the origin of galactic cosmic ray anisotropy

Paolo Desiati
University of Wisconsin - Madison
desiati@icecube.wisc.edu

Department of Physics & Astronomy
University of Delaware
October 26th, 2010
cosmic rays

- CR below the knee (∼10^6 GeV) believed to be galactic

- CR below ∼10^9 GeV believed to be predominantly galactic (transition to extra-galactic @ ∼10^9-10^10 GeV)

- galactic CR believed to be accelerated in expanding shock waves initiated by supernova explosions

- galactic CR expected to be isotropic: scrambled by galactic magnetic field over very long time
cosmic ray anisotropy in arrival direction


- Mt Norikura
- Nagoya
- Sakashita
- Hobart

Relative Intensity

Sidereal local time

- 0.02%
- 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

galactic cosmic ray anisotropy - Paolo Desiati
galactic cosmic ray anisotropy
in arrival direction

ARGO-YBJ

- data from 2008
- 365 days livetime
- $6.5 \cdot 10^{10}$ events
- median CR energy $\sim 1.1$ TeV

J.L. Zhang et al., 31st ICRC Łódź - Poland (2009)
cosmic ray anisotropy in arrival direction

Tibet-III

- data from 1997 to 2005
- 1874 days livetime
- $3.7 \times 10^{10}$ events
- angular resolution $\sim 0.9^\circ$
- modal CR energy $\sim 3$ TeV

IceCube Observatory

• IceCube
  • currently 79 strings
  • 86 strings in 2011
  • 125 m inter-string spacing
  • 17 m DOM distance
• taking data during construction
• AMANDA decommissioned on May 11, 2009
• Deep Core completed with 6 strings
galactic cosmic ray anisotropy - Paolo Desiati

detection technique
cosmic ray anisotropy in arrival direction


IceCube-22

- data from June 2007 to March 2008
- 226 days livetime
- $4.3 \cdot 10^9$ events
- median angular resolution $\sim 3^\circ$
- median CR energy $\sim 20$ TeV
cosmic ray anisotropy in arrival direction

Tibet-III

IceCube-22

- data from June 2007 to March 2008
- 226 days livetime
- $4.3 \cdot 10^9$ events
- median angular resolution $\sim 3^\circ$
- median CR energy $\sim 20$ TeV
cosmic ray anisotropy in arrival direction


dipole

\[ A_1 = (6.4 \pm 0.2_{\text{stat}} \pm 0.8_{\text{syst}}) \times 10^{-4} \]
\[ \phi_1 = 66^\circ.4 \pm 2^\circ.6_{\text{stat}} \pm 3^\circ.8_{\text{syst}} \]

quadrupole

\[ A_2 = (2.1 \pm 0.3_{\text{stat}} \pm 0.5_{\text{syst}}) \times 10^{-4} \]
\[ \phi_2 = -65^\circ.6 \pm 4^\circ.0_{\text{stat}} \pm 7^\circ.5_{\text{syst}} \]

- data from June 2007 to March 2008
- 226 days livetime
- \(4.3 \times 10^9\) events
- median angular resolution \(\sim 3^\circ\)
- median CR energy \(\sim 20\) TeV
Cosmic ray anisotropy in arrival direction

IceCube-22

IceCube-40

IceCube-59

Relative intensity
Equatorial coordinates
cosmic ray anisotropy in arrival direction

- June 07 - March 08
  - 226 days livetime
  - $4.3 \cdot 10^9$ events

- March 08 - May 09
  - 324 days livetime
  - $19 \cdot 10^9$ events

- May 09 - May 10
  - ~360 days livetime
  - ~30 $\cdot 10^9$ events

- median angular resolution $\sim 3^\circ$
- median CR energy $\sim 20$ TeV
galactic cosmic ray anisotropy
in arrival direction

Tibet-III
(5° smoothing)

IceCube-40
(3° smoothing)

equatorial coordinates

data from March 2008 to May 2009
324 days livetime
15 \cdot 10^9 events
median angular resolution \sim 3°
median CR energy \sim 20 TeV

Statistical significance

courtesy Kazuoki Munakata

\[
180° \quad 270° \quad 0° \quad 90° \quad 360°
\]

\[
5 \text{ TeV} \quad 20 \text{ TeV}
\]
anisotropy vs energy: probing different causes

Amenomori et al., ApJ. 626, L29, 2005

Amplitude [%] vs Primary energy [GeV]

- 10^{-2}
- 10^{-1}

Primary energy [GeV]:
- 10^2
- 10^3
- 10^4
- 10^5
- 10^6

Values:
- 3 \cdot 10^{-5}
- 3 \cdot 10^{-4}
- 3 \cdot 10^{-3}
- 3 \cdot 10^{-2}
- 0.3

Gyro-radius (pc):
- 7
- 70
- 700
- 7,000
- 70,000

Gyro-radius (AU):
- (3 \mu G)

Influence:
- Tail-in + galactic
- Heliospheric influence
- Galactic influence
origin of large scale anisotropy: Compton-Getting Effect?

- apparent energy-independent $\sim 10^{-3}$ dipole anisotropy due to relative motion of solar system through ISM

- motion of solar system around galactic center $\sim 220$ km/s

- reference system of cosmic rays is unknown

$$\frac{\Delta I}{I} = (\gamma + 2) \frac{v}{c} \cos \theta$$

Compton & Getting, Phys. Rev. 47, 817 (1935)
origin of large scale anisotropy : solar dipole

- apparent energy-independent \( \sim 10^{-4} \) dipole anisotropy due to relative motion of Earth around the Sun
- motion of Earth around the Sun \( \sim 29 \text{ km/s} \)
- reference system of cosmic rays is well known
origin of large scale anisotropy: solar dipole

\[ \frac{\Delta I}{I} = (\gamma + 2) \frac{v}{c} \cos \theta \]
The origin of large scale anisotropy: spurious effects

- A yearly-modulated solar diurnal variation induces a spurious sidereal modulation: *modulation in anti-sidereal time*
- Non-physical coordinate that results in “scrambling” directions
- Its modulation measures sidereal spurious effect amplitude


---

galactic cosmic ray anisotropy - Paolo Desiati
origin of large scale anisotropy: spurious effects

pseudo-equatorial coordinates


solar time
sidereal time
anti-sidereal time

galactic cosmic ray anisotropy - Paolo Desiati
our galactic neighborhood

- **Local Bubble** (~300 pc): cavity of the Orion arm with low density (~1/10 of ISM) of hot neutral H gas that emits X-rays. Produced by ancient SN (perhaps Geminga)

- **Local Interstellar Cloud** (~10 pc): thin cloud (~1/5 of ISM) is flowing from the Scorpius-Centaurus Association, a star forming region
our galactic neighborhood

- Our neighborhood is highly non-homogeneous and the ISMF is a perturbation of the galactic magnetic field.
- The solar system is in transition between the Local Interstellar Cloud and the Cloud G.


our galactic neighborhood

A cartoon of the LIC (left) viewed from the galactic north pole (see [8] for more detail). Another cloud (G cloud) is overtaking the LIC from the Galactic center on the right side. A broken line represents the LISMF line through the hemispheres just inside the LIC boundary. If the GCR density \( n \) is lower inside the LIC than outside, the BDF is expected from the pitch angle diffusion of GCRs into LIC along the LISMF line. The UDF is also expected from \( B \times G \) drift anisotropy (see text).

\[
I_{m,n} = a_{11} \cos \chi_1(n, m : \alpha_1, \delta_1) + a_{1\parallel} \cos \chi_2(n, m : \alpha_2, \delta_2) + a_2 \cos^2 \chi_2(n, m : \alpha_2, \delta_2)
\]

Amenomori et al., ICRC 2007, Mérida (Mexico)
our galactic neighborhood

Tibet-III @ 5 TeV

anisotropy almost consistent with

uni-directional flow (dipole)  
+  
bi-directional flow (quadrupole)

equatorial coordinates
our galactic neighborhood

IceCube @ 20 TeV

large scale features qualitatively well described by the global fit

it is the smaller angular features that appear to be interesting
heliosphere

- solar system moves wrt IS medium at 26 km/s
- solar wind diverts interstellar plasma at 400-800 km/s
- termination shock @ solar pressure \( \sim \) interstellar pressure : \( \sim 100 \) AU
- solar and interstellar medium (& magnetic field) separated by heliopause : \( \sim 150-200 \) AU
- heliotail size up to \( \sim 10,000 \) AU ?

scale : 100-10,000 AU
0.0005-0.05 pc
investigating on interstellar magnetic field

- Sun moving through a tenuous 20-30% ionized interstellar cloud

- Energetic Neutral Atoms (ENA) and charged particles (e⁻ and ions) enters the heliosphere from ISM

- charge exchange between ENA and ions

- angle between H and He flow (~4°) due to distortion of heliosphere: Hydrogen Deflection Plane (HDP)

- ISMF deforms heliospheric shape

ISMF ~ (205° ÷ 240°, -38° ÷ -60°)_{galactic}

off galactic plane (~ HDP)

scale: 100 AU ~ 5⋅10⁻⁴ pc

investigating on interstellar magnetic field

- ISMF @ heliosphere from IBEX observation of a ribbon of ENA
- ISMF from optical polarization for stars < 40 pc
- similar directions within ~33°
our galactic neighborhood

Tibet-III

IceCube-22

broad excess toward ISMF

relative intensity
equatorial coordinates
nearby sources of cosmic rays


- cosmic rays below the knee from SNR
  - young (<100,000 yr) / nearby (< 1,000’s pc)
    SNR might produce anisotropic random fluctuations
- anomalous diffusion and mass composition magnifies the stochastic nature of anisotropy
- connection between spectral features and anisotropy
- the knee of CR from a single source

scale: 100-1,000 pc
nearby sources of cosmic rays

Erlykin & Wolfendale 31st ICRC Łódź (Poland), 2007

- sharpness of the knee of cosmic ray spectrum
  - from cutoff of maximum acceleration energy
  - single source hypothesis where flatter spectra with cutoffs superimpose to average CR spectrum by adding features
  - Monogem (associated to PSR B0656+14)

deviation wrt CR spectrum with knee
nearby sources of cosmic rays


deviation wrt CR spectrum with knee

scale: 100-1,000 pc

Arteaga-Velázquez et al., arXiv:1009.4716
nearby sources of cosmic rays ($e^+e^-$)

Acknowledgments

Acknowledgement: Ackermann et al., arXiv:1008.3999

scale: 100-1,000 pc

Ackermann et al., arXiv:1008.5119
nearby sources of cosmic rays

- CR spectral features reproduced in a scenario with $e^+e^-$ pair production by interactions between high-energy CRs and background photons in an environment similar to young SNR

- evidence that at least a portion of CRs might be accelerated in young SNRs?
nearby sources of cosmic rays

- Monogem
- Vela
- Fermi-LAT
- IceCube-40

Significance (σ)

scale: 100-1,000 pc

Ackermann et al., arXiv:1008.5119

PRELIMINARY

galactic cosmic ray anisotropy - Paolo Desiati
nearby sources of cosmic rays

Ackermann et al., arXiv:1008.5119

Fermi-LAT

Monogem
Geminga
Vela

scale: 100-1,000 pc

scale: < 40 pc

Local Interstellar Magnetic Field

scale: 10^-3-10 pc

Local Interstellar Medium & Heliotail
large scale anisotropy

Tibet-III
3.7 \cdot 10^{10} \text{ events}
modal energy \sim 3 \text{ TeV}
(5^\circ \text{ smoothing})

IceCube-40
12 \cdot 10^9 \text{ events}
median energy \sim 20 \text{ TeV}
(3^\circ \text{ smoothing})
medium / small scale anisotropy

- Large scale anisotropy shows smaller angular features, some of which highly significant
- Their origin is unknown
- Discovery: if eliminating all angular features > 30° MILAGRO discovered two highly significant localized excess regions
- MILAGRO sky map of statistical significance
- Technique used in gamma ray searches
- CR spectrum harder than diffuse < 10 TeV

medium / small scale anisotropy


Milagro

2.2 \cdot 10^{11} \text{ events}

median CR energy \sim 1 \text{ TeV}

average angular resolution < 1^\circ

2hr time window

10^\circ \text{ smoothing}
medium / small scale anisotropy


IceCube-40

19 \times 10^9 \text{ events}

4\text{hr} \text{ time window}

25^\circ \text{ smoothing}
medium / small scale anisotropy

Milagro

ARGO-YBJ

Tibet-III
medium / small scale anisotropy

Milagro
2.2 \cdot 10^{11} \text{ events}
median energy \sim 1 \text{ TeV}
(2 \text{ hr integration} \sim 30^\circ \text{ cut-off}, 10^\circ \text{ smoothing})

IceCube-40
19 \cdot 10^9 \text{ events}
median energy \sim 20 \text{ TeV}
(4 \text{ hr integration} \sim 60^\circ \text{ cut-off}, 10^\circ \text{ smoothing})

PRELIMINARY
medium / small scale anisotropy

Milagro

\[ 2.2 \cdot 10^{11} \text{ events} \]
median energy \( \sim 1 \text{ TeV} \)
(2 hr integration \( \sim 30^\circ \) cut-off, 10\(^\circ\) smoothing)

IceCube-40

\[ 12 \cdot 10^9 \text{ events} \]
median energy \( \sim 20 \text{ TeV} \)
(4 hr integration \( \sim 60^\circ \) cut-off, 10\(^\circ\) smoothing)
origin of small scale anisotropy: CR source

- galactic cosmic ray accelerator (Salvati & Sacco)
  - Geminga (~155 pc) was closer 340,000 yr ago: ~90 pc
  - Bohm diffusion of 10 TeV ~ 65 pc
  - if turbulence frac. excess compatible with ~1.5 \times 10^{49} \text{ erg}
  - energy passband (cutoff HE, delays LE) ~ hard spectrum

- magnetic nozzle (Drury & Aharonian)
  - to avoid large angular scale of excess
  - CR freely propagating through magnetic nozzle
  - but direction to Geminga is \perp \text{ galactic magnetic field}
origin of small scale anisotropy: IS magnetic field turbulence

- anisotropic MHD turbulence in the ISM

  - pitch angle scattering peaked near the direction of magnetic field \( (k_\perp R_g(p_\perp) \approx 1) \)

  - the large scale anisotropy is “perturbed” by faint beam of collimated particles along the “magnetic” tube that connects to the source

  - outer scale of perturbation determines beam angular width and strength \( (\propto R_g(p)/l_{\text{scale}}) \)

  - \( l_{\text{scale}} \sim 1 \text{ pc}/B(\mu\text{G}) \): consistent with MILAGRO angular width, excess and max energy of region A

  - sources responsible of the beam must be within a few 100’s pc
origin of small scale anisotropy: heliospheric tail

- sub-TeV cosmic ray tail-in excess by some unknown asymmetry caused by the heliotail


Karapetyan, Astrop. Phys., 33, 146, 2010
origin of small scale anisotropy: heliospheric tail

- sub-TeV cosmic ray tail-in excess by some unknown asymmetry caused by the heliotail
- solar magnetic field reversal should affect galactic anisotropy
- origin of excess is “heliospheric”


Karapetyan, Astrop. Phys., 33, 146, 2010
The origin of small scale anisotropy is connected to the heliospheric tail. This is supported by studies showing localized excess of multi-TeV cosmic rays from the direction of the heliotail, medium/small scale modulation connected to nearby perturbations, and first-order acceleration in magnetic reconnection regions in the heliotail. These findings are based on the work of Nagashima et al. (1998) and Abdo et al. (2008).

- Localized excess of multi-TeV cosmic rays from the direction of the heliotail.
- Medium/small scale modulation connected to nearby perturbations.
- First-order acceleration in magnetic reconnection regions in the heliotail.
origin of small scale anisotropy: heliospheric tail

- magnetic polarity reversals due to the 11-year solar cycles compressed by the solar wind in the magneto-tail


origin of small scale anisotropy: heliospheric tail

- magnetic polarity reversals due to the 11-year solar cycles compressed by the solar wind in the magneto-tail

- turbulence makes reconnection fast and not affected by ohmic dissipation


Sweet, IAU Symposium 6, Electromagnetic Phenomena in Cosmical Physics, 123, 1959.
Parker, J. Geophys. Rev., 62, 509, 1957

origin of small scale anisotropy: heliospheric tail

- magnetic polarity reversals due to the 11-year solar cycles compressed by the solar wind in the magneto-tail

- turbulence makes reconnection fast and not affected by ohmic dissipation

- magnetic mirror @ reconnection as site of acceleration

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

\[ E_{\text{max}} \approx 10^{13} \text{ eV} \cdot \left( \frac{B}{1 \mu G} \right) \cdot \left( \frac{L_{\text{zone}}}{134 \text{ AU}} \right) \sim 10 \text{ TeV} \]
conclusions ... to start with

• cosmic ray anisotropy has been observed from ~10 GeV to ~100 TeV
  ‣ large scale structure with fine structures at high energy

• origin unknown: probably related to our local galactic environment

• a nearby SRN may induce a large scale anisotropy: spectral features?

• small/medium scale anisotropy to be sensitive to distance scale of the effect

• IceCube performing:
  ‣ energy dependence of anisotropy: magnetic fields, interstellar medium
  ‣ angular power spectrum of anisotropy: distance scale