LHAASO: Anisotropy Theory

Wei Liu, IHEP, CAS

Collaborate with Yi-qing Guo, Qiang Yuan

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Outline

- Observations of cosmic-ray large-scale anisotropy
- Possible origins of dipole anisotropy
- Spatial-dependent propagation plus Local source model





Observations of cosmic-ray large-scale anisotropy

anisotropy of arrival distributions of cosmic rays

relative intensities are roughly $10^{-4} \sim 10^{-3}$





Combined cosmic ray anisotropy of Tibet-ASgamma and IceCube

Energy evolution of 2D anisotropy



Amenomori et al., Science Vol. 314, pp. 439 (2006)

M. Amenomori, 2017ApJ...836..153A

Energy dependence of dipole anisotropy's amplitude and phase

$$R(\alpha) = 1 + A_1 \cos(\alpha - \phi_1)$$

 $R(\alpha)$: the relative intensity of CRs at R.A.



Possible origin of dipole anisotropy

dipole anisotropy is defined as

$$\delta \equiv \frac{f_{\max} - f_{\min}}{f_{\max} + f_{\min}} = \frac{3\mathbf{K}}{v} \frac{\nabla n_{\mathrm{CR}}}{n_{\mathrm{CR}}}$$

Compton-Getting effect

• phase-space distribution is Lorentz-invariant, $f^{\star}(\mathbf{p}^{\star}) = f(\mathbf{p})$

[Forman'70]

Lorentz boost (starred quantities in plasma rest-frame):

$$\mathbf{p}^{\star} = \mathbf{p} + \left(p + \frac{1}{2} \boldsymbol{\beta} \cdot \mathbf{p} \right) \boldsymbol{\beta} + \mathcal{O}(\boldsymbol{\beta}^3)$$

Taylor expansion

$$f(\mathbf{p}) \simeq f^{\star}(\mathbf{p}) + (\mathbf{p}^{\star} - \mathbf{p}) \nabla_{\mathbf{p}^{\star}} f^{\star}(\mathbf{p}) + \mathcal{O}(\beta^{2}) \simeq f^{\star}(\mathbf{p}) + p \beta \nabla_{\mathbf{p}^{\star}} f^{\star}(\mathbf{p}) + \mathcal{O}(\beta^{2})$$

 \rightarrow splitting in ϕ and Φ is not invariant:

[Compton & Getting'35;Jones'90]

$$\phi = \phi^{\star}$$
 $\Phi = \Phi^{\star} + \frac{1}{3}\beta \frac{\partial \phi^{\star}}{\partial \ln p}$

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

$$\boldsymbol{\delta} = \boldsymbol{\delta}^{\star} + \underbrace{(2 + \Gamma_{\mathrm{CR}})\boldsymbol{\beta}}_{\text{Compton-Getting effect}}$$

Compton & Getting, Phys. Rev. 47 (1935) 817; Gleeson & Axford, Astrophys. Space Sci. 2 (1968) 431

Cosmic rays co-rotate with local magnetic environment.

Non-uniform distribution of CR sources

 $\nabla n_{CR} \neq 0$

anisotropy scales with diffusion coefficient K



P. Blasi, E. Amato, 2012JCAP...01..011B

Local source

local source at Galactic anti-center could effectively suppress the magnitude

the magnitude problem could be partially settled



Spatial-dependent diffusion

background anisotropy is significantly suppressed

power-law dependence

Galactic center



Y. Q. Guo, Z. Tian, and C. Jin, 2016ApJ...819...54G

Local magnetic field plus Vela SNR

- strong ordered magnetic fields in the local environment
- diffusion tensor reduces to projector:

$$K_{ij}
ightarrow rac{\hat{B}_i\hat{B}_j}{3
u_\parallel}$$

- TeV–PeV dipole data consistent with magnetic field direction inferred by IBEX data [McComas et al.'09]
- 1–100 TeV phase indicates a local gradient within longitudes:

 $120^{\circ} \lesssim l \lesssim 300^{\circ}$

- phase flip induced by Vela SNR? [MA'16]
- or a luminous 2Myr old SNR? [Savchenko, Kachelrieß & Semikoz'15]



Spatial-dependent Propagation plus Local source model

Spatial-dependent diffusion model



HAWC observation

slower diffusion coefficient than predicted from B/C ratio



hardening of cosmic-ray nuclei



cosmic-ray knee



Local source, Geminga

positron excess above 10 GeV

from nearby pulsars?



M. Aguilar, et al. PRL 110, 141102 (2013)

Geminga pulsar

 250^{+120}_{-62} pc R. A. : 6h 33m 54s, Dec: +17°46′12″

spin-down age $\tau_{SD} = 340 \text{ kyr}$

proper motion is 178.2±1.8 mas/year ($\mu_{\alpha} = 142.2 \pm 1.2$ mas/year $\mu_{\delta} = 107.4 \pm 1.2$ mas/year)

from Geminga's space motion and its age, it is thought to be a runaway from the **Orion OB association**.

birthplace is R. A. : 5.5h, Dec: $+10^{\circ}$

distance to solar system is 330 pc





Results

CR nuclei spectrum



All particle spectrum

high energy cutoff of background is rigidity dependent

cutoff rigidity of proton is 6.5 PV



dipole anisotropy



dip at 100 TeV is sensitive to the cutoff energy of local source

minimum point could be used for the energy calibration of ground-base detection experiment

Summary

- We build up an integrated picture based on spatial-dependent propagation model
- The non-trivial energy evolution of dipole anisotropy below 100 TeV indicates a local CR source, Geminga could be a possible candidate, which also responsible for the positron excess
- Both CR spectra and amplitude of dipole anisotropy are well reproduced
- The phase less than 100 TeV does not well account for. Possible solutions: another nearby source, local regular magnetic field
- LHAASO, IceCube/IceTop, HAWC experiments are expected to measure the 100 TeV break of anisotropy more precisely



Thank you for your attention!









All-particle spectrum



Ec and anisotropy







- Non-uniform distribution of sources
 [Blasi & Amato 12; Sveshnikova *et al.*13]
- Local sources [Liu, Bi, *et al.*17]
- Spatial-dependent diffusion [Guo, et al. 16]
- Local magnetic field [Schwadron *et al.* 14; Mertsch & Funk 14]
- Compton-Getting effect [Compton & Getting 35]



Galactic Diffuse Gamma Rays



Spatial distribution of Cosmic rays

