THE ISOTROPY PROBLEM OF TEV COSMIC RAYS

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Anisotropy measurement by IceCube

IceCube reports the sidereal first harmonic in the CR intensity average over declination range \(-25^0\) to \(-72^0\)

\[
\delta_{obs} = (7.9 \pm 0.1_{\text{stat}} \pm 0.3_{\text{sys}}) \times 10^{-4}
\]

Why is it a problem?

Propagation models constrain diffusion rate to fit B/C

\[ D(E) \approx 10^{28} (E/GeV)^{1/3} \text{cm}^2 \text{s}^{-1} D_{28} \]

The anisotropy in 1-1000TeV energy band predicted by Isotropic diffusion with a steep source distribution is more than an order of magnitude higher than the observations.

Why Isotropic diffusion?

B/C does not constrain diffusion rate parallel to the Galactic plane.

\( S_T \): Pulsars (Trotta et al., 2011)
\( S_C \): SNRs (Case & Bhattacharya, 1998)
\( S_S \): Gamma ray Gradient (Strong et al., 2000)
Anisotropic Diffusion of Cosmic Rays

A partially ordered Galactic magnetic field breaks the isotropy of diffusion

\[ \frac{D_\perp}{D_\parallel} \gtrsim 10^{-2} \quad \text{for} \quad \frac{\delta B}{B} \approx 1 \]

A general anisotropic diffusion of the cosmic rays is described by

\[ \frac{\partial N}{\partial t} = \frac{\partial}{\partial \rho} \rho D_\rho \frac{\partial N}{\partial \rho} + \frac{\partial}{\partial \phi} D_\phi \frac{\partial N}{\partial \phi} + \frac{\partial}{\partial z} D_z \frac{\partial N}{\partial z} + Q(t) \delta(t) \delta(\rho - \rho_0) \delta(\phi) \delta(z - z_s) / \rho, \]
Cosmic Ray Flux Anisotropy

- **Flux from a source:**
  \[
  N(\rho, \phi, z) = G(z, t)N_0(\rho, \phi, t)
  \]
  \[
  G \approx \frac{1}{\sqrt{2\pi Dt}} \exp \left( -\frac{(z - z_s)^2}{4Dt} \right) (1 + \tilde{t})^{1.25} \exp(-1.5\tilde{t}^{0.97}) \quad \tilde{t} = 2Dt/H^2
  \]
  \[
  N_0(\rho, \phi, t) = \frac{\Theta(t)}{2\pi D_\perp t} \frac{Q(E)}{H} \exp \left( -\frac{\rho^2 + \rho_0^2}{4D_\perp t} \right) \left[ \frac{1}{2} I_0(\tilde{\rho}) + \sum_{n=1}^{\infty} \cos(n\phi)I_n(\tilde{\rho}) \right]
  \]
  \[
  \tilde{\rho} = \rho \rho_0 / 2D_\perp t, \quad \nu(n) = n \sqrt{D_\parallel / D_\perp}
  \]

- **Anisotropy:**
  \[
  \tilde{\delta} = 3 \left( D_\rho \frac{\partial N_{tot}}{\partial \rho} \hat{\rho} + D_\phi \frac{\partial N_{tot}}{\rho \partial \phi} \hat{\phi} + D_z \frac{\partial N_{tot}}{\partial z} \hat{z} \right) / cN_{tot}
  \]

Use the Monte Carlo method to randomly place sources in the Galaxy with a pulsar-like source distribution (a steep distribution) and source rate 1 in every 100 years.
Anisotropy at 20 TeV

- Radial anisotropy dominates for a steep source distribution.
- Radial anisotropy decreases as the radial diffusion rate is reduced.
- Azimuthal discreteness anisotropy becomes the dominant contributor to the total anisotropy for $D_\rho \gtrsim D^{iso}/10$.

Source rate: 1 per 100 yr
$H=5$ kpc

Isotropic diffusion

Anisotropic diffusion: $D_\rho = D^{iso}/10$
Anisotropy vs. Energy

- Total anisotropy at all energies goes down as the radial diffusion rate is reduced.
- Fluctuation increases with decreasing radial diffusion rate since the total number of contributing sources becomes smaller.
- Non-monotonic dependence of anisotropy on energy is due to discreteness of the sources.
Spiral Arms

- Star formation in the Galaxy takes place in spiral arms
- We lie in Local spur, between two spiral arms Sagittarius and Perseus
- Sun completes one revolution in about 280 Myr relative to the spiral arms
- CRs are assumed to diffuse in the corotating frame of the Sun
- Four spiral arms, two major and two minor, are assumed

Xu et al., Science (2006)

A tail-like distribution of sources from spiral front is assumed to model spiral arms:

\[ P(d) = \exp(-d/300 \text{ pc}) \]
Anisotropy at 20 TeV

- Anisotropy is dependent on our location with respect to the spiral arms.
- Even for isotropic diffusion, near the inner edge of the spiral arm flux cancellation causes a dip in the radial anisotropy.
- Anisotropy is smaller in the inter-arm regions due to distantness of the sources and flux cancellation.

\[ D_\rho = D_{iso}/100 \]
Anisotropy vs. Energy

- Near a spiral arm, anisotropy is higher due to proximity of sources and the fluctuation is smaller due to a larger number of contributing sources.
- Fluctuation in the dip period is comparatively large.

Anisotropic diffusion: \( D_\rho = \frac{D_{iso}}{50} \)
Nearby Supernovae

<table>
<thead>
<tr>
<th>SNR</th>
<th>Distance (kpc)</th>
<th>Age (Myr)</th>
<th>Anisotropy at 1 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geminga</td>
<td>0.25</td>
<td>0.3</td>
<td>0</td>
</tr>
<tr>
<td>Monogem</td>
<td>0.3</td>
<td>0.08</td>
<td>0.0004</td>
</tr>
<tr>
<td>Vela</td>
<td>0.25</td>
<td>0.01</td>
<td>0.025</td>
</tr>
<tr>
<td>Cygnus loop</td>
<td>0.8</td>
<td>0.015</td>
<td>0.0001</td>
</tr>
<tr>
<td>Vela Jr.</td>
<td>0.21</td>
<td>0.001</td>
<td>0.034</td>
</tr>
</tbody>
</table>

Under the assumption of **Isotropic** diffusion anisotropy due to Vela and Vela Jr. is inconsistent with the measurement
Conclusions

- Large scale radial anisotropy in case of a steep distribution is marginalized by a smaller radial diffusion rate and makes the case of a steep distribution nearly as good as flat distributions.

- Using the diffusion rate that reproduces B/C ratio, the observed anisotropy can be reproduced, but only with a small probability (~5%).

- The surprisingly low large scale anisotropy in TeV band could be due to our location in the Galaxy with respect to the spiral arms and small radial diffusion rate.

- Isotropic diffusion implies a large anisotropy from Vela SNR, strengthening the case of anisotropic diffusion.