Ultra-High-Energy Cosmic Rays from Radio Galaxies

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in collaboration with J. Rachen, L. Merten, A. v. Vliet, J. Tjus

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&
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Ultra-High-Energy Cosmic Rays (UHECRs)

Energy Spectrum

Chemical Composition

Arrival Directions

by Radio Galaxies?
The Basic Simulation Setup

- **SOURCES:**
  - Radio-loud AGNs/ Radio Galaxies (RGs)*

- **ENVIRONMENT:**
  - Local extragalactic magnetic field (EGMF) up to 120Mpc distance**
  - Photon fields by CMB & IRB

- **PROPAGATION of UHECRs:**
  - Performed with CRPropa3***

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*van Velzen et al. (2012); **Dolag et al. (2005); ***Batista et al., 2016
The Sources

- **Local RGs** ($d \leq 120$ Mpc):
  - 121 observed*
  - 617 low luminous, 100 invisible
- Derived from Radio Luminosity Function (RLF)**

*van Velzen et al. (2012); **Mauch & Sadler (2007)
The Sources

- **Local RGs** \((d \leq 120 \text{ Mpc})\):
  - 121 observed*
  - 617 low luminous, 100 invisible
    - Derived from Radio Luminosity Function (RLF)**

- **Non-local RGs** \((d > 120 \text{ Mpc})\):
  - Continuous Source Function (CSF) provides the average contribution up to \(z = 2\)
    - Derived from RLF**

*van Velzen et al. (2012);   **Mauch & Sadler (2007)
The Sources & Their Characteristics

- **CR power** is related to the radio luminosity:
  \[ Q_{\text{cr}} = Q_0 \ g_{\text{cr}} \ L_{\text{1.1GHz}}^{6/7} \quad \text{with} \quad 1 \leq g_{\text{cr}} \leq 50 \]
  ➢ Absolute normalization of the CR flux

- **Maximal rigidity** is related to **CR power**:
  \[ \hat{R} = g_{\text{acc}} \sqrt{Q_{\text{cr}}/c} \quad \text{with} \quad 0.01 \leq g_{\text{acc}} \leq 1 \]
  • Acceleration is constrained by CR escape.

- **Spectral index** at the sources from *shock acceleration theory*:
  \[ dN/dE \propto E^{-\alpha} \quad \text{with} \quad 1.7 \leq \alpha \leq 2.2 \]

- **Abundances** at the sources mostly *solar* \( f_\odot \), but enable exceptions:
  \[ f = f_\odot \ Z^q \quad \text{with} \quad 0 \leq q \leq 2 \]

- Source evolution parameter fixed to \( m = 3 \) (minor influence!)
Prior Conclusions (without any fit)

What does the physics of RGs already enable to conclude?
Prior Conclusions (without any fit)

• Average non-local RG contribution (CSF):
  • **Unable to explain** the UHECR data
  ➢ Needs to be **subdominant at** $E \gg 5\text{EeV}$
Prior Conclusions (without any fit)

- Local RG contribution:
  - Dominated by Cen A (M87, Fornax A), other RGs are negligible
  - Heavy initial abundances are needed
    - Unable to explain data around the ankle

Solar initial abundances:

Heavy initial abundances:
Prior Conclusions (without any fit)

- Additional, ultra-luminous, non-local RG needed:
  - Cygnus A (at $d \sim 250$ Mpc)
  - Light initial abundances & rather low acc. eff. are needed

High acceleration efficiency, $g_{acc}^{CygA} = 0.5$

Low acceleration efficiency, $g_{acc}^{CygA} = 0.05$
Let’s fit the (physics based) parameters of our model!
Best-Fit Results (energy spectrum & composition)

<table>
<thead>
<tr>
<th></th>
<th>$a$</th>
<th>$\bar{g}_{cr}$</th>
<th>$g_{cr}$ CenA</th>
<th>$g_{cr}$ CygA</th>
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<td>41.54</td>
<td>43.94</td>
<td>0.127</td>
<td>0.059</td>
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<td>QGSJetII-04</td>
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Local exception needed

Fit-Scenario:
- Spectral index according to Fermi acc.: $a \sim 1.8$
- Powerful Cen A: $g_{cr}^{CenA} > \bar{g}_{cr}$
- Powerful Cyg A with a low acc. eff.: $g_{cr}^{CygA} > \bar{g}_{cr}$; $g_{acc}^{CygA} < g_{acc}$
- Heavy Cen A ($q = 2$) & light Cyg A ejecta
Best-Fit Results (energy spectrum & composition)

<table>
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<tr>
<th>Model</th>
<th>$a$</th>
<th>$\tilde{g}_{cr}$</th>
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Best-Fit Results (arrival directions)

- **Compare multipole moments** with observations (without fitting):

\[ 4 \text{ EeV} \leq E \leq 8 \text{ EeV} : \]

\[ E > 8 \text{ EeV} : \]

![Graph of multipole moments compared with observations for different energy ranges.](image-url)
Conclusions

- Radio Galaxies are able to explain the UHECR data – by using 7 physics based parameters:
  - Dominant contribution of Cen A (heavy comp.) and Cyg A (light comp.).
  - Dipol at $E > 8$ EeV requires isotropized Cyg A events at $E \sim 8$ EeV.
  - Average non-local contribution needs to be subdominant at UHE.

![Graphs and plots related to high-energy cosmic rays from radio galaxies.](Image)
Outlook

- **Include:**
  - Geometrical exposure effects of the observatories
  - EGMF effects for ultra-luminous RGs beyond 120Mpc
  - Individual contribution by 3C 353 and Pictor A

- **Investigate:**
  - Possible CSF contribution below the ankle
  - Physics based difference between northern & southern UHECRs
Outlook

Björn Eichmann - Ultra-high-energy cosmic rays from local radio galaxies
Local source sample is incomplete

- 575 radio-emitting galaxies in total
  - **121 radio-loud AGNs** up to 120 Mpc
- Providing $l$, $b$, $D$, $L_{\text{radio}}$, ... 
- $\Phi_{1.4\text{GHz}} > 213\text{mJy}$
  - + low luminous RGs
- $P_V = 0.88$
  - + invisible RGs

Observational bias ($L \propto D^{-2}$)

12% of the sky is not observed
Local source sample correction

- Radio luminosity function $\Phi_{RL}$ (Mauch & Sadler, 2007) used to determine $N_{exp}(> L_{min})$

$$\Phi_{RL}(P) \propto \left[ \left( \frac{P}{P_*} \right)^{\alpha} + \left( \frac{P}{P_*} \right)^{\beta} \right]^{-1},$$

with $\alpha = 1.27$, $\beta = 0.49$, $P_* = 10^{24.59}$ W Hz$^{-1}$
Local source sample correction

- **Radio luminosity function** $\Phi_{RL}$ (Mauch & Sadler, 2007) used to determine $N_{exp}(> L_{min})$
- Add sources to match $N_{exp}$
  - Uniform spatial distribution with respect to the supergalactic plane and the EGMF strength:
    $\Phi(L, \hat{r}) = \Phi_{RL}(L)\Phi(\hat{r})$

- 121 observed, local AGNs
- 617 low luminous, local AGNs
- 100 invisible, local AGNs
Non-local source sample

• EGMF structure limits the (3D) simulation volume

➤ Analytic construction of the *Continuous Source Function (CSF)*:

\[
\Psi_0(R) = \frac{dN_{cr}}{dR \, dt \, dV} = \frac{1}{eZ} \int_0^\infty dQ \, S_{cr}(R, \hat{R}) \, \Phi_{RL}(Q), \text{ with } \hat{R} = g_{acc} \sqrt{\frac{Q_{cr}}{c}}
\]

• Uniform 1D-distribution of sources with an individual spectrum

\[
S_{cr}(R, \hat{R}) = v_0(a) \, Q_{cr} \, (R/\hat{R})^{-a} \, \Theta(\hat{R} - R)
\]

with a spectral normalization correction \(v_0(a)\).

➤ Continuation of the local source sample (and its features!)

➤ 1D-Simulation to account for *propagation effects* (energy losses)

➤ Including source evolution effects: \(\Psi(R, z) = \Psi_0(R) \, (1 + z)^{m-1}, \, z \leq 2\)
Non-local source sample

- EGMF structure limits the (3D) simulation volume

- Analytic construction of the Continuous Source Function (CSF):

\[
\Psi_0(R) = \frac{dN_{cr}}{dR \, dt \, dv} = \frac{1}{eZ} \int_0^{\tilde{Q}} dQ \, S_{cr}(R, \tilde{R}) \, \Phi_{RL}(Q), \text{ with } \tilde{R} = g_{acc} \sqrt{\frac{Q_{cr}}{c}}
\]

- \(\Psi_0(R < R_*) \propto S_{cr}(R)\)

- \(\Psi_0(R > R_*) \propto S_{cr}(R)/R\)

\[
R_* = 2 \, g_{acc} \sqrt{g_{cr}} \, \text{EV}
\]
The Sources & Their Characteristics

• **CR power** from the jet power: \( Q_{cr} \approx \frac{4}{7} Q_{jet} \), using *minimum jet energy condition* (Pacholczyk, 1970) \( Q_B \approx \frac{3}{4} (Q_e + Q_{cr}) \) & \( Q_{cr} \gg Q_e \)

• **Jet power** from extended radio emission (Willott et al., 1999):

\[
Q_{cr} = \frac{4}{7} Q_{jet} = g_{cr} Q_{jet,0}
\]
with \( 1 \leq g_{cr} \leq 50 \)
The Sources & Their Characteristics

- **CR power** from the jet power: \( Q_{cr} \approx \frac{4}{7} Q_{jet} \), using *minimum jet energy condition* (Pacholczyk, 1970) \( Q_B \approx \frac{3}{4} (Q_e + Q_{cr}) \) & \( Q_{cr} \gg Q_e \)

- **Jet power** from extended radio emission (Willott et al., 1999):

  \[
  Q_{cr} = \frac{4}{7} Q_{jet} = g_{cr} Q_{jet,0}
  \]
  \[
  \text{with } 1 \leq g_{cr} \leq 50
  \]

  \[
  \frac{Q_{jet,0}}{\text{erg/s}} = 3 \times 10^{45} \left( \frac{P_{151}}{10^{28} \text{ WHz}^{-1} \text{sr}^{-1}} \right)^{6/7}
  \]

- **Maximal Rigidity** using *min. jet energy cond.* \( Q_{jet} = \frac{7}{3} Q_B = \frac{7}{3} c \beta_{jet} \pi r^2 \frac{B^2}{8\pi} \)
  and *Hillas criterion* \( \hat{R} \equiv \frac{E_{\text{max}}}{Ze} = \frac{\beta_{sh}}{f_{\text{diff}}} B r \)

  \[
  \hat{R} \approx g_{\text{acc}} \sqrt{g_{cr} Q_{jet,0} / c}, \quad \text{with } g_{\text{acc}} = \sqrt{\frac{6 \beta_{sh}^2}{f_{\text{diff}}^2 \beta_{jet}}}
  \]
Local EGMF by Dolag et al. (2005)

- Seed field assumptions:
  - Uniform magnetic seed field
    \[ B_0 = 2 \times 10^{-12} \text{G} \]
  - Arbitrary initial orientation
- Cosmological MHD simulations determine the EGMF structure
  - \( B_{rms} \approx 1 \text{nG} \)
  - Up to a distance of \( \sim 120 \text{Mpc} \)
    ➢ Limits the 3d simulation volume

- Sampled with a resolution of 14.6 kpc & stored in a multi-resolution grid using ‘Quimby’ (Müller, 2016)

https://forge.physik.rwth-aachen.de/public/quimby/mhd/
First Fit Approach

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Björn Eichmann - Ultra-high-energy cosmic rays from local radio galaxies
First Fit Approach

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Scenario unable to explain the data!

- **Local exception** needed!
Best-Fit Results (arrival directions)

- Estimate **rms deflection of Cygnus A events** using

\[ \theta_{rms} \approx 0.8° \, \frac{E}{100 \text{ EeV}} \left( \frac{d}{10 \text{ Mpc}} \right)^{1/2} \left( \frac{\lambda_c}{1 \text{ Mpc}} \right)^{1/2} \left( \frac{B_{rms}}{1 \text{ nG}} \right) \]

**For** \( E \geq 8 \text{ EeV} : \)

**For** \( E \geq 40 \text{ EeV} : \)

Using \( \lambda_c^{1/2} B_{rms} = 6 \text{ Mpc}^{1/2} \text{ nG} \)
Best-Fit Results (arrival directions)

• Compare multipole moments with observations (without fitting):

\[4 \text{ EeV} \leq E \leq 8 \text{ EeV} :\]

\[E > 8 \text{ EeV} :\]

➢ Suff. deflection of Cyg A events for \(\lambda_c^{1/2} B_{rms} \geq 6 \text{ Mpc}^{1/2} \text{ nG}\)
Comparison of CSF in local regime

\[ 5 \text{ Mpc} \leq d \leq 120 \text{ Mpc} : \]
The (3d) Simulation Setup