Modeling of cosmic-ray anisotropy at TeV energies in an MHD model heliosphere

T. K. Sako
on behalf of the Tibet ASγ Collaboration
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Tibet ASγ Collaboration


1 Department of Physics, Hirosaki Univ., Japan.
2 Department of Physics, Shinshu Univ., Japan.
3 School of Astronomy and Space Science, Nanjing Univ., China.
4 Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, CAS, China.
5 National Astronomical Observatories, CAS, China.
6 Department of Mathematics and Physics, Tibet Univ., China.
7 Department of Physics, Hebei Normal Univ., China.
8 Univ. of Chinese Academy of Sciences, China.
9 Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong Univ., China.
10 Institute of Modern Physics, SouthWest Jiaotong Univ., China.
11 Faculty of Engineering, Yokohama National Univ., Japan.
12 Faculty of Engineering, Kanagawa Univ., Japan.
13 Faculty of Education, Utsunomiya Univ., Japan.
14 Faculty of Systems Engineering, Shibaura Institute of Technology, Japan.
15 Institute for Cosmic Ray Research, Univ. of Tokyo, Japan.
16 Polar Environment Data Science Center, Joint Support-Center for Data Science Research, Research Organization of Information and Systems, Japan.
17 National Center for Space Weather, China Meteorological Administration, China.
18 School of Information Science and Engineering, Shandong Agriculture Univ., China.
19 Department of Astronomy, School of Physical Sciences, Univ. of Science and Technology of China, China.
20 College of Industrial Technology, Nihon Univ., Japan.
21 National Institute of Informatics, Japan.
22 National Institute of Information and Communications Technology, Japan.
23 Department of Mechanical and Electrical Engineering, Shandong Management Univ., China.
24 College of Science, China Univ. of Petroleum, China.
25 Tokyo Metropolitan College of Industrial Technology, Japan.
26 Department of Physics, Konan Univ., Japan.
27 Shonan Institute of Technology, Japan.
29 Japan Atomic Energy Agency, TJapan.
30 Key Laboratory of Dark Matter and Space Astronomy, Purple Mountain Observatory, CAS, China.
Tibet Air Shower Array

@Yangbajing in Tibet, China (90.522° E, 30.102° N, 4,300 m a.s.l.)

This presentation uses data from Nov 1999 to May 2010

Scintillation Counter Array: 0.5 m$^2$ x 789 counters
Effective area: $\sim$ 37,000 m$^2$
Energy range: $\sim$ TeV - 100 PeV
F.O.V.: $\sim$ 2 sr

Relative timing information $\rightarrow$ Arrival direction
Angular Resolution $\sim$0.4° @10TeV

Charge information $\rightarrow$ Primary cosmic-ray energy
Energy Resolution $\sim$70% @10TeV
Anisotropy at TeV energies
Tibet III, Nov 1999 - May 2010

Possible causes
- Parallel diffusion
- Compton-Getting effect
- Diamagnetic drift
- Magnetic Mirror Effect

(※ with declination bias)

+ heliospheric modulation
Recent study based on intensity mapping (1)

Liouville’s theorem

Phase-space density distribution of CRs: \( f(r, p, t) \)

\[
Df = \frac{\partial f}{\partial t} + \frac{dr}{dt} \cdot \frac{\partial f}{\partial r} + \frac{dp}{dt} \cdot \frac{\partial f}{\partial p} = \left( \frac{\partial f}{\partial t} \right)_c \approx 0
\]

\( f(r_E, p_E, t) \approx f(r_B, p_B, t) \)

Intensity of CRs with \( p_E \) @ Earth || Intensity of CRs with \( p_B \) @ Outer Boundary of heliosphere

Mapping of CR intensity between Earth and outer boundary

CR anisotropy @ outer boundary

Recent study based on intensity mapping (2)

Data

Anisotropy @ Earth

Model

- Dipole amplitude along $B_{\text{ISM}}$

\begin{itemize}
  \item Dipole amplitude along $B_{\text{ISM}} \times \nabla f$
  \item (Reduced $\chi^2 = 4.5$)
\end{itemize}

Anisotropy @ outer boundary

\begin{itemize}
  \item Dipole amplitude $A_1$ along $B_{\text{ISM}}$ is dominant
  \item CR density gradient direction ($\nabla f$) close to Vela
\end{itemize}

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Table:

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Value</th>
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<tbody>
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<td>Amplitude of pitch-angle dipole</td>
<td>$A_1 = (0.165 \pm 0.002)%$</td>
</tr>
<tr>
<td>Amplitude of pitch-angle quadrupole</td>
<td>$A_2 = (0.015 \pm 0.002)%$</td>
</tr>
<tr>
<td>CR density gradient</td>
<td>$</td>
</tr>
<tr>
<td>Normalization</td>
<td>$f_0 = 1 + (0.024 \pm 0.001)%$</td>
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Recent study based on intensity mapping (2)

Data

Anisotropy @ Earth

Model

Intensity mapping using only 4 TeV monoenergy protons

CR energy spectrum & composition must be considered

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Dipole amplitude along $B_1$

Anisotropy @ outer boundary

Reduced $\chi^2 = 4.5$

Modeling must be improved

MHD model heliosphere used in this work

By N. Pogorelov
Set Earth at 4 positions ($\pm 1\text{AU}, 0, 0$), $(0, \pm 1\text{AU}, 0)$

Shoot CR particles with reversed charge into MHD heliosphere
  — initial directions (4 samplings for each data pixel)
  — Observed rigidity distribution taken into account

Record CR momentum directions @ outer boundary
  — Boundary defined as a surface where:
    Deviation in $\vec{B}_{\text{helio}}$ strength from $\vec{B}_{\text{ISM}} < 0.1\%$, and
    Deviation in $\vec{B}_{\text{helio}}$ direction from $\vec{B}_{\text{ISM}} < 0.1^\circ$
Energy spectrum & composition

Evaluate how different CR species with different energies contribute to the observed anisotropy using MC sim.

- CR energy spectrum & composition based on direct measurements


- Air shower generation and Air Shower array response simulation
- Analyze MC events in the same way as experimental data

Evaluate weight factor
Weight factor for each declination band (MC)

![Graph showing weight factor for each declination band (MC)](image)

- MC
- Number of events (weight factor)
- rigidity (GV)
- Dec = -20
- Dec =  5
- Dec =  30
- Dec =  55
- Dec =  80

Weight factor for each declination band (MC)
How to derive anisotropy @ outer boundary

1) Assume a model of relative intensity @ outer boundary as:

\[ I_{\text{ISM}} = 1 + A_{1\parallel} \cos(\mu_2) + A_{2\parallel} \cos^2(\mu_2) + A_{1\perp} \cos(\mu_1) + I_{\text{CG}} \]

- \( \mu_2 \): pitch angle
- \( \mu_1 \): angle between particle’s \( \vec{p} \) and \( \vec{B}_{\text{ISM}} \times \nabla n \)
- \( A_{1\parallel} \): dipole amplitude parallel to \( \vec{B}_{\text{ISM}} \)
- \( A_{2\parallel} \): quadrupole amplitude parallel to \( \vec{B}_{\text{ISM}} \)
- \( A_{1\perp} \): dipole amplitude perpendicular to \( \vec{B}_{\text{ISM}} \)
- \( I_{\text{CG}} \): Compton-Getting anisotropy due to heliospheric motion relative to ISM (\( v = 23.2 \) km/s \( \Rightarrow \) amplitude 0.03%)

2) Map \( I_{\text{ISM}} \) to Earth

3) Normalize the average of mapped model intensity @ Earth to one for each decl. band

4) Calculate \( \chi^2 \) between normalized model intensity and experimental data

Repeat 1) – 4) and obtain best-fit parameter values that minimize \( \chi^2 \)

4 free parameters: \( A_{1\parallel}, A_{2\parallel}, A_{1\perp}, \alpha_1 \)
(\( \alpha_1, \delta_1 \)): direction of \( \nabla n \) (CR density gradient perpendicular to \( \vec{B}_{\text{ISM}} \))
Results: fitting by dipole & quadrupole flows

\[ I_{\text{ISM}} = 1 + A_1 || \cos(\mu_2) + A_2 || \cos^2(\mu_2) + A_1 \perp \cos(\mu_1) + I_{\text{CG}} \] 

\( (\alpha_1, \delta_1) : \text{direction of } \nabla n \) 

\[ \chi^2 / \text{ndf} = 3320 / 2052 = 1.62 \]

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<th>Dipole amplitude along ( B_{\text{ISM}} )</th>
<th>Dipole amplitude along ( B_{\text{ISM}} \times \nabla n )</th>
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<tr>
<td>( A_1</td>
<td></td>
</tr>
<tr>
<td>0.234 ± 0.002</td>
<td>0.011 ± 0.004</td>
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</table>

Data @Earth

Model @Earth

Model @ Boundary

- \( A_1 \perp \) is not so small; about half of \( A_1 || \)
- CR density gradient direction (G) not close to Vela
Results: fitting by spherical harmonics

\[ I_{\text{ISM}}(\theta, \phi) = 1 + \sum_{l=1}^{l_{\text{max}}} \sum_{m=-l}^{l} f_{lm} Y_{lm}(\theta, \phi) + I_{\text{CG}} \]

\[ L_{\text{max}} = 24 \text{ (624 parameters)} \]

\[ \chi^2 / \text{ndf} = 1393 / 1432 = 0.973 \text{ (76.4 %)} \]

Data @ Earth

Model Fitting @ Earth

Model @ Boundary

- Unrealistic small-scale anisotropy appears @ outer boundary

\[ B_{\text{ism}}, V_{\text{H}}, V_{\text{He}} \]

- interstellar \( B \)
- interstellar H & He flow

- elliptic plane
- magnetic equator
- hydrogen deflection plane
L ≥ 20 terms are needed @ outer boundary to get reasonable $\chi^2$

Spectrum flatter @ outer boundary than @ Earth

Results: Power spectrum

$$C_l = \left( \frac{1}{4\pi} \right) \left( \frac{1}{2l + 1} \right) \sum_{m=-l}^{l} f_{lm}^2$$

CR intensity distributions at different boundaries?

XZ plane (Y=0)

- 3980 AU
- 1580 AU
- 630 AU

|B| (μG)
Results: intensity distributions @ different outer boundaries

**Observed at Earth**

**Reproduced at Earth**

- $r_B = 630$ AU
- $r_B = 1580$ AU
- $r_B = 3980$ AU

**Best-fit at boundary ($r=r_B$)**

- $L_{\text{max}} = 4$ 
  - $N_{\text{param.}} = 26$
  - $\chi^2 / \text{ndf} = 0.962$

- $L_{\text{max}} = 8$ 
  - $N_{\text{param.}} = 80$
  - $\chi^2 / \text{ndf} = 0.982$

- $L_{\text{max}} = 20$ 
  - $N_{\text{param.}} = 440$
  - $\chi^2 / \text{ndf} = 0.942$
Effect of particle scattering with magnetic irregularities in the heliosphere ??
Diffusion coefficient


\[ D = \beta D_0 \left( \frac{\rho}{\rho_0} \right)^{\delta} \]

\[ D_0 = 6.1 \times 10^{28} \text{ [cm}^2\text{s}^{-1}] \]

\[ \rho_0 = 4 \text{ [GV]} \]

\[ \delta = \frac{1}{3} \]

Mean free path

\[ D = \frac{1}{3} vL \quad (v \approx c) \]

\[ L \sim 5 \times 10^6 \text{ AU for 7 TeV proton} \]

Assuming \( T \sim 60 \text{ days from boundary to Earth} \)

\[ \Rightarrow dl = 1 \times 10^4 \text{ AU for 7 TeV proton} \]

\[ \Rightarrow \sqrt{\langle \Theta^2 \rangle} \sim 4^\circ \]

Yasue+, Planet Space Sci. 33, 1057 (1985)

The projected angle \( \Theta \) is defined as the angle between \( \mathbf{V} \) and the projection of the scattered velocity on one of the planes, and has the following probability distribution:

\[ \Phi(\Theta) = \frac{1}{\sqrt{2\pi}\langle \Theta^2 \rangle} \exp \left( -\frac{\Theta^2}{2\langle \Theta^2 \rangle} \right), \]

where \( \langle \Theta^2 \rangle \) is the mean square angle of \( \Theta \) for \( dl \) and is related with the scattering mean free path \( L \) as

\[ \langle \Theta^2 \rangle = \left( \frac{\pi}{2} \right)^2 \left( \frac{dl}{L} \right), \]

in which

\[ L(r, P) = L_0 \left( \frac{P}{10 \text{ GV}} \right)^2 \exp \left( \frac{r-1}{33 \text{ a.u.}} \right) \text{(a.u.)} \]

for \( P > 10 \text{ GV} \). (3)

The radial dependence of \( L \) is quoted from Fulks (1975) and its rigidity dependence is based on a theoretical consideration (Parker, 1958; Jokipii, 1971) and seems to be supported by observations in the low rigidity region (\( P \sim 10 \text{ GV} \)) (Fulks, 1975; Lockwood and Webber, 1979; Zusmanovich, 1981). The magnitude of \( L_0 \) is set to 0.77 a.u. by the normalization at 10 GV to the one obtained in the lower rigidity region by Garcia-Munoz et al. (1977).
Results: best-fit relative intensity distributions

\[ L_{\text{max}} = 5 \ (35 \text{ parameters}) \]

\[ \chi^2/\text{ndf} = 2042/2021 = 1.01 \ (36 \%) \]

Data @Earth

Model Fitting @Earth

Model @ Outer boundary

- \( L \leq 5 \) terms are sufficient @ outer boundary to get reasonable \( \chi^2 \)
- Amplitude @ outer boundary becomes percent-level

Max: +2.3%
Min: −1.2%
Terms with $L \geq 3$ larger at outer boundary than at Earth

⇒ intensity-mapping method needs more improvement??

Summary

Quantitative study on the origin of TeV CR anisotropy based on intensity mapping

✔ Rigidity distribution of observed CR particles taken into account
✔ Modeling @ boundary improved using spherical harmonics
  ➡ Intensity distribution @ boundary needs \( L \geq 20 \) terms to get reasonable \( \chi^2 \)
✔ Tentative study of scattering by magnetic irregularities in the heliosphere
  ➡ Intensity distribution @ boundary can be expressed with \( L \leq 5 \) terms
    But still terms with \( L \geq 3 \) larger @ boundary than @ Earth

Future prospects

➢ Suppress the apparent high-order terms in the power spectrum
  ➡ Using a “snapshot” MHD model of the heliosphere may be a problem
    (Data covers 10 years (2000-2009) of A<0 phase of 23rd solar cycle)
➢ Compare the results with other MHD heliosphere models
    (e.g. by Washimi+ and Opher+)
➢ Examine the observed energy dependence of anisotropy around 100 TeV
Thank you for your attention!
Distribution of the time from Earth to Boundary

Scattering angle distribution
Washimi MHD model A

\( A < 0 \)

Washimi MHD model B

\( A > 0 \)
Power spectrum

\[ C_l = \left( \frac{1}{4\pi} \right) \left( \frac{1}{2l + 1} \right) \sum_{m=-l}^{l} f_{lm}^2 \]

Large-scale: less affected by $B_{\text{helio}}$ structure

Mid- to small-scale: affected by $B_{\text{helio}}$ structure

$A < 0$

$A > 0$