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Simulating the galactic cosmic ray with non-uniform grids

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The input of local source information and propagation parmeters at a scale of $O(10)$ pc are necessary in order to accurately repeat the large scale 2D anisotropy of cosmic ray from TeV to PeV. However, simulating the CR propagation using the normal finite-difference method (FDM) with $O(10)$ pc grids would occupy too much memory and thus could not be performed in usual servers. To solve this problem, we suggested a non-uniform-grid method to allow a set of fine enough grids in vicinity of the solar system. In this work, besides the decription and validation of the method, our calculation successfully explains the observed transition of 2D cosmic ray anisotropy map between TeV and PeV energies.

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1. Introduction

The 2-dimensional (2D) cosmic-ray (CR) anisotropy has been observed in a wide energy region [1–21] from sub TeV to several PeV. In these observations, it is found that the amplitude of CR anisotropy is around 10^{-3} in this region, and the phase of CR anisotropy around TeV is almost opposite to that around PeV. The TeV measurements show the excess of CR flux around the direction of the local regular magnetic field, while the PeV measurements show the excess of CR flux toward the direction of the Galactic center.

This phenomenon could be attributed to a nearby source located around the Galactic anti-center and/or the fact that CR would diffuse faster along the direction of the magnetic field [22–24]. The Galactic magnetic field has been found to contain a notable large-scale regular component [25, 26] whose direction would be rapidly changed nearby the Galactic disk. On the other hand, the observation of the local regular magnetic field indicates an almost constant interstellar field within a region ~ 20 pc [27]. Simulating the effect caused by a magnetic field of this size would require a resolution $\sim \mathcal{O}(10)$ pc in the space. However, the numerical CR propagation solution with such a high resolution would cost too much memory and is inaccessible for usual servers.

The CR propagation function is always numerically solved with the finite-difference method (FDM), in which the Galaxy is usually divided into grids in size $\sim$ kpc [28, 29]. When all the grids are directly shrunk to $\sim \mathcal{O}(50)$ pc, over 1000 times of the memory would be required. Therefore, we need a more efficient method that could shrink the target grids while avoiding unnecessary costs.

In this work, we first introduce a non-uniform-grid method to solve this efficiency problem. Then two simple isotropic propagation cases are adopted to verify this method. Afterward, by using this method, we take into account the injection effect from a nearby source and a propagation effect due to the local regular magnetic field to calculate the large-scale 2D CR anisotropy.

The rest of this paper is organized as follows: In Sec. 2, we briefly introduce non-uniform-grid method and verify it in two simple cases. In Sec. 3, we describe the anisotropic diffusion model based on the Galactic large-scale regular magnetic field and perform a realistic simulation of CR propagation. In the simulation, the contribution of a nearby source is also added. Sec. 4 is reserved for the conclusion.

2. Non-uniform-grid method

In order to efficiently predict the local interstellar CR distribution with high resolution, we divide the Galaxy into non-uniform grids. However, the well studied FDMs, i.e. the Crank-Nicolson method and the Hundsdorfer-Verwer method [30], would always require uniform grids. Therefore, we perform a non-linear coordinate transformation and ensure that the grids in the new coordinate are uniform, then apply the FDM in the new coordinate to solve the propagation equation.

Denoting the origin physical coordinate (x_1, x_2, x_3) and the new coordinate (x'_1, x'_2, x'_3), then we can describe the transformation as $x_i = f_i(x'_i)$. We carefully choose the transformation function f_i to ensure that when the x'_i evenly varying, the x_i around the sun would change much slower than that in the other position.

Note that this transformation would also change the form of the propagation equation. The propagation equation that contains only the diffuse effect is

$$\frac{\partial}{\partial t}\psi = q + \sum_{i,j}\frac{\partial}{\partial x_i}D_{ij}\frac{\partial}{\partial x_j}\psi, \tag{1}$$

where ψ is the particle density, and D_{ij} is the 3×3 diffusion tensor. When the non-diagonal term of D_{ij} is non-zero, this equation could describe the anisotropic propagation, i.e. the case in which the CR particles propagate faster along the magnetic field [24]. As the particle number in a certain grid is invariant, the transformation of particle density ψ follows $\psi \mathrm{d}x_1\mathrm{d}x_2\mathrm{d}x_3 = \psi'\mathrm{d}x_1'\mathrm{d}x_2'\mathrm{d}x_3'$. For the same reason, the transformation of source term q follows $q\mathrm{d}x_1\mathrm{d}x_2\mathrm{d}x_3 = q'\mathrm{d}x_1'\mathrm{d}x_2'\mathrm{d}x_3'$. As a result, Eq. 1 in the new coordinate is

$$\frac{\partial}{\partial t}\psi' = q' + \sum_{i,j}\frac{\partial}{\partial x_i}\frac{D_{ij}}{f_j'}\frac{\partial}{\partial x_j}\frac{\psi'}{f_i'}. \tag{2}$$

In the non-uniform-grid method, we use the FDM to solve Eq. 2 and then transform the density ψ' back to ψ to obtain the final prediction of CR density. In order to validate this method, we

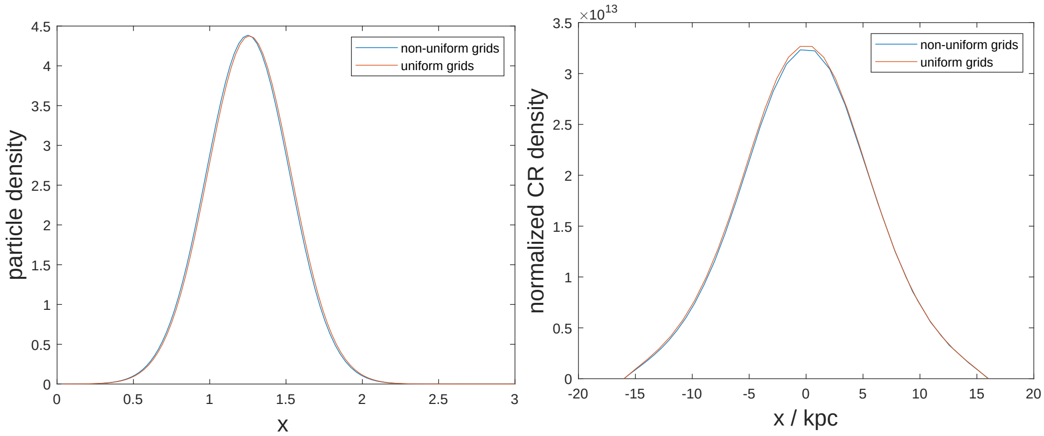

Figure 1: Left: The comparison of result obtained from normal FDM method and non-uniform-grid method for a simple 1D propagation toy model. Right: The same comparison but for the x-axis distribution of a 3D isotropic propagation.

use this procedure to solve a 1-dimensional (1D) propagation equation and a 3-dimensional (3D) isotropic propagation equation, and then compare their expectation with the result obtained from normal FDM method in Fig. 1. It shows that the non-uniform-grid method consists with the normal FDM method well in both 1-dimensional (1D) and 3-dimensional (3D) cases.

3. Prediction on CR anisotropy

The phase transition of the CR anisotropy is expected to be able to explained with a nearby CR source together with the local interstellar magnetic field (LISM). In this section, we would adopt a non-uniform-grid simulation to demonstrate this scenario quantitatively.

The measurements of the CR proton spectrum show a break at tens of TeV [31, 32], which indicates a nearby source whose contribution would dominant around TeV and cut at $\sim$ 30TeV [23]. Such a TeV CR source, when located opposite the Galactic center, would lead to the TeV anisotropy direct towards the outside direction of the Galaxy. In this work, we assume that this nearby source is the Supernova remnant (SNR) of Geminga. This SNR started to inject the CR particles about 340 thousand years ago. The Geminga is currently located at 250 pc away from the sun at the direction $(l, b) = (175.2°, 16.33°)$ in Galactic coordinate [33]. With a projected velocity $\sim$ 200km/s, the Geminga is supposed to be about 70 pc away from its original site 340 thousand years ago [34]. This uncertainty of the injection position is not so important for this work as our scenario is not quite sensitive to the precise location of the nearby source. Therefore, we assume that the nearby source is injected from a random position inside this 70 pc area.

On the other hand, the CR particles are supposed to propagate faster along the regular magnetic field [24]. This anisotropic diffusion effect would decrease with the energy. At the energy $\sim$ TeV, the diffusion is supposed to be anisotropic, thus the CR anisotropy would direct along the LISM [22] and has less to do with the precise direction of the source. Around 100 TeV, the contribution from the nearby source becomes negligible and thus the direction of CR anisotropy is directly inversed but still direct along the LISM. For the energy above PeV, the diffusion becomes isotropic, and the direction of CR flux excess would shift to the Galactic center.

In practice, we need to separate the contribution from the nearby source and that from all the other sources. The former is calculated with an short-term injection thus its time step needed to be carefully chosen to avoid the irreversible calculation error. The latter adopts a set of stable sources, and the calculation error introduced by the large time steps would be finally suppressed when the system converges.

At first, we calculate the contribution from the whole Galaxy except the nearby source. In this calculation, the diffusion coefficient D_{ij} is decomposed into two component, $D_{\parallel}$ and $D_{\perp}$, which refer to the diffusion coefficient parallel to and perpendicular to the regular magnetic field. With the regular magnetic field $\mathbf{B}$ given, the diffusion coefficient tensor follows the relation [24]

$$D_{ij} = D_{\perp}\delta_{ij} + (D_{\parallel} - D_{\perp})B_i B_j/|\mathbf{B}|^2, \tag{3}$$

where B_i is the i-th component of the vector $\mathbf{B}$.

The parallel and perpendicular components are assumed to follow two different power-law

$$\begin{aligned} D_{\parallel} &= D_{0\parallel}\left(\frac{R}{R_0}\right)^{\delta_{\parallel}} \\ D_{\perp} &= D_{0\perp}\left(\frac{R}{R_0}\right)^{\delta_{\perp}} \equiv \varepsilon D_{0\parallel}\left(\frac{R}{R_0}\right)^{\delta_{\perp}}, \end{aligned} \tag{4}$$

where $\varepsilon \equiv D_{0\perp}/D_{0\parallel}$ is the ratio of the two components at the reference rigidity R_0. Practically, we would assume the index of the perpendicular component $\delta_{\perp}$ to be larger than the index of the parallel component $\delta_{\parallel}$, thus the ratio $D_{\perp}/D_{\parallel}$ would increase with the energy. As there is no reason for us to assume a faster propagation for the perpendicular direction, for energy region that $D_{\perp}$ goes larger than $D_{\parallel}$, we keep them the same and the diffusion becomes isotropic.

The regular magnetic field $\mathbf{B}$ is adopted following Ref. [24]. A little tunning is also performed to ensure that the direction of $\mathbf{B}$ at solar system is consistent with the LISM.

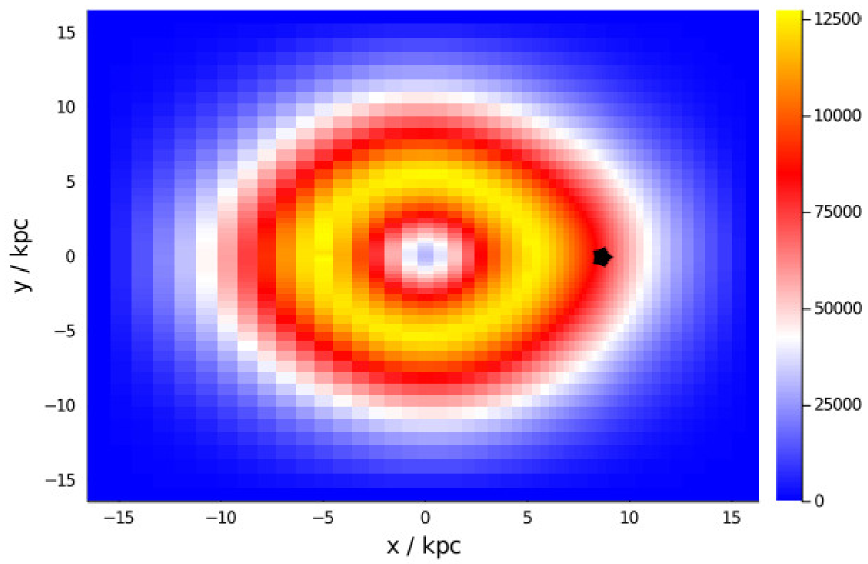

Figure 2: The xOy distribution (right) derived in the anisotropic diffusion scenario around 6 TeV. The black mark indicate the solar system.

With all the details mentioned above considered, we perform a non-uniform-grid simulation to calculate the CR distribution with no nearby source and show the result in Fig. 2. It could be seen that the CR particles are globally confined in a ring by the spiral Galactic regular field, and our simulation could show more details around the solar system (8.3 kpc, 0 kpc).

With the same assumption on diffusion, we then perform a simulation for an instant injection at the position of Geminga. We assumed that the injection happened 340 thousand years ago, and its injection spectrum is a power-law with an index ~ -2.3 and an exponential cut at 40TeV. We sum up the contribution from this source and the contribution shown in Fig. 2 and use the final distribution to derive the 2D CR anisotropy observed at the earth. The calcuated 2D CR anisotropy

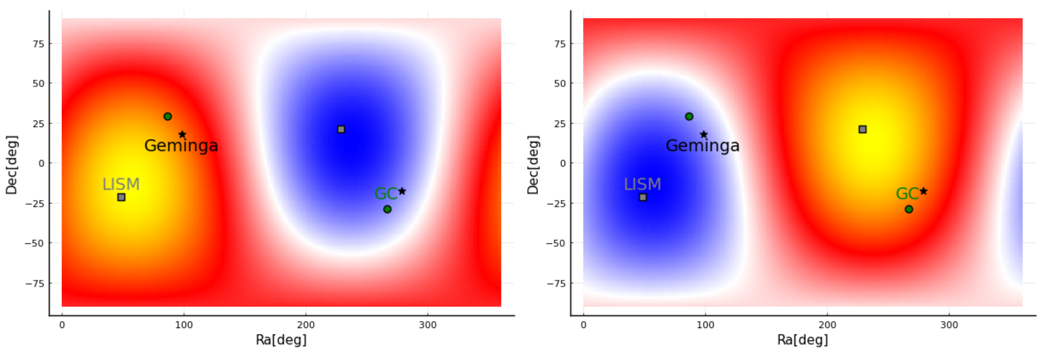

Figure 3: The 2D CR anisotropy predicted at 2.5 TeV (left) and 1.6 PeV (right).

for different energies is shown in Fig. 3. It could be seen that the direction of the excess of CR flux is reversed along the LISM as the energy increased.

4. Conclusion

In this work, we introduced a non-uniform-grid method to approach a high-resolution simulation around the sun. We performed two simple cases to verify the validity of this method. This method is then applied to an anisotropic diffusion model described by a realistic Galactic large-scale regular magnetic field. Taking into account the nearby source in this model, we finally reach a reasonable explanation of the phase transition on CR anisotropy observation. In the future, we would consider more details in the simulation and approach the calculation for higher energy and show that the excess of CR flux would finally direct to the Galactic center.

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