n+\pi^+$ or $n+\gamma \rightarrow n+\pi^0$, $p+\pi^-$)

These processes also lead to the production of secondary particles: nucleons, $e^-e^+$ pairs, neutrinos, gamma rays

Few public Monte Carlo codes available: SimProp (Aloisio et al. 2018), CRPropa (Alves Batista et al. 2016)
Modification of the proton spectrum due to interactions

$$\eta = \frac{\text{actual spectrum}}{\text{spectrum in the absence of interactions}}$$

Berezinsky, Gazizov, Grigorieva 2006

Protons with spectrum $E^{-\gamma}$ and two hypothesis for source evolution

Modification factor independent of $\gamma$

source evolution:
Star Formation Rate

\[
\begin{cases} 
(1 + z)^{3.44} & z < 0.97 \\
(1 + z)^{-0.26} & z > 0.97 
\end{cases}
\]

→ more weight to far away sources
→ relative enhancement of flux at low energies wrt the no evolution case
Modification of the spectrum for nuclei: heaviest fragment and secondary protons

expansion & pair creation $\rightarrow$ change $\Gamma$

photo-disintegration $\rightarrow$ changes $A$

notice that composition at Earth is changed

modification factor independent of $\gamma$

more secondary protons for harder spectrum

SFR evolution $\rightarrow$ enhancement of flux at low energies

SM Roulet 2019
Effect of the intergalactic magnetic field

turbulent field with rms amplitude \( B \) and coherence length \( l_c \)

Larmor radius \( r_L = \frac{E}{ZeB} \)

Critical energy \( r_L(E_c) = l_c \rightarrow \) for \( E < E_c \) large deflections for distances < \( l_c \)

\[
E_c = ZeBl_c \approx 0.9Z \frac{B}{nG \text{ Mpc}} \text{ EeV}
\]

Diffusion length: deflection \( \sim 1 \) rad

\[
l_D(E) \approx l_c \left[ 4 \left( \frac{E}{E_c} \right)^2 + 0.9 \left( \frac{E}{E_c} \right) + 0.23 \left( \frac{E}{E_c} \right)^{1/3} \right]
\]

(Kolmogorov spectrum)

For a source at distance \( r_s \)

\[
l_D(E) \approx r_s
\]

Angular distribution wrt the source direction

\[
\langle \cos \theta \rangle = \frac{1}{3R} \left[ 1 - \exp \left( -3R - \frac{7}{2}R^2 \right) \right] \equiv C(R) \approx \begin{cases} 
1 - r_s/3l_D & r_s \ll l_D \\
l_D/3r_s & r_s \gg l_D 
\end{cases}
\]

Harari SM Roulet 2014
Magnetic horizon effect: suppression of the flux at low energies for a discrete source distribution in the presence of a turbulent magnetic field

Solution of diffusion eq. for protons in an expanding universe

\[
J_{\text{tot}}(E) = \sum_s J_s(E) = \frac{c}{4\pi} \int_0^{z_{\text{max}}}\,\mathrm{d}z \left| \frac{\mathrm{d}t}{\mathrm{d}z} \right| \frac{Q[E_g(E, z), z]}{(4\pi \lambda^2)^{3/2}} \frac{\mathrm{d}E_g}{\mathrm{d}E} \sum_s \exp\left[-\frac{r_s^2}{(4\lambda^2)}\right]
\]

\[
\lambda^2(E, z) \simeq \frac{c}{3H_0} \int_0^z\,\mathrm{d}z' \frac{1 + z'}{\sqrt{\Omega_m(1 + z')^3 + \Omega_\Lambda}} l_D((1 + z')E)
\]

\[E_g(E, z)\] accounts for energy losses

For small source separation (large density)

\[\sum_s \rightarrow n_s \int \mathrm{d}r \, 4\pi r^2\]

\[
\int_0^{\infty} \mathrm{d}r \, 4\pi r^2 \exp\left(-\frac{r^2}{4\lambda^2}\right) \frac{1}{(4\pi \lambda^2)^{3/2}} = 1
\]

→ no effect on the spectrum: Propagation theorem

Aloisio & Berezinsky 2004
Discrete distribution of sources: the spectrum gets suppressed at low energies. Low energy particles take longer than the age of the universe to arrive from the closest sources.

\[ G(E/E_c) = \frac{J_{\text{tot}}(E)}{J_{\text{cont}}(E)} \]

\[ G(x) = \exp \left[ - \left( \frac{a X_s}{x + b(x/a)^\beta} \right)^\alpha \right] \]

\[ x = \frac{E}{E_c} \]

Suppression factor depends on the source density through

\[ X_s \equiv \frac{d_s}{\sqrt{R_H l_c}} \approx \frac{d_s}{65 \text{ Mpc}} \sqrt{\frac{\text{Mpc}}{l_c}} \quad d_s = 1/n_s^{1/3} \]

larger \( X_s \) \( \rightarrow \) more suppression: sources farther away

and on \( B \) through \( E_c \)

It has a (weaker) dependence on \( z_{\text{max}} \), spectral index and evolution of the sources, \((1+z)^m\)
Combined fit of spectrum & composition measurements above the ankle

Each mass component significantly contributes to the flux in a limited range of energies

\[ J_A(E) \propto E^{-\gamma} \times \begin{cases} 1 & \text{for } E/Z_A < R_{\text{cut}} \\ \exp(1 - E/Z_A R_{\text{cut}}) & \text{for } E/Z_A > R_{\text{cut}} \end{cases} \]

Sources with low rigidity cutoff and hard spectrum:

\[ R_{\text{cut}} \sim 5 \text{ EV}, \quad \gamma \sim [0 - 1] \]

Auger 2017
Effect of the magnetic horizon suppression on a combined fit to spectrum and composition

Spectrum and composition may be fitted with Fermi type spectrum ($\gamma \sim 2$) and the effectively harder spectrum at low energies be due to magnetic horizon effects.
Spectrum from one source:

diffusion leads to enhancement of the density around it

Steady source

\[ n(E, r_s)4\pi r_s^2 c\langle \cos \theta(E, r_s) \rangle = Q(E) \]

density enhanced wrt rectilinear propagation by

\[ \xi = \frac{n(E, r_s)}{Q(E)/(4\pi r_s^2 c)} = \frac{1}{\langle \cos \theta \rangle} \]

related to dipolar amplitude by \[ \Delta = 3 \langle \cos \theta \rangle = 3/\xi \]
Source emitting since initial redshift $z_i$: enhancement of local density

density $n(E, r_s)$ obtained from the solution of diffusion eq. (Berezinsky & Gazizov 2006)

$$n(E, r_s) = \frac{Q(E)}{4\pi c r_s^2} \xi_i$$

$$\xi_i \approx \frac{1}{C(r_s/l_D)} \exp \left[ - \left( \frac{r_s^2}{0.7 l_D(E) d(z_i)} \right)^{0.82} \right]$$

$magnetic horizon$: low energy particles need longer than the source emitting time to reach $r_s$

$rectilinear propagation$

$maximum at$

$$l_D(E_{\text{max}}) \approx 1.1 \frac{r_s^2}{d(z_i)}$$

$d(z_i)$

$independent parameters: E_c, r_s/l_c, d(z_i)/l_c$
Source emitting since initial redshift $z_i$: dipolar anisotropy

anisotropy at low energies larger than for the steady source (particles with long trajectories arriving from behind are missing)

$$\Delta = l_D |\nabla n|/n$$

$$\Delta \approx 3 \langle \cos \theta \rangle \approx 3 \frac{C(r_s/l_D)}{\left[ 1 + 1.64 \left( \frac{r_s^2}{0.7l_Dd(z_i)} \right)^{0.82} \right]}$$

nuclei: change $E \rightarrow E/Z$

(good approximation: attenuation is small at these energies for a nearby source)
Scenario with a strong nearby extragalactic source

- **A nearby source within the Local Supercluster:**

  with large magnetic field in the region enclosing observer & source (Vallee 2002) emitting since a recent $z_i$ (or with a burst at a recent $z_b$), and a mixed composition with common rigidity-dependent spectrum (power law index $\gamma_s$ and cutoff at $Z\varepsilon_{cut}^s$)

  → each component contributes in a limited energy range as result of the diffusion and magnetic horizon effects

- **Diffuse extragalactic contribution from farther away sources:**

  assumed isotropic, with mixed composition (power law spectrum $E^{-\gamma}$ and cutoff $Z\varepsilon_{cut}$) with SFR source evolution
Local source scenario:

- Source emitting since $z_i$

### Magnetic Field

- $B = 100$ nG
- $l_c = 0.03$ Mpc

### Nearby Source

- $r_s = 4$ Mpc
- $z_i = 0.07$

### Diffuse Flux

- $\gamma = 2.7$
- $f_H = 0.45, f_{He} = 0.33$
- $f_N = 0.15, f_{Si} = 0.05$
- $f_{Fe} = 0.02$

### E$^s_{cut}$

- $E^s_{cut} = E_{cut} = 20$ EeV
Summary

The interaction of UHECRs with the radiation backgrounds modifies the spectrum at the highest energies and constrains the distance of the possible sources.

The effect of a turbulent extragalactic magnetic field is to suppress the spectrum at low energies of a distribution of sources.

A good combined fit to the spectrum and composition data with a softer spectral index at source can be obtained considering the EGMF effect.

If local EGMF is strong, most of CRs above the ankle could come from a single local source, with the diffuse flux from farther away sources explaining the extragalactic contribution at lower energies.
Scenario with a strong nearby extragalactic source

**Flux from the nearby source:** mixed composition - 5 components with common rigidity-dependent spectrum (power law index $\gamma_s$ and cutoff at $ZE_{\text{cut}}^s$)

$$\Phi^s(E, r_s) = \Phi_0^s \sum_i f_i^s \left( \frac{E}{\text{EeV}} \right)^{-\gamma_s} \xi(E/Z_i, r_s) \frac{1}{\cosh(E/Z_i E_{\text{cut}}^s)}$$

- $i = \text{H, He, N, Si, Fe}$

**Diffuse extragalactic contribution:** assumed isotropic
- 5 components (power law $\gamma$ and $ZE_{\text{cut}}$) with SFR source evolution

$$\Phi^{\text{dif}}(E) = \Phi_0 \sum_i f_j \left( \frac{E}{\text{EeV}} \right)^{-\gamma} \eta_j(E) \frac{1}{\cosh(E/Z_j E_{\text{cut}})}$$

- secondary protons

$$\Phi^p(E) \simeq \Phi_0 \sum_j f_j \left( \frac{E}{\text{EeV}} \right)^{-\gamma} \frac{A^{2-\gamma}G(E)}{\cosh(2E/E_{\text{cut}})}$$
Examples:

magnetic field

\[ B = 50 \text{ nG} \]
\[ l_c = 0.05 \text{ Mpc} \]
\( (E_c \approx 2.2 \text{ EeV}) \)

nearby source

\[ r_s = 4 \text{ Mpc} \]
\[ z_b = 0.015 \]

\[ \gamma_s = 2 \]
\[ f^s_N = 0.34, \quad f^s_{He} = 0.30 \]
\[ f^s_N = 0.27, \quad f^s_{Si} = 0.05 \]
\[ f^s_{Fe} = 0.04 \]

diffuse flux:

same parameters as previous example
**Source properties**

<table>
<thead>
<tr>
<th></th>
<th>4D with EGMF</th>
<th>4D no EGMF</th>
<th>1D no EGMF$^1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$</td>
<td>$1.61^{+0.08}_{-0.07}$</td>
<td>$0.61^{+0.05}_{-0.06}$</td>
<td>$0.87^{+0.08}_{-0.06}$</td>
</tr>
<tr>
<td>$\log_{10}(R_{\text{cut}}/\text{eV})$</td>
<td>$18.88^{+0.03}_{-0.07}$</td>
<td>$18.48^{+0.01}_{-0.02}$</td>
<td>$18.62^{+0.02}_{-0.02}$</td>
</tr>
</tbody>
</table>
**Physical properties of some large astronomical objects**

<table>
<thead>
<tr>
<th>Object type</th>
<th>Mean density $n$ (cm$^{-3}$)</th>
<th>Mean magnetic field $B$ (μG)</th>
<th>Mean size $D$ (pc)</th>
<th>Mean temperature $T$ (K)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas in supercluster of galaxies</td>
<td>$10^{-6}$</td>
<td>0.5</td>
<td>$5 \times 10^7$</td>
<td>$10^7$</td>
<td>Vallée (1990d)</td>
</tr>
<tr>
<td>Gas in clusters of galaxies</td>
<td>$10^{-4}$</td>
<td>1</td>
<td>$5 \times 10^6$</td>
<td>$10^7$</td>
<td>Vallée (1990d)</td>
</tr>
<tr>
<td>Gas in galactic halos</td>
<td>$10^{-3}$</td>
<td>4</td>
<td>$5 \times 10^4$</td>
<td>$10^6$</td>
<td>Vallée (1990d)</td>
</tr>
<tr>
<td>Spiral arm interstellar gas</td>
<td>0.5</td>
<td>4</td>
<td>$10^4$</td>
<td>$10^4$</td>
<td>Vallée (1991c)</td>
</tr>
<tr>
<td>Large supershells-initial</td>
<td>0.8</td>
<td>3</td>
<td>300</td>
<td>$10^3$</td>
<td>Vallée (1993e)</td>
</tr>
<tr>
<td>Large supershells-actual</td>
<td>2</td>
<td>8</td>
<td>20</td>
<td>$10^3$</td>
<td>Vallée (1993e)</td>
</tr>
<tr>
<td>Large HII regions</td>
<td>5</td>
<td>10</td>
<td>30</td>
<td>$10^4$</td>
<td>Heiles and Chu (1980)</td>
</tr>
<tr>
<td>HI gas in diffuse clouds</td>
<td>3</td>
<td>5</td>
<td>10</td>
<td>100</td>
<td>Troland and Heiles (1986)</td>
</tr>
<tr>
<td>HI gas in interclumps</td>
<td>90</td>
<td>15</td>
<td>10</td>
<td>100</td>
<td>Troland and Heiles (1986)</td>
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