The Potential Effects of Galactic Magnetic Fields on UHECR from Local Sources

Know Thyself

Galaxy
Galactic B-field Interaction with Cen A CR Flux

Inferred indirectly from:
- Synchrotron Emission maps
- Rotation Measure maps following the adoption of thermal and non-thermal particle models

Jansson & Farrar (2012)
Galactic Magnetic Field and Cosmic Ray Energy Content

\[
\begin{align*}
U_B^{\text{disk}} &= 8 \times 10^{53} \text{ erg} \\
U_B^{\text{toroid}} &= 4 \times 10^{54} \text{ erg} \\
U_B^{\text{X-field}} &= 3 \times 10^{54} \text{ erg} \\
U_{\text{CR}} &\approx 3 \times 10^{55} \text{ erg}
\end{align*}
\]
Deflections of CR From Local Sources

\[ L > 3 \times 10^{42} \frac{1}{\beta^2} \left( \frac{E_p}{3 \times 10^{18} \text{ eV}} \right)^2 \text{ erg s}^{-1} \]

Pe'er et al. (2009), 0911.1776

\[ L_X > 10^{42.5} \text{ erg s}^{-1} \]

The locality of Cen A offers opportunity to use this candidate source to probe Galactic magnetic field effects

Norman et al. (1995)
“Low Energy” Spectral Suppression of CR from Cen A

System Setup
$E_p = 3 \times 10^{18}$ eV

“Shadowing”

**X-field component**

**Toroidal field component**

**Disk field component**
Cosmic Ray Anisotropy from Cen A?

Angular arrival distribution of parallel beam from Cen A fired at Galactic magnetic field

Observer position: (-8.5 kpc, 0.0 kpc, 0.0 kpc)
Spatial bin size: 1.0 kpc, $E_p=3.2\times10^{18}$ eV
Full Bfield

Can be compared to Keivani et al. (2015)
Cosmic Ray Anisotropy from Cen A?

X-field component

Toroidal field component

Importance in role of X-field component of the Galactic Magnetic in shifting position of Cen A in arriving flux from beam injected
Tunnel Vision- How Isotropic Cosmic Rays at Earth Sample the Isotropic Extragalactic Sky

….and lastly, back-tracking isotropic particles from Earth to see which parts of extragalactic sky are preferentially sampled at these energies

Michael named this effect “tunnel vision”!
Tunnel Vision - How Isotropic Cosmic Rays at Earth Sample the Isotropic Extragalactic Sky

Importance in role of Toroidal Field in Selecting Extragalactic Regions Probed
Turbulent B-field Effects

Turbulent B-fields introduce on top a Gaussian smearing of particle trajectories of size

$$\Delta \theta = \delta \theta \left( \frac{R_{\text{Gal}}}{l_{\text{coh}}} \right)^{1/2}$$

Farrar et al. (2017)

$$\delta \theta = 0.6^\circ \left( \frac{l_{\text{coh}}}{10 \text{ pc}} \right) \left( \frac{1 \text{ kpc}}{R_{\text{Lar}}} \right)$$
Galactic B-field Interaction with Cen A CR Flux

Note weakness of this component at Galactic halo distances.
This contrasts with radio bubbles.

Carretti et al. (2013) Nat. Vol. 493

Note

\[ U_{CR}^{FB} \approx 7 \times 10^{55} \text{ erg} \]

Crocker et al. 2015
Conclusions

The role 3 components (disk, toroidal, x-field) of the coherent magnetic field structure in the Jansson and Farrar Galactic magnetic field model have on UHECR propagation from Cen A/extragalactic sky:

• Shadowing is dominated by toroidal B-field component

• Deflection of the source position is dominated by the x-field component

• Tunnel vision of the extragalactic sky is dominated by the x-field component

The presence of magnetic structures associated with the Fermi bubbles/outflows may further hinder the arrival of UHECR into the Galactic magnetosphere.

Indirect probes of the Galactic magnetic field are a limiting factor. Are more direct probes possible? (astro-ph/1903.08675)
Extra Slides
Injection from Source or Back-tracking from Earth?

- Observer position: (-8.5 kpc, 0.0 kpc, 0.0 kpc)
- Spatial bin size: 0.5 kpc
- $E_p = 3.2 \times 10^{18}$ eV
- Full Bfield

- Observer position: (-8.5 kpc, 0.0 kpc, 0.0 kpc)
- Spatial bin size: 0.5 kpc
- $E_p = 3.2 \times 10^{18}$ eV
- Without x-field

- Observer position: (-8.5 kpc, 0.0 kpc, 0.0 kpc)
- Spatial bin size: 0.5 kpc
- $E_p = 4.0 \times 10^{18}$ eV
- X-field
Cosmic Ray Anisotropy from Cen A?

Importance in role of X-field component of the Galactic Magnetic in shifting position of Cen A in arriving flux from beam injected

Only X-field

Only Toroidal + Disk Fields

observer position- (-8.5 kpc, 0.0 kpc, 0.0 kpc)
spatial bin size- 1.0 kpc, $E_p = 3.2 \times 10^{18} \text{ eV}$

observer position- (-8.5 kpc, 0.0 kpc, 0.0 kpc)
spatial bin size- 1.0 kpc, $E_p = 3.2 \times 10^{18} \text{ eV}$
wo x-field
Tunnel Vision- How Isotropic Cosmic Rays at Earth Sample the Isotropic Extragalactic Sky

Importance in role of Toroidal Field in Selecting Extragalactic Regions Probed

Only Toroidal Field

<table>
<thead>
<tr>
<th>( \sin(b) )</th>
<th>( l ) [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1</td>
<td>-150</td>
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<tr>
<td>0</td>
<td>150</td>
</tr>
<tr>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0.5</td>
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</tbody>
</table>

\[ r_{\text{max}} = 32.0 \text{ kpc} \]

\[ E_p = 3.2 \times 10^{18} \text{ eV} \]

Only Disk + X-Field

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\[ r_{\text{max}} = 32.0 \text{ kpc} \]

\[ E_p = 3.2 \times 10^{18} \text{ eV} \]
Comparison of Galactic B-field with CRPropa Authors

Toroidal Field (linear scale XZ plane)

X field Field (linear scale XZ plane)
compensated for solar abundance ratios

\[ \frac{dN_{\text{CR}}}{dE_{\text{CR}}} \left[ \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \right] \]

\[ \frac{E_{\text{CR}}}{A} \left[ \text{eV per nucleon} \right] \]
Low Energy CR Composition Investigation

ATIC data

CREAM data

composition ratios of CR at 10^9 GeV per nucleon

<table>
<thead>
<tr>
<th>( x_i )</th>
<th>proton</th>
<th>He</th>
<th>C</th>
<th>O</th>
<th>Si</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x_i )</td>
<td>1.0</td>
<td>0.04</td>
<td>0.001</td>
<td>0.001</td>
<td>0.0002</td>
<td>0.0002</td>
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</table>
Low Energy CR Composition Investigation

solar system abundance ratios

<table>
<thead>
<tr>
<th>element</th>
<th>proton</th>
<th>He</th>
<th>C</th>
<th>O</th>
<th>Si</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_i$</td>
<td>1.0</td>
<td>0.1</td>
<td>0.0004</td>
<td>0.0008</td>
<td>0.00003</td>
<td>0.00003</td>
</tr>
</tbody>
</table>

compensated for solar abundance ratios

$E_{CR}/A$ [eV per nucleon]

$E_{A} \frac{dN_{A}}{dE_{A}} \left( \frac{E_{A}}{A} \right) = f_{A} E_{p} \frac{dN_{p}}{dE_{p}} (E_{p})$

$f_{A} = \frac{Z^2}{A} f_{SA}$
## Cosmic Ray Spectrum from Cen A?

<table>
<thead>
<tr>
<th>isotope</th>
<th>mass entrained (single lobe) ($M_\odot$)</th>
<th>mass rate (twin lobes) ($M_\odot$ yr$^{-1}$)</th>
<th>number rate (twin lobes) ($s^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1$H</td>
<td>$7.4 \times 10^4$</td>
<td>$2.6 \times 10^{-4}$</td>
<td>$1.0 \times 10^{46}$</td>
</tr>
<tr>
<td>$^3$He</td>
<td>$3.1 \times 10^1$</td>
<td>$1.1 \times 10^{-7}$</td>
<td>$1.4 \times 10^{42}$</td>
</tr>
<tr>
<td>$^4$He</td>
<td>$2.7 \times 10^4$</td>
<td>$9.6 \times 10^{-5}$</td>
<td>$9.1 \times 10^{44}$</td>
</tr>
<tr>
<td>$^{12}$C</td>
<td>$9.5 \times 10^1$</td>
<td>$3.4 \times 10^{-7}$</td>
<td>$1.1 \times 10^{42}$</td>
</tr>
<tr>
<td>$^{14}$N</td>
<td>$7.2 \times 10^1$</td>
<td>$2.6 \times 10^{-7}$</td>
<td>$7.0 \times 10^{41}$</td>
</tr>
<tr>
<td>$^{16}$O</td>
<td>$3.3 \times 10^2$</td>
<td>$1.2 \times 10^{-6}$</td>
<td>$2.8 \times 10^{42}$</td>
</tr>
<tr>
<td>$^{20}$Ne</td>
<td>$5.5 \times 10^1$</td>
<td>$2.0 \times 10^{-7}$</td>
<td>$3.7 \times 10^{41}$</td>
</tr>
<tr>
<td>$^{22}$Ne</td>
<td>$5.0 \times 10^0$</td>
<td>$1.8 \times 10^{-8}$</td>
<td>$3.1 \times 10^{40}$</td>
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<tr>
<td>$^{24}$Mg</td>
<td>$1.8 \times 10^1$</td>
<td>$6.4 \times 10^{-8}$</td>
<td>$1.0 \times 10^{41}$</td>
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<tr>
<td>$^{26}$Mg</td>
<td>$2.7 \times 10^0$</td>
<td>$9.6 \times 10^{-9}$</td>
<td>$1.4 \times 10^{40}$</td>
</tr>
<tr>
<td>$^{28}$Si</td>
<td>$2.3 \times 10^1$</td>
<td>$8.2 \times 10^{-8}$</td>
<td>$1.1 \times 10^{41}$</td>
</tr>
<tr>
<td>$^{32}$S</td>
<td>$1.6 \times 10^1$</td>
<td>$5.7 \times 10^{-8}$</td>
<td>$6.8 \times 10^{40}$</td>
</tr>
<tr>
<td>$^{56}$Fe</td>
<td>$4.1 \times 10^1$</td>
<td>$1.5 \times 10^{-7}$</td>
<td>$9.9 \times 10^{40}$</td>
</tr>
</tbody>
</table>

astro-ph: 1706.08229
*Note- no hardening of the spectrum at low energies has here been taken into account*
Galactic Magnetic Field “Shadowing”

\[ U_B^{\text{toroid}} = 4 \times 10^{54} \text{ erg} \]

\[ U_B^{\text{disk}} = 8 \times 10^{53} \text{ erg} \]

\[ U_B^{X-\text{field}} = 3 \times 10^{54} \text{ erg} \]

Michael & I had intended to produce a short paper on this “shadowing” effect.
Galactic B-field Interaction with Cen A CR Flux

Toroidal field component

z=2 kpc

z=-2 kpc
Non-Thermally Luminous Objects

(Swift 58 month Hard X-Ray catalogue)