A Method of Searching for Origins of Cosmic Rays correcting for Galactic Field Deflections and Charge Composition

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Current status

Separate Analyses
→ Point source searches
→ Large scale anisotropy
→ Mass composition

Source Searches

UHECRs

Composition

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Motivation

Galactic Magnetic Field Spectrometer

Source Searches

UHECRs

Composition

Galactic magnetic field allows for unified analysis

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Galactic Magnetic Field Correction

- Magnetic field models tuned to Faraday rotation and synchrotron emission measurements

- Cosmic rays with different rigidities $R = \frac{E}{Z}$ arrive on Earth at different directions
  - Source directions can only be found at edge of galaxy
  - Magnetic field corrections depend on cosmic ray charges
- Correction of deflections in magnetic field using a probabilistic approach
Analysis Strategy

1. Detected Cosmic Rays
2. Galactic Magnetic Field
3. Origin probability maps
4. Background suppression
5. Cluster identification
6. Expected arrival directions
7. Galactic Magnetic Field
8. Likelihood analysis
Monte Carlo Simulation

Energy spectrum with $E^{-2.6}$
Signal fraction: $f_s = 15\%$

Most abundant charges: H, He, C, N, O

Sources: M87, Cen A & Fornax A
smearing: $\delta = 3^\circ$

Rigidity $R=E/Z$ needed for projection to edge of galaxy, but charge?
→ Assign equal probability for each charge to each cosmic ray
Projection to the edge of the galaxy

Galactic magnetic field

- Regular field by Jansson and Farrar
- Lensing technique
  - Probability to observe cosmic rays originating from \((\varphi,\theta)\) at the Galaxy at direction \((\varphi',\theta')\) on Earth
  - Rigidity dependent
- Transposed lens to project to edge of galaxy
Cluster identification

Superimposed maps (rigidities)

1000 isotropic simulations

→ accept only directions exceeding 90% quantile

probability of origin [A.U]
Clusters and expected arrival directions

- Search for directions with high arrival probability
- DBSCAN algorithmus (Ester, M. et al. (1996) KDD-96)

- Use cluster centers as source candidates
- Calculate expected arrival directions on Earth using GMF

- Standard point source search with likelihood ratio
Likelihood analysis

Model:
\[ \mathcal{L} = \prod_{\text{CRs}} \left[ f \cdot S_{\delta}^{\text{Earth}}(l', b') + (1 - f) \cdot B(l', b') \right] \]

- Anticipated signal fraction
- Signal distribution
- Smearing to account for random fields
- Background distribution
- Cosmic ray direction on Earth

Graphs show the distribution of data and simulated isotropic data with a red dashed line indicating the isotropy scenario excluded.
Charge determination

Update charge probabilities using projected source directions

 Cosmic Ray E=80 EeV → C = E / R = 8

\[ Z_{\text{fit}} \]: most probable charge

\[ \text{Charge resolution of } \pm 2.31 \]
Repeat analysis with updated rigidity distributions

- **Sources directions**
  - improved directional reconstruction
  - Additional (unwanted) source candidate
- Improved charge resolution ± 1.65
Conclusion and Outlook

- Method to identify source candidates by charge dependent corrections for deflections in GMF
  - Search for extragalactic directions
  - Evaluation of validity by likelihood ratio method
  - Cosmic ray charge resolution ≈ ± 2

- Comparison of different magnetic field models
- Inclusion of uncertainties, i.e. energy, direction
- Application to data
Backup
Magnetic Field Lenses

- Backtracking **anti-protons** from Earth to edge of galaxy
  - Using HEALPix scheme with nside=64
  - 175 rigidity bins between $10^{17.00} \text{ eV}$ and $10^{20.49} \text{ eV}$ with bin width $\log_{10}(R/V)=0.02$
- Matrices projecting a probability distribution from edge of galaxy on Earth

\[
\vec{m}_{\text{Earth}} = L(R) \cdot \vec{m}_{\text{gal}}
\]

| l_{1,1} | \cdots | l_{1,n_{\text{pix}}} |
| ----- | \cdots | ----- |
| \vdots | \vdots | \vdots |
| l_{n_{\text{pix}},1} | \cdots | l_{n_{\text{pix}},n_{\text{pix}}} |

Pixel on Earth

Pixel at galaxy

- Transposed lens answers question how probable cosmic rays at direction $(\varphi, \theta)$ on earth originate from direction $(\varphi', \theta')$ at edge of galaxy
Lens Examples for $\log_{10} R = 18.7$ and $\log_{10} R = 19.7$
Galactic Magnetic Field - Cosmic Ray Flux
Galactic Magnetic Field: Mean Deflections

JF12

PT11

\[ \langle \beta \rangle \text{ / deg} \]

\[ R / \text{EV} \]

JF12
- North
- Disk
- South

PT11
- North
- Disk
- South

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Galactic Magnetic Fields: Deflection Variances

JF12

PT11

![Graphs showing deflection variances for JF12 and PT11 with labels for North, Disk, and South regions.](chart.png)
Results for 5% signal fraction

- **Graph 1:**
  - Y-axis: $N$ (log scale)
  - X-axis: $\log_{10}(E/eV)$
  - Data points for different sources (Isotropic, Source 0, Source 1, Source 2)

- **Graph 2:**
  - Cartesian coordinates in the $(\log_{10}(R/V), \sigma)$ plane
  - Color scale indicating data distribution

- **Graph 3:**
  - Hyperbolic scatter plot
  - Data points showing spatial distribution
  - Color scale indicating data density