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Power spectrum of the TeV-PeV cosmic ray anisotropy

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Propagating individual cosmic rays in synthetic three-dimensional Kolmogorov turbulence, we calculate their anisotropy at the location of an observer. These are the first calculations of the cosmic ray anisotropy down to TeV energies for values of the turbulence coherence length that are realistic for the interstellar medium. We calculate the power spectrum C_l, of the cosmic ray anisotropy for different observer locations, and compare with observations. We also decompose the anisotropy onto spherical harmonics, and show that an important distinction should be made between higher order multipoles that are aligned with the local direction of the magnetic field at the observer's location, and those that are not.

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1. Introduction

Cosmic ray(CR) anisotropies at the level of 0.1% have been observed at different energy ranges by the experiments[1–6]. If it is postulated that the origin of these small-scale anisotropies is the turbulent magnetic field in the interstellar medium(ISM), the angular power spectrum of the small-scale anisotropies can be inferred through the theoretical framework of [7].

In our work, we calculate the angular power spectrum of CR anisotropy using the results from our numerical simulations.

2. Method

We use the same method as in Ref[8] to do the simulation. We propagate individual cosmic ray particles inside a Kolmogorov turbulent magnetic field, we obtain anisotropy skymaps at different observer positions. These simulation results are the first simulation with CR energies down to several TeV with the coherence length similar to those in the ISM. The number of simulated particles reached the order of millions. Under the aforementioned simulation conditions, we consider the effective signal of the calculated angular power spectrum to extend to $l > 32$.

For calculating the angular spectrum of cosmic ray anisotropy, $f(E, \mu, \phi)$, we use the following formulation to normalize the coefficients $f_l{}^m(E)$:

$$f(\mu, \phi) = \sum_{l=0}^{L_{max}} \sum_{m=-l}^{l} f_l^m(E) Y_l^m(\mu, \phi) \quad (1)$$

In the following, we abbreviate $f(E, \mu, \phi)$ as $f(\mu, \phi)$, and the coefficients $f_l{}^m(E)$ are abbreviated as $f_l{}^m$. The angular power spectrum for the anisotropy is defined as in [6]:

$$C_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |f_l^m|^2 \quad (2)$$

We plot the calculation results of anisotropies at some observer locations in the ISM. For each location, we vary the CR energy from 3 TeV to 3000 TeV.

3. Power Spectrum results

3.1 Anisotropy power spectrum at different cut off surfaces

What we call the "cut off surface" is the sphere up to which CRs are backtracked like in Ref[8]. In Figure 1, We compute the anisotropy angular power spectrum at different cutoff surfaces with 3 TeV. The multipole structure of the power spectrum extends up to $l = 64$. Clearly, changing the cutoff radius does not result in significant differences in the curve at different values of l in the region of the effective signal. However, reducing the radius of the cutoff surface effectively reduces the level of noise in the power spectrum. At the same time, this also significantly reduces the total time required for the simulation, which means that in the following section, we can still obtain results from simulations with a higher number of particles within a reasonable computational time frame.

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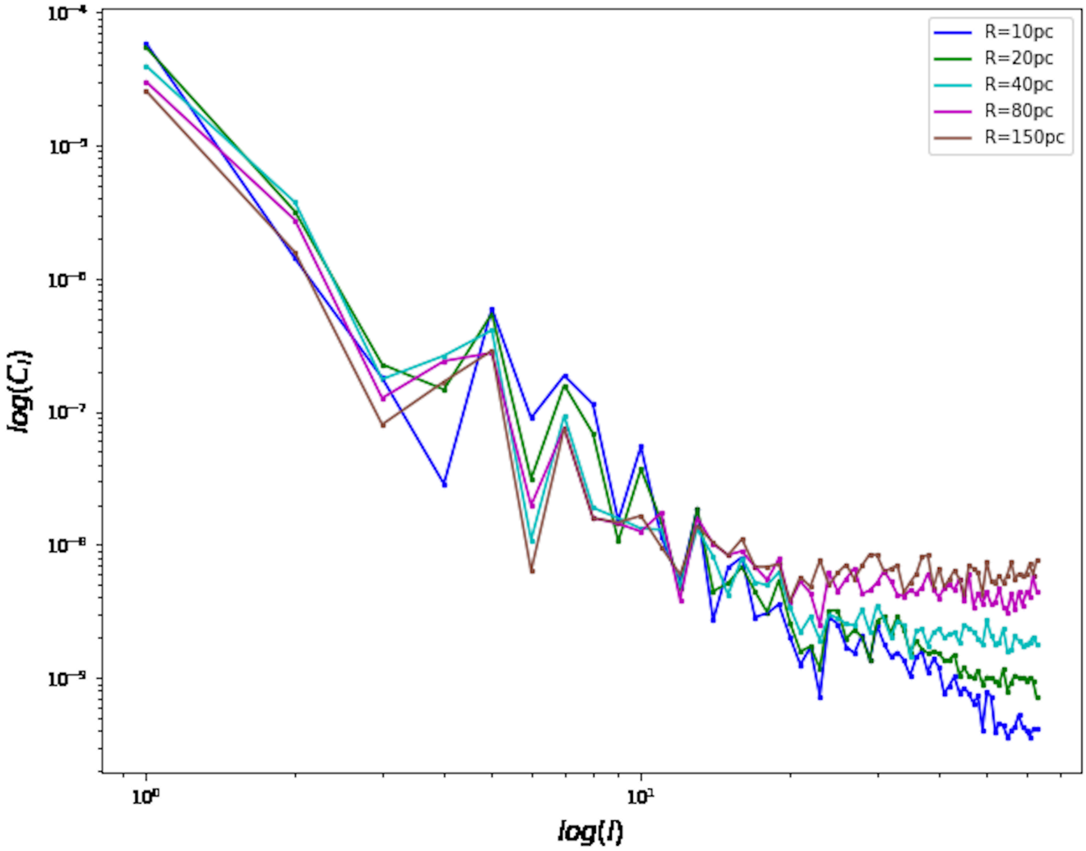

Figure 1: Anisotropy angular power spectrum at different cutoff radii. The overall shape of the power spectra is approximately the same at l<20, but the spectra with smaller radii exhibit lower noise levels.

3.2 Anisotropy power spectrum at different observer locations

In Figure 2,we present the anisotropy angular power spectrum with 3 TeV at five randomly selected observer positions in the simulation. The radius of the cutoff surface in these simulations is set to 10 pc, and the energy of CR particles is set to 3 TeV. At these five observer positions, the differences in the dipole moment and other low-l structures of the angular power spectra are evident. However, for the corresponding small-scale structures smaller than around 20 degrees, which roughly correspond to $l > 10$ multipoles, the trend of the angular power spectrum is similar. At the same time, the noise levels of the angular power spectrum at these five positions are approximately of the same order.

3.3 Anisotropy along observed dipole moment and local magnetic field line directions

The dipole moment is expected to follow approximately the direction of local magnetic field lines at the observer location. Therefore, it is crucial to investigate the angular power spectra along the observed dipole moment direction or the local magnetic field lines for studying anisotropic power spectra. This has never been considered yet. In Figure 3, we present the angular power spectrum with 3 TeV calculated along different directions and with the coefficients of the $m = 0$

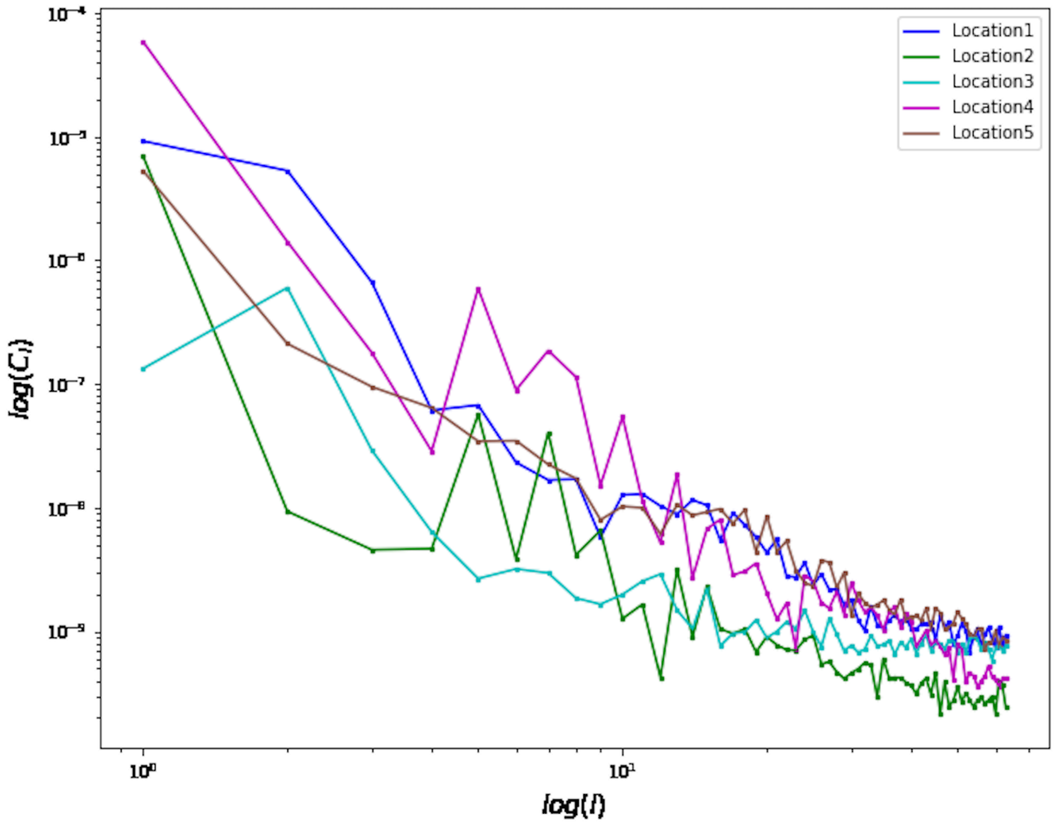

Figure 2: Anisotropy angular power spectrum at different observer locations at 3 TeV.

expansion term along that direction. The solid lines represent the C_l power spectrum and the dashed lines represent the $m = 0$ components. It can be observed that after calculating along the dipole moment or magnetic field direction, the contribution of the $m = 0$ component is significantly higher compared to the initial angular power spectrum. However, the overall angular power spectra, C_l, of the three cases do not show significant differences.

4. Conclusion

In this work, we have done the first calculations of the cosmic ray anisotropy down to TeV energies for values of the turbulence coherence length that are realistic for the interstellar medium. Moreover, we can save the computation time by decreasing the radii of cut off surfaces in the simulation without significantly affecting the anisotropies. We analyze the angular power spectra along both the dipole direction and the direction of the local magnetic field lines.

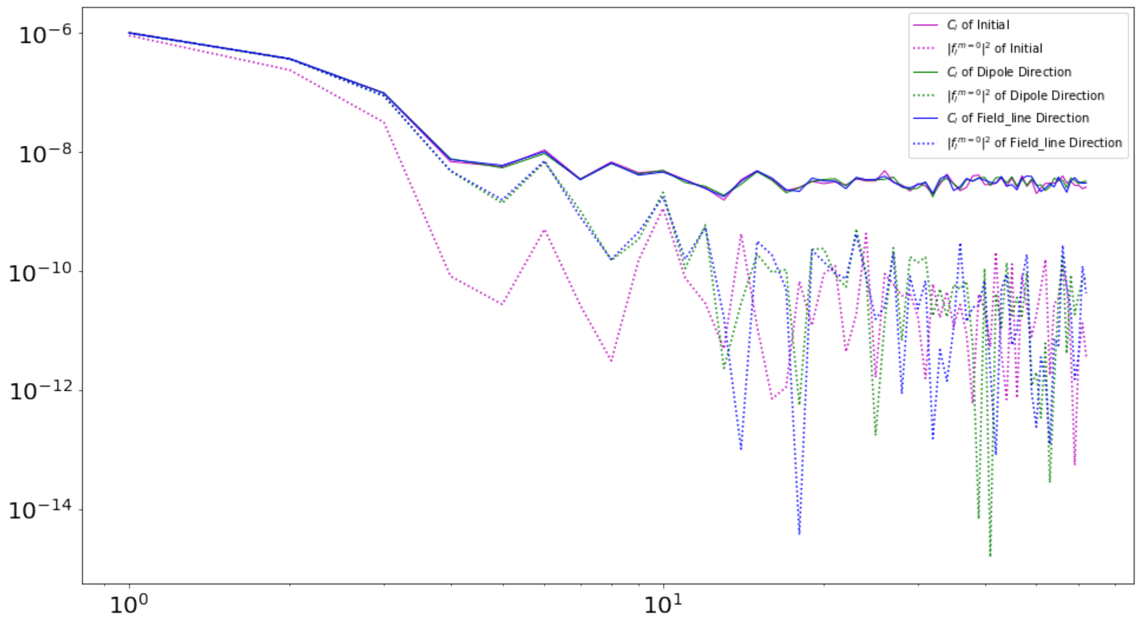

Figure 3: Anisotropy angular power spectrum and the spectrum along dipole and magnetic field line directions.

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