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Large-scale test particle simulation of galactic cosmic rays invading the heliosphere

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Although most of the galactic cosmic rays (GCRs) in the interstellar space are prevented from entering the heliosphere, a fraction of them can propagate deep inside the heliosphere and be observed on the Earth. Their motions in the heliosphere are quite complex because of the solar modulation effect. Our goals in this study are to understand how the GCRs invade and reach deep inside the heliosphere and to determine the statistical behaviors of the modulation in the level of particle trajectory.

Using a steady electromagnetic structure reproduced by a global MHD simulation[1], large-scale test particle simulations are performed to investigate the behavior of the GCRs invading the heliosphere. The inner boundary of the MHD simulation is at 50AU from the Sun. The solar magnetic field has positive (northward) polarity with zero tilt angle. GCR protons are injected from outside the heliosphere. Figure 1(a) and (b) show the distribution of the arrival position on the inner boundary for the GCRs with ~10^{10}eV and 10^{12}eV, respectively[2]. Horizontal and vertical axes are the longitude φ and the latitude θ. The longitude φ is defined so that $90° \leq \varphi \leq 270°$ ($0° \leq \varphi \leq 90°$, $270° \leq \varphi \leq 360°$) 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.

- ~10^{10}eV GCRs

The GCRs with ~10^{10}eV tend to arrive in the mid-high latitude, $-90° \leq \varphi \leq -45°$ or $45° \leq \varphi \leq 90°$. Two types of propagation patterns are confirmed. The GCRs of the first type follow spiral magnetic field in the tail region and are then captured by the polar current vortex. The GCRs of the second type initially propagate in the equatorial current sheet and then drift poleward along the termination shock. During the poleward drift, they are accelerated through the shock drift mechanism[3].

- ~10^{12} eV GCRs

The GCRs with ~10^{12}eV tend to arrive in the mid-low latitude $-60° \leq \theta \leq 60°$ of the tail region. We found that many GCRs come from high latitudes while moving around the current vortex. They precipitate along the polar current vortex. The motion shows the feature like the meandering motion.

Although the inner boundary of the MHD simulation is at 50 AU from the sun, we extend the boundary further inside the heliosphere to 1 AU by assuming steady solar wind with Parker spiral magnetic field so that we can follow test particle motions down to 1 AU. We discuss some statistics of the GCRs with ~$10^{9\text{-}13}$ eV reaching the extended inner boundary, e.g., distribution of arriving latitude/longitude, and energy dependence of arrival rate. Then, these statistical features are related to the characteristics of GCR trajectories.

References
[1] Washimi et al, ApJ, 809, 16, 2015
[2] Yoshida et al, APPB proceedings, 2022, accepted
[3] Yoshida et al, ApJ, 916 29, 2021

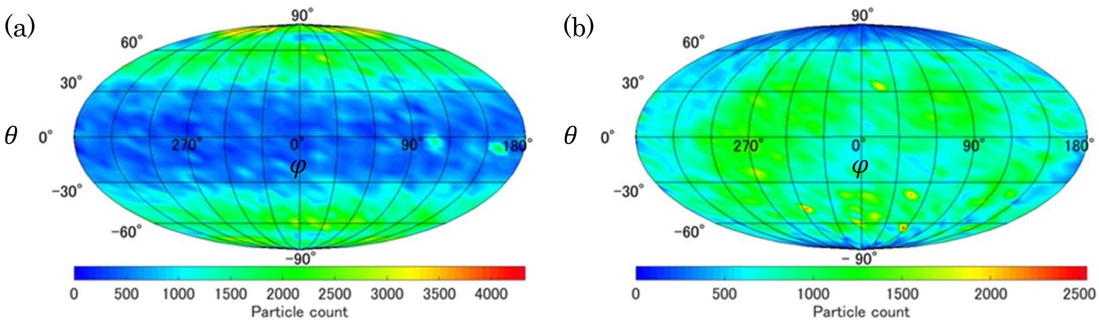

Figure 1. The distribution of the arrival position on the inner boundary for the GCRs with (a) ~ 10^{10}eV and (b) ~ 10^{12} eV.