Modeling Solar Wind Particles Transport Into the Plasma Sheet With Test Particle Simulation

Ding Li, Richard Marchand, Konstantin Kabin and Robert Rankin

Department of Physics, University of Alberta, Edmonton, Alberta, Canada

Solar wind plasma is an important source of inner magnetosphere and magnetic reconnection is a critical entry mechanism. After solar wind particles cross the magnetopause, some particles in the Low latitude boundary layer (LLBL) drift along the flank region and populate in the near-midnight plasma sheet. Test particle simulation is a very direct approach to modeling the plasma transport during the solar wind/ magnetosphere interaction. Coupled with a global MHD simulation, we use a test particle approach to show the process of plasma transport from the solar wind to the plasma sheet. The results are shown to be consistent qualitatively with the recent observations.

1. Introduction

Solar wind particles transport to inner magnetosphere, and its dependence on the IMF has been investigated in previous simulations (Richard et al., 2002; Peroomian, 2003 and Walk et al. 2003), which showed that reconnection regions have significant impact on plasma transport. Recently, many observation results suggest the low-latitude boundary layer (LLBL) play a pivotal role in supplying plasma to the plasma sheet (Wing et al., 2002; Nishino et al., 2003; Øieroset et al., 2003). We use test particle simulation technique coupled with global MHD simulation to show the process of plasma transport from the solar wind to the plasma sheet.

2. Methodology

In our simulation we trace test particles orbits in the time-dependent electric and magnetic fields obtained from a global MHD model (BATS-R-US, Gombosi et al., 2003) of the magnetosphere and its interaction with the solar wind. We mainly use the low energy ions (mostly protons) as tracer for defining different source regions of magnetosphere. When the Kappa parameter (Buchner et al., 1989) satisfies $\kappa >> 1$, the guiding-center approximation is used to trace the particle orbits, which allows large-scale time step and, thus, saves computation time.

$$\frac{d\vec{r}}{dt} = \vec{v}_{//} + \vec{v}_d$$

$$\vec{v}_d = \frac{\vec{E}\times\hat{b}}{B} + \frac{\mu}{qB\gamma}\hat{b}\times\nabla B + \frac{\gamma m v_{//}^2}{qB}\left(\nabla\times\hat{b}\right)_\perp$$

$$\frac{dp_{//}}{dt} = qE_{//} + \frac{p_{//}}{B}\vec{E}\bullet\left(\nabla\times\hat{b}\right)_\perp - \frac{\mu p_{//}}{qB\gamma}\left(\nabla\times\hat{b}\right)_\perp\bullet\nabla B - \frac{\mu}{\gamma}\hat{b}\bullet\nabla B$$

$$p_{//} = \gamma m v_{//}, \mu = \frac{\gamma^2 m v_\perp^2}{2B}$$

Where $v_{//}$ and $p_{//}$ are the velocity and momentum parallel to the magnetic fields, v_d is the drift velocity, and $\hat{b}$ is the unit vector along the magnetic field. The time varying fields used in our calculations are obtained from interpolations of solutions calculated at discrete times with the global MHD model. In order to avoid large interpolation errors near the Earth, the spatial interpolation of the field is calculated from reduced BATS-R-US fields, in which the dominant dipole field has been subtracted. The dipole component of the field (with its time varying inclination) is added analytically in the calculation of the trajectories, which uses the fourth-order Runge-Kutta integration.

3. Simulation Results

We use idealized solar wind parameter and IMF conditions to drive the BATS-R-US simulation. In this case, the initial IMF is southward (B_z=$-5nT$), and then flips northward (B_z=$5nT$) after one hour. The time dependence of the dipole tilt is also taken into account.

The simulation domain for test particles consists of are rectangular prism made of 101 by 81 by 81 nodes, which extends from $-80R_E \le x \le 20R_E, -40R_E \le y \le 40R_E$ and $-40R_E \le z \le 40R_E$. The positive directions for coordinate x, y, z axes are sunward, duskward, northward, respectively. The grid size is $1R_E$ and a fixed time step of Δt=1.0 second is used throughout. Initially, 10,000,000 ion particles of thermal energy T_i=10ev with Maxwell distribution are continuously injected across the $x = 19R_E$ plane. Each particle carries a relative weight determined at the time of injection in order to account for the specified flux of solar wind, $2.0\times10^{12} m^{-2}s^{-1}$. When particles arrive at the outer boundaries of simulation box or when they precipitate on the Earth ($R\le1R_E$), they are removed from the simulation and re-injected from the $x = 19R_E$ plane.

Figure 1a and 1b show the results obtained at t=3hours during northward IMF, we can recognize the structures of magnetosheath, magnetopause, cusp, plasma sheet and plasma mantle. Figure 1a suggests that some particles come through the dayside cusp region and get trapped around the Earth. Some particles in the plasma mantle region drift along the open field lines into the flanks of the magnetotail. Consistent with the previous studies of Richard et al. [2002], Peroomian [2003], and Walk et al. [2003]. The high-density regions in the noon-midnight meridian plane lie in the Entry layer and dayside Low-latitude boundary layer, which are thought to be the important entrance for solar wind particles to the inner magnetosphere. Figure 1b shows the high-density region in dayside LLBL and along the flank magnetopause in the equatorial plane. Particles in the dayside LLBL drift tailward and populate the near-nightside plasma sheet and flanks. We see the peaks of density at both the near-Earth dusk and dawn flanks, which is in qualitatively agreement with the DMSP observation results (Wing et al., 2002). Figure 2 shows the dawn-dusk asymmetry via the total particle number in the sampling near-Earth dusk and dawn flank region (defined as $-10R_E<x<0, 10R_E<|y|<15R_E$) and the near-midnight plasma sheet (defined as $|y|<8R_E, -20R_E<x<-10R_E$) as a function of time step. With a northward IMF, the total number of particles in these three regions increases as a function of time and the total number on the dawn side flank is larger than in the two other regions.

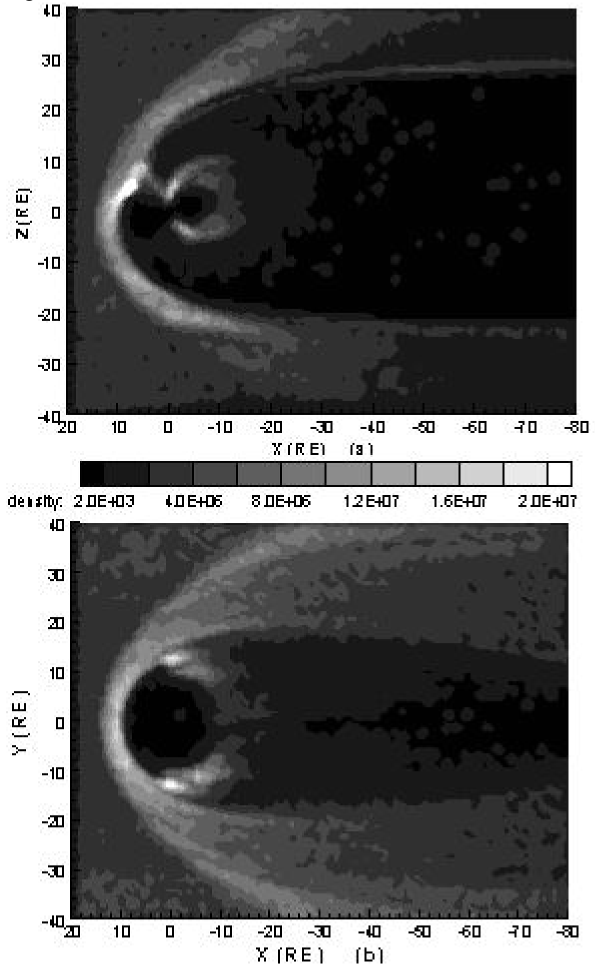

Fig. 1. Two-dimensional profiles of proton density at (a) y=0 plane, (b) z=0 plane for time step=10800, each point is averaged over $1\times1\times1R_E^3$.

4. Conclusion

Using a test particle code and results from a time dependent global MHD simulation of the magnetosphere, we investigate transport of solar wind particles into the inner magnetosphere and, in particular, in the flanks of the plasma sheet in northward IMF condition. The simulation results are qualitatively consistent with the observation cited above. The cusp is an important region for solar wind particles to enter the magnetosphere. The low-latitude boundary layer has significant effect on plasma transport to plasma sheet flanks and the near-Earth plasma sheet (Wing et al., 2002). In the future, we will use our code to calculate the particles energy distribution and compare with the observation of plasma sheet temperature.

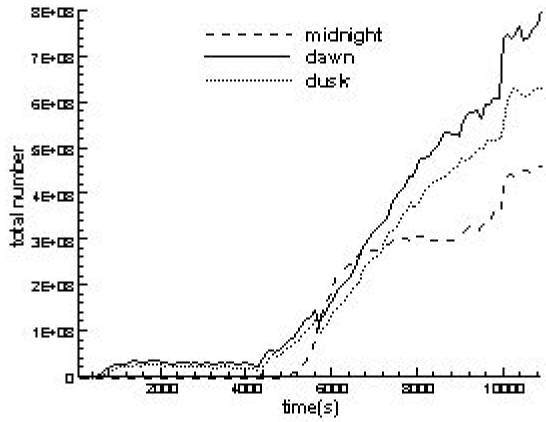

Fig. 2. Total particle numbers in the dusk, dawn flanks and near-midnight plasma sheet sampling regions via the time step.

Acknowledgments This work was supported by the National Science and Engineering Research Council of Canada. We also thank the University of Alberta and WestGrid for their computational support.

References

Buchner, J., and L. M. Zelenyi, Regular and chaotic charged particle motion in magnetotaillike field reversals, 1, Basic theory of trapped motion, *J. Geophys. Res., 94*, 11281, 1989.

Gombosi,T. I., D.L. De Zeeuw, K.G. Powell, A.J. Ridley, I.V. Sokolov, Q.F. Stout, and G. Tóth, Adaptive Mesh Refinement MHD for Global Space Weather Simulations, in "*Space Plasma Simulation*", edited by J. Büchner, C. T. Dum, M. Scholer, Lecture Notes in Physics, 615, 251-279, Springer, 2003.

Nishino, M. N., T. Terasawa, and M. Fujimoto, Observational signatures of plasma transport across the Low-latitude boundary layer, in *Earth's Low-Latitude Boundary Layer*, *Geophys. Monogr. Ser.*, vol. 133, edited by P. Newell and T. Onsager, p. 265, 2003.

Øieroset, M., T. D. Phan, M. Fujimoto, L. Chan, R. P. Lin, and R. Skoug, Spatial and temporal variations of the cold dense plasma sheet: Evidence for a Low-Latitude Boundary Layer source, in *Earth's Low-Latitude Boundary Layer*, *Geophys. Monogr. Ser.*, vol. 133, edited by P. Newell and T. Onsager, p. 253, 2003.

Peroomian, V., The influence of the interplanetary magnetic field on the entry of solar wind ions into the magnetosphere, *Geophys. Res. Lett.*, *30*(7), 1407, doi:10.1029/2002GL016627, 2003.

Richard, R. L., M. El-Alaoui, M. Ashour-Abdalla, and R. J. Walker, Interplanetary magnetic field control of the entry of solar energetic particles into the magnetosphere, *J. Geophys. Res.*, *107*(A8), 1184, doi:10.1029/2001JA000099, 2002.

Walker, R. J., M. Ashour-Abdalla, T. Ogino, V. Peroomian, and R. L. Richard, Modeling magnetospheric sources, in *Earth's Low-Latitude Boundary Layer*, *Geophys. Monogr. Ser.*, vol. 133, edited by P. Newell and T. Onsager, p. 33, 2003.

Wing, S., and P. T. Newell, 2D plasma sheet ion density and temperature profiles for northward and southward IMF, *Geophys. Res. Lett.*, *29*(9), 1307, doi:10.1029/2001GL013950, 2002.