Analyzing UHECR arrival directions through the Galactic magnetic field in view of the local universe as seen in 2MRS

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UHECRs and the GZK Cutoff

We know for $E > \sim 50$ EeV

$$p + \gamma_{\text{CMB}} \rightarrow \Delta^+ \rightarrow n + \pi^+$$

A horizon of a few 100 Mpcs

No obvious clustering
The Local Universe as Seen in 2MRS

Densest all-sky redshift survey available. Complete to $z=0.03$. ~45000 galaxies down to K band magnitude of 11.75

Note the Supergalactic plane and the Virgo and Perseus Pisces Superclusters. More than 30% of the Galaxies within 20 MPc are within 10 degrees of Virgo.
A population of standard candle sources

- Should follow the matter distribution of the universe
- Source density,
  - Test $1e^{-5}$, $1e^{-4}$ and $1e^{-3} \, /Mpc^3$
  - JCAP 1305 (2013) 009, Auger
- Composition is unknown
  - Test pure proton, Si and Fe at source
- Spectrum is unknown
  - Test $E^{-2.0}$ and $E^{-0.9}$
- Redshift evolution – $(1 + z)^3$, like SFR

Zone of avoidance due to Galactic plane is randomly filled in.

Sources beyond 120 Mpc are filled in isotropically (conservative)
Propagation in Extragalactic space

• Account for losses due to photopion production, electron pair production and photodisintegration in CMB and IRB, as well as nuclear decay for heavier nuclei. CRPropa3 JCAP 1605(2016)no.05, 038

\[ \theta_{\text{def}} = 0.025^\circ \left( \frac{D}{\lambda} \right)^{1/2} \left( \frac{\lambda}{10\text{Mpc}} \right) \left( \frac{B}{10^{-11} \text{G}} \right) \left( \frac{E}{10^{20} \text{eV}} \right)^{-2} Z \]

random deflections, Gaussian beam smoothing. Test B=1.e-11, 1.e-10 and 1.e-9 G

Increasing distance shells
Propagation in Galactic magnetic field - Backtracking

- Galaxy: Sphere of radius 30 Kpc
- Observer: At 8.5 Kpc from center.
- Magnetic Field: JF2012 (also PT2011)
- Forward propagating computationally impossible
- Propagate anti-nucleons of charge $-Z$ from Earth to outside the Galaxy.
- Apply weights corresponding to direction and composition at Galactic boundary.
Example maps

All proton, $E^{-0.9}, 10^{-3}/Mpc^3, B_{\text{Extragal}} = 10^{-11} G$

All Fe at source, $E^{-2.0}, 10^{-5}/Mpc^3, B_{\text{Extragal}} = 10^{-9} G$
Quantifying Anisotropy

Power Spectrum

\[ C_\ell = \frac{1}{4\pi N} \quad \sigma_\ell = \frac{1}{4\pi N} \sqrt{\frac{N - 1}{N}} \frac{2}{2\ell + 1} \]

Current Auger + TA data are compatible with isotropy at \( p = 10.4\% \) level.

\( l_{\text{max}} \) determined by counting nodal zones of \( Y_{lm} \) s.

Likelihood

Compare directly against data

\[ L = \prod_{i=1}^{N} \frac{\Phi(u_i)}{\omega(u_i)} \]

\[ TS = -2\log \frac{L}{L_0} \]
Results

Best Fit hypothesis:
All Fe (at source), $E^{-2.0}, 10^{-5}/Mpc^3, B_{E_{Xtragal}} = 10^{-9} G$

(At Earth on average this corresponds to 10-40% Silicon, 30-60% Oxygen, 20-50% Nitrogen)

Compatible with data at $p = 9.8$

The best all proton hypothesis has $p < 5.6 \times 10^{-6}$ (4.6σ).
No map in 18000 trials are as isotropic as data.

Silicon is compatible at $p \sim 0.00058$ (3.4σ)

Best Fit hypothesis:
All Fe (at source), $E^{-0.9}, 10^{-5}/Mpc^3, B_{E_{Xtragal}} = 10^{-9} G$

Best proton hypothesis disfavored at $TS = 121$, disfavoured at 11σ
Best silicon hypothesis disfavoured at $TS = 31$ (5.6σ)
The PT2011 Galactic magnetic field?

All Fe at source, $E^{-2.0} \times 10^{-5}/\text{Mpc}^3$, $B_{\text{Extragal}} = 10^{-9} G$

JF2012 Field

Same realization of the same hypothesis, through the PT2011 Field

The best fit hypothesis now is All Fe (at source), $E^{-2.0} \times 10^{-5}/\text{Mpc}^3$, $B_{\text{Extragal}} = 10^{-9} G$
Non standard candle sources

• Real sources have a luminosity distribution. Unknown.

• Assume gaussian in log(Luminosity), with variance = 0.4 (similar to X-Ray luminosities of QSOs in the XMM-XXL catalogue)

Best proton hypothesis still disfavored at 10.4 σ

From JF2012 Paper:

<table>
<thead>
<tr>
<th>Field</th>
<th>Best fit Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disk</td>
<td>$b_1 = 10.81 \pm 2.33 \mu G$</td>
<td>field strengths at $r = 5$ kpc</td>
</tr>
<tr>
<td>component</td>
<td>$b_2 = 6.96 \pm 1.58 \mu G$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$b_3 = 9.59 \pm 1.10 \mu G$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$b_4 = 6.96 \pm 0.87 \mu G$</td>
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<tr>
<td></td>
<td>$b_5 = 1.96 \pm 1.32 \mu G$</td>
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<tr>
<td></td>
<td>$b_6 = 16.34 \pm 2.53 \mu G$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$b_7 = 37.29 \pm 2.39 \mu G$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$b_8 = 10.35 \pm 4.43 \mu G$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$b_{\text{int}} = 7.63 \pm 1.39 \mu G$</td>
<td>field strength at $r &lt; 5$ kpc</td>
</tr>
<tr>
<td></td>
<td>$z_0^{\text{disk}} = 0.61 \pm 0.04$ kpc</td>
<td>Gaussian scale height of disk</td>
</tr>
<tr>
<td>Halo</td>
<td>$B_0 = 4.68 \pm 1.39 \mu G$</td>
<td>field strength</td>
</tr>
<tr>
<td>component</td>
<td>$r_0 = 10.97 \pm 3.80$ kpc</td>
<td>exponential scale length</td>
</tr>
<tr>
<td></td>
<td>$z_0 = 2.84 \pm 1.30$ kpc</td>
<td>Gaussian scale height</td>
</tr>
<tr>
<td>Striation</td>
<td>$\beta = 1.36 \pm 0.36$</td>
<td>striated field $B_{\text{stri}}^2 = \beta B_{\text{reg}}^2$</td>
</tr>
</tbody>
</table>

But, to quote 1707.02339:

"This difference leads to a reduction of random field strength, by up to a factor of four in the disk, relative to JF12 [13]."

Random component of the field washes out structure, regular component maps it.
Conclusions

• The relative isotropy of UHECR arrival directions favours heavier compositions.

• Pure proton hypotheses are rejected at at least 4.6 sigma

• Best fit hypothesis is 100% Fe at source, favouring strong extragalactic magnetic fields $(10^{-9} \text{G})$ and low source density $(10^{-5} / \text{Mpc}^3)$. 

• The results are not significantly different with the PT2011 Galactic magnetic field model, or by considering a wide spread in source luminosities