ULTRAHIGH-ENERGY COSMIC RAYS & NEUTRINOS FROM LIGHT NUCLEI COMPOSITION

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Huge number of events at low energy but still few at $> 10^{20}$ eV

A rollover of the spectrum is confirmed but physical origin is controversial and complicated

Significant differences exist in energy calibration among experiments
The sources of CRs above $10^{19}$ eV should be very nearby to avoid catastrophic energy losses during propagation: GZK radius $\sim$ few hundred Mpc.
For heavy nuclei such as Fe the GZK radius is similar, but nuclear processes such as photo disintegration change the species.

**Comparisons of UHECR proton and Fe**

**Nuclear isotopes interesting for CR propagation**

Puget, Stecker & Bredekamp 1976

Boncioli, Fedynitch & Winter 2017
UHECR Composition

Two main indicators:
- Average shower profile maximum $<X_{\text{max}}>\$
- Variation of $X_{\text{max}}$ from shower to shower

... and a lot of Monte Carlo simulations!

Comparison with other experiment: Telescope Array (TA)

Pure proton composition of UHECR is disfavored at $> 10^{19}$ eV

Caveats:
- No collider data exists at this energies
- Significant differences exists among high-energy particle interaction models
Earlier Attempts to Model w/Mix Comp.

$E^2 \text{[eV]} \times \text{km}^2 \text{sr}^{-1} \text{yr}^{-1}$

$E_{\text{max}} \text{[EeV]}$

H (red)
He (grey)
N (green)
Fe (blue)

Auger Collab. 2017
CRPropa 3.0 Propagation Code

Sources are distributed uniformly in space in comoving volume, each emitting the same spectra of UHECRs.

Interactions and energy losses are simulated.

Secondary particles are tracked until they reach observer or drop out of the flux.

We use this code to model UHECR spectrum measured by Pierre Auger with light nuclei composition.

TALYS 1.8 photodisintegration + Dominguez et al. EBL.
CRPropa Simulations Setup

Injection spectra of nuclei:

\[ \frac{dN}{dE} = A_0 \sum_i K_i E^{-\alpha} \times f_{\text{cut}}(E, ZR_{\text{cut}}) \]

\[ f_{\text{cut}}(E, ZR_{\text{cut}}) = \begin{cases} 1 & (E < ZR_{\text{cut}}) \\ \exp \left( 1 - \frac{E}{ZR_{\text{cut}}} \right) & (E > ZR_{\text{cut}}) \end{cases} \]

Evolution of number of sources with redshift: \( \sim (1+z)^m \)

Ranges of parameters scanned

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha )</td>
<td>Source spectral index</td>
<td>( 2.2 \leq \alpha \leq 2.6 )</td>
</tr>
<tr>
<td>( R_{\text{cut}} )</td>
<td>Cut-off rigidity</td>
<td>( 40 \leq R_{\text{cut}} \leq 100 \text{ EV} )</td>
</tr>
<tr>
<td>( z_{\text{min}} )</td>
<td>Minimum redshift</td>
<td>( z_{\text{min}} = 0.0007 )</td>
</tr>
<tr>
<td>( z_{\text{max}} )</td>
<td>Cut-off redshift</td>
<td>( 2 \leq z_{\text{max}} \leq 4 )</td>
</tr>
<tr>
<td>( m )</td>
<td>Source evolution index</td>
<td>( 0 \leq m \leq 3 )</td>
</tr>
<tr>
<td>( K_i )</td>
<td>abundance fraction</td>
<td>( 0.0% \leq K_i &lt; 100% )</td>
</tr>
<tr>
<td>( A_0 )</td>
<td>Flux normalisation</td>
<td>( A_0 &gt; 0 )</td>
</tr>
</tbody>
</table>

Deflection in intergalactic and Galactic magnetic fields ignored - OK for diffuse flux.
Fitting procedure for Auger Spectrum

- Simple Chi^2 fits with 17 d.o.f.
- Parameters vary in restricted ranges
- Acceptable fits when Chi^2 < 27.95
- Some models are disfavored from composition data and/or neutrino flux upper limits
Best Fits for injection index 2.2 (H+He)

FIG. 1: UHECR spectra (left) and cosmogenic neutrino spectra (right) for $\alpha = 2.2$. The top (case 2) and bottom (case 12) panels show the best-fit cases listed in Appendix A for which the difference in the cosmogenic neutrino flux is the maximum.
FIG. 2: UHECR spectra (left) and cosmogenic neutrino spectra (right) for $\alpha = 2.4$. The top (case 13) and bottom (case 23) panels show the best-fit cases listed in Appendix A for which the difference in the cosmogenic neutrino flux is the maximum.
Best Fits for injection index 2.6 (H+He)

FIG. 3: UHECR spectra (left) and cosmogenic neutrino spectra (right) for $\alpha = 2.6$. The top (case 25) and bottom (case 33) panels show the best-fit cases listed in Appendix A for which the difference in the cosmogenic neutrino flux is the maximum.
Correlation between Fit Parameters (H+He)

- Not all the parameters are independent, but it is not known a priori the mathematical nature of dependence
- Use large grid space to explore the confidence intervals for the parameters

- $40 \text{ EV} < R_{\text{cut}} < 100 \text{ EV}$ with 0.5 EV spacing
- $0 < m < 6$ with 0.03 spacing
- $0 < K_p < 100$ with 0.01 spacing

121 x 201 x 101 grid points!
Best Fits but Rejected! (H+He)

Neutrino flux violates upper limit

FIG. 6: UHECR spectrum (left) and cosmogenic neutrino flux (right) for the best-fit case corresponding to $\alpha = 2.2$ and $z_{\text{max}} = 3$, found by scanning over a wide range of parameter space.

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>$z_{\text{max}}$</th>
<th>$m$</th>
<th>$R_{\text{cut}}$</th>
<th>$K_p$</th>
<th>$K_{\text{He}}$</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2</td>
<td>3</td>
<td>5.22</td>
<td>45.5 EV</td>
<td>96%</td>
<td>4%</td>
<td>8.29086</td>
</tr>
<tr>
<td>2.2</td>
<td>4</td>
<td>5.31</td>
<td>45.5 EV</td>
<td>96%</td>
<td>4%</td>
<td>7.04839</td>
</tr>
<tr>
<td>2.4</td>
<td>3</td>
<td>2.73</td>
<td>47.0 EV</td>
<td>100%</td>
<td>0%</td>
<td>12.01026</td>
</tr>
</tbody>
</table>
Neutrino flavor ratio: H+He Model

$R_{\text{cut}}$ is varied between $40 - 100$ EV. The source evolution index $m$ is varied through 0, 1, 2, 3. We take $z_{\text{min}} = 0.0007$, and vary $z_{\text{max}}$ through 2, 3 and 4. We investigate three cases, $\alpha = 2.2, 2.4, 2.6$. We vary $K_p$ and $K_{\text{He}}$ from 0 to 100% with a precision of 0.1%, restricted by the condition, $K_p + K_{\text{He}} = 100\%$.

Can be an important indicator to discriminate between models - break parameter degeneracies
More Complex (H+He+N+Si) model

FIG. 8: UHECR spectra for the best-fit parameters of CTD model as found by PAO for $m = 0$ (top left), and that calculated in this work for $m = 0, -3, -6$ by extending the range of $\alpha$ used to scan the parameter space. The top right, bottom left and bottom right spectrum corresponds to $m = 0, m = -3$ and $m = -6$ respectively as indicated in the figure labels.
Implications for \((H+He+N+Si)\) Model

- No constraints on the models from neutrino observations by current or future detectors.

- No or negative evolution of the sources — fewer and fewer sources of UHECRs at higher redshift.

- Very hard injection index required — difficult to explain with commonly believed Fermi shock-acceleration processes.

**TABLE III.** Best-fit values in parameter space \([H + He + N + Si]\) and in the energy range \(E > 10^{18.7} \text{ eV}\).

<table>
<thead>
<tr>
<th>(m)</th>
<th>(\alpha)</th>
<th>(\log_{10}(R_{\text{cut}}/V))</th>
<th>(K_H)</th>
<th>(K_{He})</th>
<th>(K_N)</th>
<th>(K_{Si})</th>
<th>(\chi^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-1.8</td>
<td>18.1</td>
<td>39</td>
<td>59</td>
<td>2</td>
<td>0.03</td>
<td>2.59</td>
</tr>
<tr>
<td>-3</td>
<td>-1.6</td>
<td>18.1</td>
<td>17</td>
<td>81</td>
<td>2</td>
<td>0.04</td>
<td>2.57</td>
</tr>
<tr>
<td>-6</td>
<td>-1.5</td>
<td>18.1</td>
<td>57</td>
<td>41</td>
<td>1</td>
<td>0.02</td>
<td>2.66</td>
</tr>
</tbody>
</table>
Summary and Outlook

We present new fits to the Pierre Auger UHECR spectrum with uniform astrophysical source distribution

- **Light nuclei composition:** H+He (Can fit spectrum \( \sim 10^{19} \text{ eV} \))
  - Injection index: -2.2, -2.4
  - Source evolution index: 0–5
  - Rigidity cutoff: \(~50–80 \text{ EV}\)
  - Redshift range: 0.0007–4
- **Light-intermediate nuclei composition:** H+He+N+Si (Can fit spectrum \( \sim 5 \times 10^{19} \text{ eV} \))
  - Injection index: -1.5, -1.8
  - Source evolution index: -6–0
  - Rigidity cutoff: \(~1 \text{ EV}\)
  - Redshift range: 0–1
- Detection of cosmogenic neutrinos can severely constrain the light-intermediate nuclei composition models
  - Additional constraints from neutrinos (flux and flavor ratios) can shed lights on degeneracies between model parameters
  - Science driver for upcoming/planned neutrino detectors
Invitation!

Important Dates

2019 Nov 01 - Abstracts Due
2019 Nov 07 - Early Registration Deadline
2019 Dec 07 - Regular Registration Deadline
2020 Jan 23 - Late Registration Deadline
2020 Jan 23 - Late Posters Deadline

Contact email: capp@uj.ac.za
We vary $\alpha$ in the interval $[-2.5, 0]$ and $\log_{10}(R_{\text{cut}}/V)$ in the range $[17.8, 18.3]$. Since, for $Z > 1$, only particles originating from $z \lesssim 0.5$ are able to reach earth with $E > 10^{18.7}$ eV, we consider $z_{\text{max}} = 1$ in the simulations and $z_{\text{min}} = 0$ to cover the highest energy data points. The composition is restricted by the condition, $K_{\text{H}} + K_{\text{He}} + K_{\text{N}} + K_{\text{Si}} = 100\%$.
A pure p-composition with alpha = 2.4, z_max = 3, m = 3 produces maximum allowed gamma-ray flux.

Mix composition lowers the gamma-ray flux.

For alpha = 2.4 case m = 0–2, z_max = 2—4 are allowed.

Most alpha = 2.2 cases are allowed because of high He fraction.

**Diffuse gamma-ray flux from UHECRs**

**FIG. 7**: Cosmogenic photon fluxes for the m = 0 best-fit cases, with α = 2.6 and z_max = 2, 3, and 4. The measured diffuse gamma-ray background by Fermi-LAT is also shown.