anisotropy of TeV cosmic rays
and the outer heliospheric boundaries

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cosmic ray anisotropy large scale

Relative intensity

equatorial coordinates

IceCube-59

360° 0°

-1.5 -1 -0.5 0 0.5 1 1.5

ΔN/N [×10^{-3}]

IceCube-59

360° 0°

-1.5 -1 -0.5 0 0.5 1 1.5

ΔN/N [×10^{-3}]

IceTop-59/73/81

360° 0°

-3 -2 -1 0 1 2 3

Relative intensity [×10^{-3}]

20 TeV

400 TeV

2 PeV

Abbasi et al., ApJ, 718, L194, 2010

Abbasi et al., ApJ, 746, 33, 2012

Aartsen et al., arXiv:1210.5278 accepted to ApJ

Abbasi et al., ApJ, 746, 33, 2012

deficit 6.3 \( \sigma \)

\[ \Delta I \equiv \frac{N_i - \langle N \rangle}{\langle I \rangle} \]

NOT A DIPOLE ANISOTROPY

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cosmic ray anisotropy \( \text{large scale } \rightarrow \text{ small scale} \)

**Tibet-III**
Amenomori et al., ICRC 2011

360°

**IceCube-59**
Abbasi et al., ApJ, 746, 33, 2012

5 TeV

20 TeV

equatorial coordinates

**relative intensity**

**Milagro + IceCube TeV Cosmic Ray Data (10° Smoothing)**

2 hr = 30°

360°

Milagro
Abdo et al., PRL, 101, 221101, 2008

1 TeV

IceCube
Abbasi et al., ApJ, 740, 16, 2011

4 hr = 60°

20 TeV

3

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cosmic ray anisotropy
heliospheric influence

heliospheric size of $O(100-10,000)$ AU influences cosmic rays up to $O(10-100)$ TeV
heliospheric perturbations
solar cycles

- solar wind modulated over a solar cycle, affecting heliospheric dynamics

- complex heliotail structure shaped by solar cycles

Zank & Müller 2003
Pogorelov+ 2009
Washimi+ 2011, 2012

Nerney & Suess 1995

3D simulation of heliosphere/heliotail Pogorelov+ 2009
cosmic ray anisotropy & acceleration
stochastic magnetic reconnection

turbulent reconnection Lazarian & Vishniac 1999
1st order Fermi acceleration de Gouveia dal Pino & Lazarian 2003, 2005

\[ E_{\text{max}} \approx 0.5 \left( \frac{B}{1 \mu G} \right) \left( \frac{L_{\text{zone}}}{100 \text{ AU}} \right) \text{TeV} \approx 0.5 - 6 \text{ TeV} \]
Lazarian, PD 2010 - PD, Lazarian 2012

\[ dN/dE \propto E^{\gamma} e^{-E/E_c} \]
Milagro observation Abdo+ 2008

\[ \gamma < \gamma_{\text{elsewhere}} \text{ at 4.6 } \sigma \text{ level} \]
\[ E_c = 3 - 25 \text{ TeV} \]
detailed modeling of heliotail very important
cosmic ray anisotropy & scattering
heliospheric perturbations

LIMF direction compatible with
• Ca II absorption & H I lines, Frisch (1996)
• radio emission from inner heliosheath, Lallement et al. (2005), Opher et al. (2007)
• polarization measurements, Frisch (2010)

Funsten et al. (2009)
Schwadron et al. (2009)
Heerikhuisen et al. (2010)

Milagro + IceCube TeV Cosmic Ray Data (10° Smoothing)
cosmic ray anisotropy & scattering
heliospheric perturbations

Pogorelov & Zank (2004)

PD & Lazarian 2013

equatorial coordinates
magnetic equator

Milagro + IceCube TeV Cosmic Ray Data (10° Smoothing)
cosmic ray anisotropy & scattering
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LIMF
deficit

relative
ecliptic
equator

relative
equator

north

TS

magnetic
equator

Milagro + IceCube TeV Cosmic Ray Data (10° Smoothing)
heliospheric perturbations

- Rayleigh-Taylor instabilities driven and mediated by interstellar neutral atoms

Liewer et al. 1996
Zank et al. 1996

- plasma-fluid instabilities at the flank of HP by charge exchange processes

Zank 1999
Florinski++ 2005
Borovikov et al. 2008
Zank 2009
Shaikh & Zank 2010
cosmic ray anisotropy
influence of perturbed heliotail

anisotropy re-directed due to *scattering* on magnetic perturbations on the heliospheric boundary
scattering on heliospheric boundary toy model

- @ energy scale of 10 TeV - proton resonant scattering with perturbations at largest scale - scrambling of cosmic ray arrival directions
scattering on heliospheric boundary toy model

- @ energy scale of 10 TeV - proton resonant scattering with perturbations at largest scale - scrambling of cosmic ray arrival directions
- < 10 TeV - resonant scattering with smaller scale perturbations - pitch angle variations from $p^2\perp/B$ at larger scale
- > 10 TeV - non-resonant scattering with smaller scales - amplitude decreases, intensity gradient become smoother
- > 100 TeV - $r_L >$ heliosphere - heliospheric influence dissipates

- CR mass composition - smearing of transition scale
- re-directed anisotropy not a dipole
scattering on heliospheric boundary toy model
scattering on heliospheric boundary
toy model

detailed modeling of heliotail very important

PD & Lazarian 2013
conclusions

• high energy **cosmic ray anisotropy** to probe into their **origin** and **propagation**

• astrophysical scenarios need understanding of local phenomena

• <100 TeV cosmic rays to be affected by heliosphere

• **scattering** with perturbation on heliopause

• **re-acceleration** mechanism from heliotail

> heliospheric modeling to be extended along **heliotail** with fine resolution: turbulence & global structure. Particle trajectory integration studies will follow → predictive model
thank you
backup
from the Galaxy to our local interstellar medium

\[ R_g \approx \frac{200}{Z} \left( \frac{E}{1\text{ TeV}} \right) \left( \frac{\mu G}{B} \right) \text{ AU} \]

Milky Way

Local Bubble

\(< 500 \text{ pc } > \quad (1.4 \text{ EeV})\)

Local Interstellar Cloud

\(< 10-50 \text{ pc } > \quad (30 \text{ PeV} - 140 \text{ PeV})\)

\(< 30,000 \text{ pc } > \quad (80 \text{ EeV})\)

\(< 3 \text{ TeV} - 140 \text{ TeV} > \quad < 200 \text{ AU} - 10^4 \text{ AU} >\)
low energy cosmic ray anisotropy
in arrival direction

Nagashima et al., J. Geophys. Res., Vol 103, No. A8, Pag. 17,429 (1998)

Relative Intensity

Sidereal local time

Mt Norikura
Nagoya
Sakashita
Hobart

E ~ 10^4 GeV
E ~ 66 GeV
E ~ 60 GeV
E ~ 331 GeV
E ~ 387 GeV
E ~ 180 GeV

heliospheric-tail
loss-cone region
tail-in excess region
cosmic ray anisotropy

Nagashima et al. (1998)
Hall et al. (1999)

Amenomori et al. (2006)
Super Kamiokande
Guillian et al. (2007)

Abdo et al. (2009)
Milagro

Abbasi et al. (2010)
IceCube

ARGO-YBJ
Zhang et al. (2009)

equatorial coordinates

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cosmic ray anisotropy

large scale energy dependency

\[ \delta A = \sum_{SNR} \frac{eD(E)}{c} \cdot \frac{\nabla \phi_{CR}}{\phi_{CR}}(E) \]

anisotropy amplitude \( \sim 10^{-4} - 10^{-3} \)

\[ D(E) \approx (3 - 5) \times 10^{28} \cdot E^{0.3 - 0.6} \quad [cm^2 s^{-1}] \]

diffusion coefficient

\[ \Rightarrow \delta A \propto E^{0.3 - 0.6} \]

anisotropy increases vs energy
cosmic ray anisotropy
angular scale structure
cosmic ray anisotropy small scale

IceCube

relative intensity

raw map

\[ \Delta N / \langle N \rangle [ \times 10^{-3} ] \]

sky map contains correlations at several angular scales

in gray 60% and 95% of simulated isotropic bands

large and small scales separated @ \( \sim 20 \, \text{TeV} \)?

\[ \chi^2 / \text{ndf} = 14743.4 / 14187 \]

\[ \text{Pr}(\chi^2 / \text{ndf}) = 0.05\% \]

Abbasi et al., ApJ, \textbf{740}, 16, 2011
spectral feature associated to anisotropy

Abdo A.A. et al., Phys. Rev. Lett., 101, 221101 (2008)

Harder spectrum in region A

Milagro & ARGO-YBJ

Di Sciascio et al., arXiv:1202.3379

Harder than average spectrum from region A

$\gamma < 2.7$ at 4.6 $\sigma$ level

$E_c = 3 - 25$ TeV

Similar to hardening of “diffuse” cosmic rays by Pamela, CREAM, ATIC-2, or something else?

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cosmic rays observations
all-particle spectrum

Pamela
Adriani et al. (2011)

He \approx E^{-2.48}
He (\times 0.1) \approx E^{-2.71}

\begin{align*}
\text{Pamela} & \quad \text{Adriani et al. (2011)} \\
\text{CREAM} & \quad \text{Ahn et al. (2010)} \\
\end{align*}
origin of spectral hardening?

- magnetic polarity reversals due to the 22-year solar cycles produces large scale sectors

- converging of turbulent magnetic field lines can trigger reconnection and make it fast

- magnetic mirror @ single reconnection as site of acceleration (test particle)

Sweet (1959) & Parker (1957)

Lazarian & Vishniac, ApJ, 517, 700 (1999)
stochastic magnetic reconnection

- magnetic polarity reversals due to the 22-year solar cycles produces large scale sectors

- converging of turbulent magnetic field lines can trigger reconnection and make it fast

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- 1st order Fermi acceleration

\[ N(E) \, dE \sim E^{-5/2} \, dE \]
stochastic magnetic reconnection

\[ N(E) \, dE \sim E^{-5/2} \, dE \]
stochastic magnetic reconnection

Kowal et al., ApJ 735, 102 (2011)

\[ \mathbf{v}_\perp > \mathbf{v}_\parallel \]

\[ \mathbf{v}_\parallel > \mathbf{v}_\perp \]
stochastic magnetic reconnection

- 2nd order Fermi acceleration is dominant in purely turbulent plasmas with no converging magnetic flow

- if converging flow occurs 1st order Fermi acceleration is the most important

- acceleration by reconnection is efficient if scattering does not isotropize particles. Scattering expected to be minimal along the tail line of sight

\[ E_{\text{max}} \approx 0.5 \left( \frac{B}{1 \mu G} \right) \left( \frac{L_{\text{zone}}}{100 \text{AU}} \right) \text{TeV} \approx 0.5 - 6 \text{TeV} \]

- cosmic rays re-accelerated as long as trapped in large scale reconnection regions

Kowal et al., PRL 2012
spectral feature associated to anisotropy

Abdo A.A. et al., Phys. Rev. Lett., 101, 221101 (2008)

Milagro

\( \gamma < 2.7 \) at 4.6 \( \sigma \) level

\( E_c = 3 - 25 \) TeV

\( E_{\text{flux}}(10\text{GeV}-10\text{TeV}) \sim 10^{-9} - 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1} \) \( (\gamma = 2.7 - 2.0) \)

\( \langle P_{\text{re-acc}} \rangle \sim 10^{20} - 10^{22} \text{ erg s}^{-1} \)

\( \langle P_{\text{solar wind}} \rangle \sim 10^{27} \text{ erg s}^{-1} \) \( (\text{Parker, 1962}) \)

PD, Lazarian, NPG, 19, 1, 2012
cosmic ray anisotropy
astrophysical origin?

- stochastic effect of recent nearby CR sources
  - influences spectrum and global arrival direction
  - diffusive scenarios to explain observed features

- propagation effects in turbulent ISMF

- convection from persistent magnetized flow field from old SNRs

- breakdown of diffusion regime via scattering with ISMF turbulence

- diffusion cannot explain the observed **non-dipolar** topology & **small angular scales**

- limitations on single power-law assumption and spacial dependency of diffusion coeff.
scattering on heliospheric boundary toy model

\[ N_b = n_{CR} \, P_s \, R_E^2 \int_{R_H}^{R_H + dR_H} dr \int_0^{2\pi r} dl \int_0^\infty \frac{dz}{z^2 + r^2} \]

\[ = n_{CR} \, P_s \, \pi^2 \, R_E^2 \, dR_H, \]

\[ N_d = n_{CR} \, 4\pi \, R_E^2 \, c \, \tau. \]

\[ \delta = \frac{N_b - N_d}{N_b + N_d} = \frac{N_b / N_d - 1}{N_b / N_d + 1}, \]

\[ \frac{N_b}{N_d} = \frac{3\pi}{4} \, P_s \, \frac{dR_H}{c \, \tau}. \]

\[ \delta \gtrsim 0, \quad P_s \gtrsim \frac{100}{dR_H} \]
IceCube Observatory

Digital Optical Module - DOM with 10” PMT & local DAQ electronics

air shower detection @ 2835 m altitude (680 g/cm²)
muon detection @ 1450-2450 m depth

IceTop
81 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
324 optical sensors

IceCube Array
86 strings including 8 DeepCore strings
60 optical sensors on each string
5160 optical sensors

December, 2010: Project completed, 86 strings

DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors

Eiffel Tower
324 m

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detection principle

$\nu_\mu$ CC-int

$\nu_e \nu_T$ CC-int & $\nu_i$ NC-int

cascade

Cherenkov light

muon track