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Effects of heliospheric boundary structures on galactic cosmic ray transport : Global MHD and large-scale test particle simulations

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The statistics of galactic cosmic rays (GCRs) invading the heliosphere are investigated using numerical simulations. First, a time stationary global heliosphere is reproduced using an MHD simulation. Then, motions of a large number of GCR protons with initial Lorentz factor 10 ($\sim$ 10 GeV) and 1000 ($\sim$ 1 TeV), distributed in the interstellar space around the heliosphere, are numerically solved. We map the positional distribution of the GCRs arriving at 50 AU from the Sun. Our results show that the arrival position of GCRs depends on their energies. We discuss the statistical behavior of the arriving GCRs at each energy.

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1. Introduction

Galactic cosmic rays (GCRs) observed on the ground or near the Earth provide us with information to understand the global heliospheric structures. It is well known that the GCRs spectrum below several ten GeV is strongly modified by the solar activities. Voyager 1 directly observed the significant change of the spectral intensity between inside and outside the heliosphere [**?**]. Also well known is the directional anisotropy of TeV CRs arriving at the Earth. The observed anisotropy (relative intensity) is known to be 10^{-4} to 10^{-3} (e.g. [**? ? ?**]).

We have presented the trajectory analysis of GCR protons invading the heliosphere using an MHD simulation and test particle simulation [**?**]. We showed that the GCR trajectories are characterized by the relative scale between the GCR gyroradii and heliospheric structures. In this paper, we focus on the statistical behavior of the GCRs arriving deep inside the heliosphere to investigate the effect of heliospheric boundary structures on GCR statistics in the level of particle trajectories. After briefly presenting simulation settings and statistical analysis method, we show our analysis results and discuss statistical tendency of the GCRs with initial Lorentz factor 10 ($\sim$ 10 GeV) and 1000 ($\sim$ 1 TeV).

2. Simulation and Statistical Analysis Methods

The MHD simulation assumes the steady solar wind, whose magnetic moment has north polarity (solar magnetic field in the northern hemisphere is directed outward from the Sun) with zero tilt angle. The basic algorithm is described in [**?**]. Simulation parameters are as follows. The solar wind velocity, density, magnetic field strength, and temperature at 1 AU are set to be 400 km/s, 5.0 /cc, 50 μG, and 10^5 K, respectively. These quantities are all assumed to be constant in time, and they are simply extrapolated to the inner boundary of the simulation at 50 AU from the Sun. For the outer boundary at 900 AU, the corresponding parameters of the stationary interstellar plasma are 23 km/s, 0.1 /cc, 6,300 K, and 3 μG, respectively. Using the above parameters, the simulation is performed until a steady state heliosphere is reproduced. The details of the simulation results are described in Fig.1 of [**?**].

Using the data obtained from the MHD simulation, we perform a test particle simulation to compute the GCR trajectories. Test particles (GCR protons) are initially distributed on a surface outside the heliopause, which is away from the heliopause by a distance of the typical GCR gyroradius (indicated by the magenta surface in Fig.**??**). The number of GCRs is 3×10^6. The heliopause is defined as the iso-temperature surface of 57,500 K. In Fig.**??**, the color of the heliopause denotes magnetic field strength normalized to $B_{ISM} = 3\mu G$. The initial velocity distribution function of the GCRs is given by a mono-energetic shell distribution. We performed two runs with different GCRs Lorentz factors, $\gamma = 10$ ($\sim$ 10GeV) and $\gamma = 1000$ ($\sim$ 1 TeV). In the following, we analyze the statistics of the GCRs that reached the inner boundary.

In our simulation, GCRs are uniformly distributed on the initial surface (Fig.**??**), and also distributed uniformly on the shell distribution in the velocity space. Fig.**??** (a) shows the latitude-longitude distribution of the initial GCRs shown in Fig.**??**. Horizontal and vertical axes are the longitude ϕ and the latitude θ, respectively. The longitude ϕ is defined so that $90^\circ \leq \phi \leq 270^\circ$ ($0^\circ \leq \phi < 90^\circ$, $270^\circ < \phi < 360^\circ$) corresponds to the nose (tail) region of the heliosphere. The latitude θ is defined so that $\theta > 0$ (< 0) corresponds to the northern (southern) hemisphere. As shown in Fig.**??** (a), there is an eminent anisotropy in the initial directional distribution. This initial anisotropy should be compensated when we discuss GCR statistics. So, we need to apply a weighting function to all the GCR so that the initial distribution becomes uniform. Fig.**??** (b) is the initial directional distribution after applying the weighting function. GCR statistics at the end of the simulation were evaluated using the same weighting function. Note that there is a region in the tail where no initial GCRs are present.

3. Results

4. Summary

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acknowledgments in my mothertongue...and after in english

References

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