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Effects of heliospheric structures on trajectories and statistics of galactic cosmic rays

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Most of the galactic cosmic rays (GCRs) coming from interstellar space are prevented from entering the heliosphere. A fraction of them can propagate deep inside the heliosphere and be observed on the earth. The motion of a charged particle in the heliosphere is quite complex. Our goals in this study are to understand how GCRs enter and reach deep inside the heliosphere and to determine the statistical behaviors of solar modulation of GCRs in the level of particle trajectory.

We perform three-dimensional relativistic test particle simulations using global electromagnetic field data of the heliosphere reproduced by an MHD simulation[1]. In the MHD simulation, time stationary solar wind is continuously injected from the inner boundary at 50 AU from the Sun. The outer boundary at 900 AU is also adjoined to a time stationary interstellar wind. The solar magnetic field has positive (northward) polarity with zero tilt angle. GCR protons are injected from outside the heliosphere. Their velocity distribution function is given by mono-energetic shell distribution.

In this presentation, characteristic trajectories and statistical behaviors of ~10 GeV and ~1TeV protons are discussed[2]. The results are as follows.

- ~10 GeV

At this energy level, some particles enter the heliosphere from many parts (nose, flank, and tail) of the heliopause. Figure 1 shows the snapshot of the particles projected onto the (a) y = 0 AU and (b) x = 200 AU planes. The invading particles propagate in the region where local magnetic field is weak e.g., the heliopause and the equatorial current sheet. Particles are unlikely to propagate upstream the termination shock due to the supersonic outflow of the solar wind. Because of the polarity of the solar magnetic field, the particles approaching the inner boundary tend to drift poleward. Therefore, a relatively large number of particles reach the high latitude region at the inner boundary. There are various patterns of invading particle trajectories such as current sheet drift, polar drift, spiral motion, shock drift, and Fermi-like acceleration. In the latter two motions, particles are accelerated.

- ~1 TeV

Particles at this energy level are almost insensitive to the small-scale structures of the heliosphere because of their large gyro radius. Hence, a relatively larger number of particles easily come in and out the heliosphere. More particles tend to reach the low latitude tail region at the inner boundary. Some particles exhibit motions due to resonant interaction with the large-scale eddies in the tail region. Some other particles passing by the heliosphere are mirror reflected by the bottleneck structure of interstellar magnetic field surrounding the heliosphere and return back, entering the heliosphere.

In the current simulation realistic effects such as the presence of MHD waves, the variation of magnetic polarity due to the solar activity, finite tilt angle of the solar magnetic moment, are omitted. These effects are essential for more accurate discussions and should be included in future work.

References
[1] H. Washimi, et al. 2015, ApJ, 809, 16
[2] K. Yoshida, et al. 2021, ApJ. Accepted

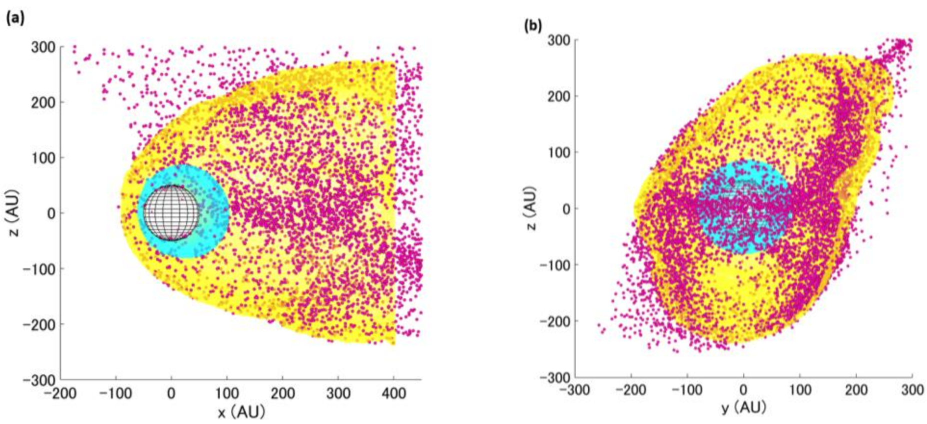

Fig 1. Snapshot of ~10 GeV particles (magenta dots) projected onto the (a) y = 0 AU and (b) x = 200 AU planes. The surface (region) depicted by the yellow (cyan) color is heliopause (supersonic solar wind region)[2].