9th Asia-Pacific Conference on Plasma Physics, 21-26 Sep, 2025 at Fukuoka

Three-dimensional global hybrid simulations of plasma transport and energy conversion during solar wind-magnetosphere interactions

San Lu[1,2,3], Jin Guo[1,2,3], Quanming Lu[1,2,3]
[1] School of Earth and Space Sciences, CAS Center for Excellence in Comparative Planetology, CAS Key Laboratory of Geospace Environment, University of Science and Technology of China, Hefei, China, [2] Deep Space Exploration Laboratory, Hefei, China, [3] Collaborative Innovation Center of Astronautical Science and Technology, Harbin, China.
e-mail (speaker): lusan@ustc.edu.cn

Space weather is controlled by the solar wind-magnetosphere interaction, during which the energy and plasma in the solar wind can enter the magnetosphere through the magnetopause, the outer boundary of the magnetosphere. The orientation of the magnetic field in the solar wind, referred to as the interplanetary magnetic field (IMF), dictates how the solar wind energy and plasma enter the magnetosphere and how they are converted and transported, respectively, therein.

When the IMF is southward, it can allow efficient transport of plasma and energy through magnetic reconnection between the southward IMF and the northward geomagnetic field at the low-latitude magnetopause on the dayside. These energy and plasma are then convected toward the nightside magnetotail where magnetic reconnection can also occur to release the magnetic energy, and the energy and plasma are then transported both earthward and tailward after such magnetotail reconnection. The earthward portion is injected into the inner magnetosphere, and the tailward portion is lost and returns to the solar wind.

When the IMF is northward, energy and plasma can transport between the solar wind and the magnetosphere through the Kelvin-Helmholtz instability (KHI) at the low-latitude magnetopause on the flanks. At the same time, the northward IMF can cause magnetic reconnection at the high-latitude magnetopause, which allows plasma entry into the high-latitude magnetosphere, and then the plasma can be injected into the cusps, illuminating auroral spots.

More recent studies show that under radial IMF, ultra-low frequency (ULF) waves are formed in the foreshock and can propagate into the magnetosheath and even the magnetosphere. At the same time, high-speed jets are formed in the magnetosheath, which can strike the magnetopause to trigger surface waves and magnetic reconnection thereon, creating auroral signatures. These processes may cause transfer of energy and plasma between the solar wind and the magnetosphere, which can even cause strong geomagnetic disturbances, such as substorms.

The above mechanisms of energy conversion and plasma transport during solar wind-magnetosphere interactions are mostly descriptive because they are obtained from limited spacecraft observations in vast space. To justify the importance of these mechanisms, it is crucial to examine them quantitatively. The previous quantitative analyses were based on either magnetohydrodynamic (MHD) simulations which lacked the crucial particle kinetics and the Hall effects or hybrid simulations which were two-dimensional (2-D) and limited mostly to the dayside. Here, using three-dimensional (3-D) global simulations with self-consistent particle tracing and particle kinetic effects, we quantify the energy conversion and plasma transport in the solar wind-magnetosphere system under different IMF conditions. The main findings are summarized below.

1. When the IMF is northward, the magnetosphere expands on the dayside and shrinks on the nightside. The number of particles in the magnetosphere increases; the volume of the magnetosphere and the magnetic energy therein decrease. Particles and electromagnetic energy flow into the magnetosphere slowly at low rates. Magnetic reconnection does not occur in the magnetotail plasma sheet so that the particles in the magnetosphere are well preserved.

2. When the IMF is southward, the magnetosphere shrinks on the dayside and expands on the nightside, corresponding to a strong inflow in Poynting flux and a strong particle outflow. Strong magnetic reconnection occurs, and a strong energy conversion from the magnetic field to the plasma. Such processes under southward IMF cause a loading and then an unloading of magnetic energy $\sim 3\times10^{15}$ J in ~1 hour. At the same time, the volume of the magnetosphere increases by a factor of ~1.6 during loading and then recovers during unloading. After the strong magnetotail reconnection, the original magnetosphere particles are mostly lost, which are replaced by the particles from the solar wind, corresponding to a strong particle inflow into the magnetosphere.

3. When the IMF is radial, strong disturbances are generated on the magnetopause, and the volume of the magnetosphere increases. Despite of the strong disturbances, the total ion flux across the magnetopause is small. At the same time, the total Poynting flux across the magnetopause and the total energy conversion in the magnetosphere are also small, even smaller than those under northward IMF.