The Anisotropy in the Arrival Directions of Galactic Cosmic Rays
– Expectations vs. Observations –

Markus Ahlers
Niels Bohr Institute, Copenhagen

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VILLUM FONDEN
Galactic Cosmic Rays

- **Standard paradigm:**
  Galactic CRs accelerated in **supernova remnants**

  - sufficient power: \( \sim 10^{-3} \times M_\odot \) with a rate of \( \sim 3 \) SNe per century

  [Baade & Zwicky’34]

- galactic CRs via diffusive shock acceleration?

  \[
  n_{CR} \propto E^{-\Gamma_{CR}} \quad \text{(at source)}
  \]

- energy-dependent **diffusion** through Galaxy

  \[
  n_{CR} \propto E^{-\Gamma_{CR}-\beta} \quad \text{(observed)}
  \]

- arrival direction **mostly isotropic**
Cosmic ray anisotropies up to the level of one-per-mille at various energies (Super-Kamiokande; Milagro; ARGO-YBJ; EAS-TOP, Tibet AS-\(\gamma\); IceCube; HAWC)

HAWC & IceCube @ 10TeV

Equatorial

intensity \([10^{-3}]\)

[IceCube & HAWC'17]
Expected Dipole Anisotropy

- Spherical harmonics expansion of relative intensity yields:

\[
I(\Omega) = 1 + \delta \cdot \hat{n}(\Omega) + \sum_{\ell \geq 2} \sum_{m} a_{\ell m} Y_{\ell m}(\Omega)
\]

- Cosmic ray density \( n_{\text{CR}} \propto E^{-\Gamma_{\text{CR}}} \) and dipole vector \( \delta \) from diffusion theory:

\[
\partial_t n_{\text{CR}} \simeq \nabla (K \nabla n_{\text{CR}}) + Q_{\text{CR}} \quad \text{and} \quad \delta \simeq 3K \nabla \ln n_{\text{CR}}
\]

- Diffusion tensor \( K \) in general anisotropic (background field \( B \)):

\[
K_{ij} = \kappa_{\parallel} \hat{B}_i \hat{B}_j + \kappa_{\perp} (\delta_{ij} - \hat{B}_i \hat{B}_j) + \kappa_A \epsilon_{ijk} \hat{B}_k
\]

- Relative motion of the observer in plasma rest frame (\( \star \)): [Compton & Getting’35]

\[
\delta = \delta^\star + (2 + \Gamma_{\text{CR}})v/c
\]

Compton-Getting effect
• Most ground-based detectors need to be \textit{calibrated} by cosmic ray data.

\textgreater{} This introduces \textit{degeneracies} w.r.t. anisotropy and local detector acceptance.

\texttimes{} Only certain spherical harmonics \((m \neq 0)\) can be unambiguously reconstructed!

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Observed Dipole Anisotropy

- RA phase [degree]
- Projected amplitude $[10^{-3}]$
- Energy [GeV]

Graph showing the observed dipole anisotropy in the arrival directions of Galactic CRs, with data points from various experiments such as Super-K, IceCube, MACRO, IceTop, K-Grande, Baksan, EAS-TOP, ARGO-YBJ, and others. The graph includes energy bins and RA phase angles, with data points distributed across different energies and RA phases.

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Local Magnetic Field

- reconstructed diffuse dipole:
  \[ \delta^* = \delta - (2 + \Gamma_{\text{CR}}) \beta = 3K \cdot \nabla \ln n^* \]
  
- projection onto equatorial plane:
  \[ \delta^*_{\text{EP}} = (\delta^*_{0h}, \delta^*_{6h}) \]

- strong regular magnetic fields in the local environment reduce diffusion tensor to projector:
  \[ K_{ij} \rightarrow \kappa \| \hat{B}_i \hat{B}_j \]

- TeV–PeV dipole data consistent with magnetic field direction inferred by IBEX data [McComas et al.’09]
Known Local Supernova Remnants

- projection maps source gradient onto $\hat{B}$ or $-\hat{B}$

- dipole phase $\alpha_1$ depends on orientation of magnetic hemispheres

- intersection of magnetic equator with Galactic plane defines two source groups:

  $120^\circ \lesssim l \lesssim 300^\circ \rightarrow \alpha_1 \approx 49^\circ$

  $-60^\circ \lesssim l \lesssim 120^\circ \rightarrow \alpha_1 \approx 229^\circ$
Phase-Flip by Vela SNR

- 1–100 TeV phase indicates dominance of a local source within longitudes:
  \[120^\circ \lesssim l \lesssim 300^\circ\]

- **plausible scenario:** Vela SNR [MA’16]
  
  - **age:** \(\sim 11,000\) yrs
  
  - **distance:** \(\sim 1,000\) lyrs
  
  - **SNR rate:** \(R_{\text{SNR}} = 1/30\) yr\(^{-1}\)
  
  - (effective) isotropic diffusion:
    \[K_{\text{iso}} \sim 4 \times 10^{28}(E/3\text{GeV})^{1/3}\text{cm}^2/\text{s}\]
  
  - **Galactic half height:** \(H \sim 3\) kpc
  
  - **instantaneous CR emission** \((Q_*)\)
Relative position of the five closest known SNRs. The magnetic field direction (IBEX) is indicated by blue $\times$ and the magnetic horizon by a dashed line.
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  - **Galactic half height**: \( H \simeq 3 \) kpc
  - **instantaneous CR emission** \( (Q_\star) \)

![Graph showing predicted anisotropy](image)
• Observation of cosmic ray anisotropies at the level of one-per-mille is challenging.

• Reconstruction methods introduce bias.

• **Dipole anisotropy** can be understood in the context of standard diffusion theory:
  • TeV-PeV dipole phase aligns with local ordered magnetic field.
  → **New method** of measuring local magnetic fields
  • Amplitude variations as a result of local sources
  • Plausible & natural candidate: **the Vela supernova remnant**

• Cosmic ray data show significant **small-scale anisotropies**.
  • Effect of heliosphere? [e.g. review by MA & Mertsch’16]
  • Result of local magnetic turbulence? [Giacinti & Sigl’12; MA’14; MA & Mertsch’15]
Appendix
Backtracking in Local Turbulence

Assume a homogeneous, but anisotropic dipolar state \( [\text{MA} \& \text{Mertsch'15}] \). In that case, the CR back-tracking "flow" starts ballistically away from the observer only, and the observed sky map will be the same as the assumed dipole. However, as the strength of the turbulent field increases (cf. Fig. 12), the anisotropy map will show the first small-scale structures: Particles will have experienced similar magnetic configurations and their moment correlate. (Compare the different magnetic fields and their momenta will lose correlation. (Compare the different magnetic fields and their momenta will lose correlation.

At early times, the back-tracked particles will have travelled sufficiently far, that particles sent out back-tracking into very different directions for very different scales of a regular magnetic field. In that case, the CR back-tracking starts ballistically. However, as the strength of the turbulent field increases (cf. Fig. 12), the anisotropy map will show the first small-scale structures: Particles will have experienced similar magnetic configurations and their moment correlate. (Compare the different magnetic fields and their momenta will lose correlation. (Compare the different magnetic fields and their momenta will lose correlation.

The formation of small-scale anisotropies can be understood in the following thought experiment: Assume a homogeneous, but anisotropic dipolar state \( [\text{MA} \& \text{Mertsch'15}] \). In that case, the CR back-tracking "flow" starts ballistically away from the observer only, and the observed sky map will be the same as the assumed dipole. However, as the strength of the turbulent field increases (cf. Fig. 12), the anisotropy map will show the first small-scale structures: Particles will have experienced similar magnetic configurations and their moment correlate. (Compare the different magnetic fields and their momenta will lose correlation. (Compare the different magnetic fields and their momenta will lose correlation.

In principle, the same technique can be applied to the case of small-scale anisotropies from local turbulence. The appropriate choice of the back-tracking time \( \tau \) becomes larger (cf. middle panel of Fig. 12). However, neighboring CRs (cf. the red and orange trajectory) will have experienced similar magnetic configurations and their moment correlate.
Small-Scale “Theorem”

• **Assumptions:**
  - absences of cosmic ray sources and sinks
  - isotropic and static magnetic turbulence
  - initially, homogeneous phase space distribution

• **Theorem:** The sum over the ensemble-averaged angular power spectrum is constant:

\[
\sum_{\ell} (2\ell + 1) \langle C_\ell (t) \rangle = \text{const}
\]

• Proof via Liouville’s theorem and angular auto-correlation function. [MA’14]

→ Wash-out of individual moments by diffusion (rate \(\nu_\ell \propto \ell(\ell + 1)\)) has to be compensated by generation of small-scale anisotropy.

→ Theorem implies small-scale angular features from large-scale average dipole anisotropy. [Giacinti & Sigl’12; MA’14; MA & Mertsch’15]
Local Magnetic Field

- **IBEX ribbon**: enhanced emission of energetic neutral atoms (ENAs) observed with Interstellar Boundary EXplorer [McComas et al.’09]

- interpreted as local magnetic field ($\lesssim 0.1$ pc) draping the heliosphere

- circle center defines field orientation (in Galactic coordinate system): [Funsten et al.’13]

  \[ l \simeq 210.5^\circ \quad \& \quad b \simeq -57.1^\circ \]
  \[ (\Delta \theta \simeq 1.5^\circ) \]

- consistent with starlight polarization by interstellar dust ($\lesssim 40$ pc) [Frisch et al.’15]

  \[ l \simeq 216.2^\circ \quad \& \quad b \simeq -49.0^\circ \]
Cosmic Ray Dipole Anisotropy

- cosmic-ray (CR) arrival directions described by **phase-space distribution**

\[ f(t, r, p) = \frac{\phi(t, r, p)}{4\pi} + 3\hat{p}\frac{\Phi(t, r, p)}{4\pi} + \ldots \]

- monopole
- dipole

- local CR spectral density \([\text{GeV}^{-1}\text{cm}^{-3}]\)

\[ n(p) = p^2\phi(t, r_\oplus, p) \propto p^{-\Gamma_{\text{CR}}} \]

- \(\propto p^{-(\Gamma_{\text{CR}}+2)}\)

- in the absence of sources, follows Liouville’s equation (\(\dot{f} = 0\))

→ **quasi-stationary dipole** (\(\partial_t \Phi \simeq 0\)):

\[ \partial_t \phi \simeq \nabla_r (K \nabla_r \phi) \quad \text{and} \quad \Phi \simeq -K \nabla_r \phi \]

- Fick’s law
- diffusion equation

- diffusion tensor \(K\):

\[ K_{ij} = \kappa_\parallel \hat{B}_i \hat{B}_j + \kappa_\perp (\delta_{ij} - \hat{B}_i \hat{B}_j) + \kappa_A \epsilon_{ijk} \hat{B}_k \]

→ **dipole anisotropy**: \(\delta = 3K \cdot \nabla_r \ln n\)
Compton-Getting Effect

- phase-space distribution is **Lorentz-invariant**

\[ f^*(p^*) = f(p) \]

- consider *relative motion of observer* \((\beta = \mathbf{v}/c)\) in plasma rest frame (*): 

\[ p^* = p + p\beta + \mathcal{O}(\beta^2) \]

- Taylor expansion:

\[
f(p) \simeq f^*(p) + (p^* - p) \nabla_p f^*(p) + \mathcal{O}(\beta^2) \simeq f^*(p) + p\beta \nabla_p f^*(p) + \mathcal{O}(\beta^2) \]

- splitting in \(\phi\) and \(\Phi\) is **not invariant**:

\[
\phi = \phi^* \quad \text{and} \quad \Phi = \Phi^* + \frac{1}{3} \beta \frac{\partial \phi^*}{\partial \ln p}
\]

- remember: \(\phi \sim p^{-2} n_{CR} \propto p^{-2-\Gamma_{CR}}\)

\[
\delta = \delta^* + \left(2 + \Gamma_{CR}\right)\beta
\]

Compton-Getting effect