SOLAR WIND-MAGNETOSPHERE INTERACTION AS SIMULATED BY A 3-D EM PARTICLE CODE

KEN-ICHI NISHIKAWA
Department of Physics and Astronomy, The University of Iowa, Iowa City, Iowa 52242, USA

TORSTEN NEUBERT
Space Physics Research Laboratory, The University of Michigan, Ann Arbor, Michigan 48109, USA

and

OSCAR BUNEMAN*
STAR Laboratory, Department of Electrical Engineering, Stanford University, Stanford, California 94305, USA

Abstract. We have studied the solar wind-magnetosphere interaction using a 3-D electromagnetic particle code. The results for an unmagnetized solar wind plasma streaming past a dipole magnetic field show the formation of a magnetopause and a magnetotail, the penetration of energetic particles into cusps and radiation belt and dawn-dusk asymmetries. The effects of interplanetary magnetic field (IMF) have been investigated in a similar way as done by MHD simulations. The simulation results with a southward IMF show the shrunk magnetosphere with great particle entry into the cusps and nightside magnetosphere. This is a signature of a magnetic reconnection at the dayside magnetopause. After a quasi-stable state is established with an unmagnetized solar wind we switched on a solar wind with an northward IMF. In this case the significant changes take place in the magnetotail. The waving motion was seen in the magnetotail and its length was shortened. This phenomena are consistent with the reconnections which occur at the high latitude magnetopause. In our simulations kinetic effects will determine the self-consistent anomalous resistivity in the magnetopause that causes reconnections.

Key words: Solar wind, Magnetosphere, IMF, Magnetic Reconnection

1 Introduction

The solar wind interaction with the Earth's magnetic field gives rise to a number of important and intriguing phenomena many of which are only partially understood. These include reconnection between the solar wind magnetic field at the dayside magnetopause and flux transfer events, the drag of the solar wind exerted on the magnetotail and associated instabilities at the magnetopause, plasma convection in the magnetosphere/ionosphere, and the generation of field-aligned current systems. Reviews of these and other phenomena can be found in (Haerendel and Paschmann, 1982; Elphic, 1987; Huang, 1987; Mauk and Zanetti, 1987). The range of physical processes

* Deceased January 24, 1993; R. Buneman *et al.* 1993.

Astrophysics and Space Science **227**: 265–276, 1995.
© 1995 *Kluwer Academic Publishers. Printed in Belgium.*

involved in the solar wind-magnetosphere system is quite overwhelming, and consequently a wide array of methods have been used to study these, ranging from detailed studies of select phenomena with the assumption of a specific field geometry or set of boundary conditions, to fully three dimensional simulations with less spatial resolution but self-consistent particle or field geometries and with no (little) influence of the boundary conditions.

The first 3-dimensional (3-D), global magnetohydrodynamic (MHD) simulations of the solar wind-magnetosphere system was reported by (Brecht *et al.* 1981; Leboeuf *et al.* 1981; Wu *et al.* 1981). Since then, global 3-D MHD simulations have been used with some success to study a range of processes including reconnection in the tail (Brecht *et al.*, 1982; Walker *et al.*, 1987), reconnection at the day-side magnetopause (Sato *et al.*, 1986), the dependence on the interplanetary magnetic field (IMF) orientation of magnetospheric convection and field-aligned currents (Ogino *et al.*, 1985, 1986, 1994; Ogino, 1986; Walker *et al.*, 1993), the solar wind-magnetosphere-ionosphere current-voltage relationship (Fedder and Lyon, 1987), the self-excitation of auroral arcs (Watanabe and Sato, 1988), and the reconnection voltage between the closed geomagnetic field and the IMF as a function of the IMF clock angle (Fedder *et al.*, 1991).

In MHD-codes the micro-processes are represented by statistical (macroscopic) constants such as diffusion coefficients, anomalous resistivity, viscosity, temperature, and the adiabatic constant. Recently, Winglee (1994) has developed magnetoplasma dynamics (MPD) including the surface current due to the ambipolar electric field set up by the different penetration between electrons and ions.

To include particle dynamics explicitly, a number of simulations have been performed using hybrid codes (fluid electrons, particle ions) and full particle codes in one and two dimensions. With such codes local problems have been investigated such as shocks formed in the solar wind as it encounters the magnetosheath (Quest, 1988; Burgess, 1989; Omidi *et al.*, 1990; Thomas *et al.*, 1990; Thomas and Winske, 1990; Winske *et al.*, 1990) and the current layer at the dayside magnetopause (Gary and Sgro, 1990; Berchem and Okuda, 1990; Okuda, 1991,1992,1993). Recently also global problems have been investigated in three dimensions with hybrid codes, namely the solar wind interaction with the dayside of Venus (Moore *et al.*, 1991) and the solar wind interaction with Mars and Venus (Brecht and Ferrante, 1991, 1993).

With the model presented here, we intend to take the full step, namely the global simulation of the solar wind interaction with a planetary magnetic field using a particle code which contains the complete particle dynamics. As will be shown below, the advantage is that the model contains the complete physics. The price to be paid is that some scaling of plasma parameters must be done at the present time.

2 A 3-D EM Particle Simulation Model

Our code is a successor to the TRISTAN code (Buneman *et al.*, 1980; Peratt *et al.*, 1980; Peratt, 1986). Its new features (Buneman, 1994) are: (1) Poisson's equation and Fourier transforms have been eliminated by updating the fields locally from the curl equations and depositing the particle currents according to charge-conserving formulas (Villasenor and Buneman, 1992), (2) radiating boundary conditions are applied to the fields using a first order Lindman approximation (Lindman, 1975), (3) filtering is done locally, (4) localisation makes the code ideally suited to modern parallel machines which call for minimising data paths, (5) the code is in Fortran and fully transportable: modest versions run on PCs and on workstations. In the past, the TRISTAN code has successfully simulated large scale space plasma phenomena such as the formation of systems of galaxies (Peratt, 1986). The new version of the code (Buneman, 1994) has been applied to the study of the dynamics of low-β plasma clouds (Neubert *et al.*, 1992) and the whistler wave driven by Spacelab 2 electron beam (Nishikawa *et al.*, 1994a), electron-positron plasmas (Zhao *et al.* 1994a,b) and current loop coalescence (Nishikawa *et al.*, 1994b: Sakai *et al.*, 1994).

For the simulation of solar wind-magnetosphere interaction the following boundary conditions were used for the particles: (1) Fresh particles representing the incoming solar wind (in our test run unmagnetized) are continuously injected across the yz-plane at $x = x_{min}$ with a thermal velocity plus a bulk velocity in the $+x$ direction, (2) thermal solar particle flux is also injected across the sides of our rectangular computation domain, (3) escaping particles are arrested in a buffer zone and redistributed there more uniformly by making the zone conducting in order to simulate their escape to infinity. They are then written off.

For the fields, boundary conditions were imposed just outside these zones: radiation is prevented from being reflected back inward, following Lindman's ideas (Lindman, 1975). The lowest order Lindman approximation was found adequate: radiation at glancing angles was no problem. However, special attention was given to conditions on the edges of the computational box.

In order to bring naturally disparate time- and space-scales closer together in this simulation of phenomena dominated by ion inertia and magnetic field interaction, the natural electron mass was raised to 1/16 of the ion mass and the velocity of light was lowered to twice the incoming solar wind velocity. This means that charge separation and anomalous resistivity phenomena are accounted for qualitatively but perhaps not with quantitative certainty. Likewise, radiation related phenomena (e.g. whistler modes) are covered qualitatively only.

3 Simulation Results

A first test exploring the solar wind-magnetosphere interaction was run on the CRAY-YMP at NCAR using a modest 105 by 55 by 55 grid and only 200,000 electron-ion pairs (Buneman *et al.*, 1992). We also have reported on our second test run on the CRAY-2 at NCSA using a larger 215 by 95 by 95 grid and about 1,000,000 electron-ion pairs for unmagnetized solar wind (Buneman *et al.*, 1994). Initially, these fill the entire box uniformly and drift with a velocity $v_D = 0.5c$ in the $+x$ direction, representing the solar wind. The electron thermal velocity is $v_{th} = 0.02c$ while the magnetic field is initially zero. A circular current generating the dipole magnetic field is increased smoothly from 0 to a maximum value reached at time step 65 and kept constant at that value for the rest of the simulation. The center of the current loop is located at (70.5Δ, 47.5Δ, 48Δ) with the current in the xy-plane and the axis in the z-direction. The initial expansion of the magnetic field cavity is found to expel a large fraction of the initial plasma. The solar wind density is about 0.7 electron-ion pairs per cell, the mass ratio is $m_i/m_e = 16$, and $\omega_{pe}\Delta t = 0.84$.

In this report we concentrate on the simulation results with the solar wind with southward or northward IMF. Figure 1 is shown the electron density in the center xz-layer containing the dipole center at time step 768. (Data were recorded at 64 step intervals and while no fully steady state was approached, no major change was seen between steps 768 and 1024 (Buneman *et al.*, 1992, 1994).) The electron density is color coded and the magnetic field component in the plane is shown with arrows at every third grid point. The magnitude of the field has been scaled in order to see the field direction for weak fields. Thus the length of the vectors is not a true representation of the field magnitude. The plasma is flowing through the simulation domain from left to right (low to high x-values). In the process the dipolar field is compressed at the side facing the plasma wind and is extended to a long tail on the down-wind side, just as the Earth's magnetic field in the solar wind.

Some particles have entered the cusp regions and, on the down-wind side (night side), particles have gathered on closed field lines in what could be equivalent to the radiation belt. The particles at the up-wind magnetopause are forming a bow shock. The temperature of these particles is much elevated from the background temperature. Also seen up-wind from the magnetopause is what could be a second shock or a foreshock. The magnitude of both shocks has a minimum at the sub-solar point and is increasing to a maximum at some distance from the sun-Earth line.

The system becomes quasi-steady around time step 768 shown in Fig. 1. At this point in time a southward IMF is introduced gradually with the injection of solar wind particles from the left boundary. The value of the southward IMF is set as slightly larger than the noise level outside the magne-

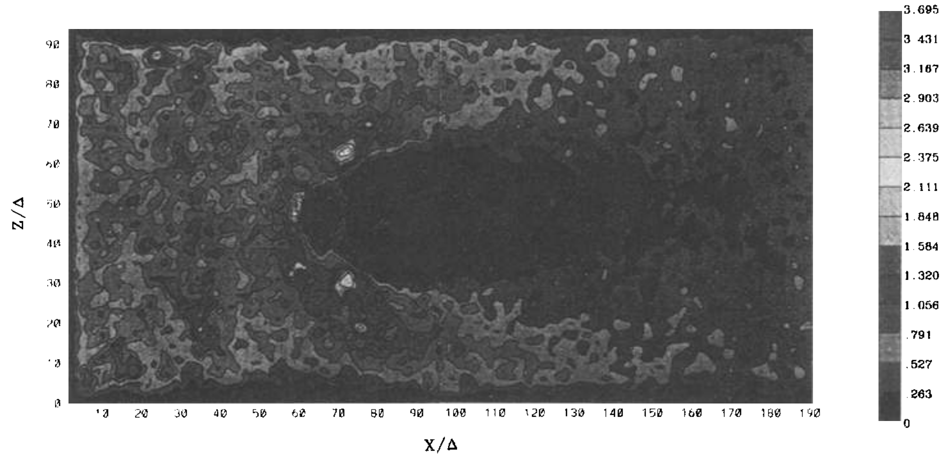

Fig. 1. Electron density in the center xz-layer containing the dipole center at step 768. "Relative amplitude" on color bar signifies simulation units.

topause ($B_z = -0.4$). The induced electric field ($E_y = -v_D \times cB_z$) is applied at the boundary with the form of $0.5*(1-\tanh((10-(step-768))/5))$ $step >$ 768. After about 20 steps the applied IMF becomes constant. After 394 steps the front of the solar wind with the southward IMF reaches $x/\Delta = 100$, if it is not slowdown by the magnetopause and the magnetosphere. Figure 2 shows the electron density at time step 1152.

Even the solar wind with the constant southward IMF is attacking at the magnetopause only for about 150 steps, the more electrons are penetrated through the cusps and the magnetopause as shown in Fig. 2. Consequently the magnetosphere is shrunk and more electrons trapped in the nightside. Ion density also shows the similar change as the electron density. Figure 3 shows the electron and ion fluxes along the z-direction at the noon-midnight meridian cross-section ($y = 48\Delta$) near the earth. The x point is located around $x = 58\Delta$, $z = 51\Delta$. The close examination reveals that the shape and intensities of fluxes are difference between the electrons and ions. The electrons and ions are move out from the x point.

Based on these simulation results we believe a magnetic reconnection

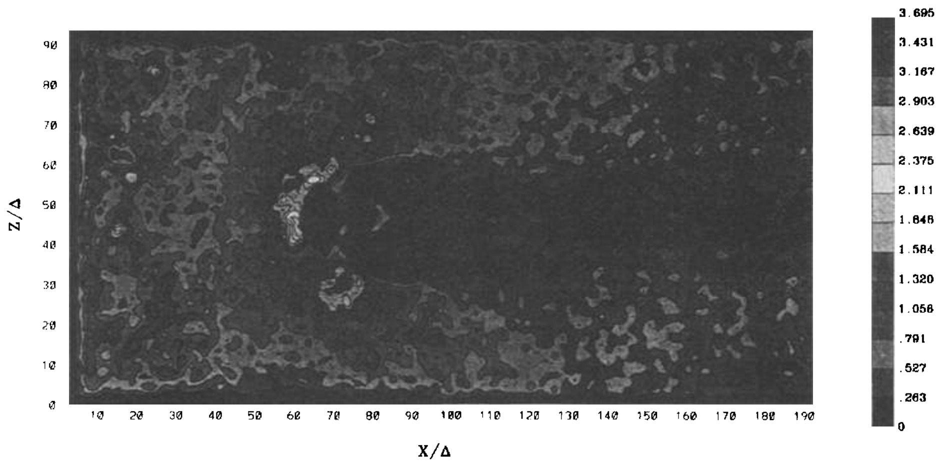

Fig. 2. Electron density in the center xz-layer containing the dipole center with a switched southward IMF at step 1152.

takes place in the dayside magnetopause as in MHD simulations. In our 3-D EM particle simulations the (anomalous) resistivity is in principle self-consistently determined by the particles and the electric and magnetic fields (waves) in the dayside magnetopause.

At step 768 the northward IMF is switched on. The magnetotail is shifted toward south and slightly shortened as shown in Fig. 4. This may be due to the reconnection at the higher magnetopause. The more particles are penetrated into the magnetotail near the earth. Obviously, we need a wider system to avoid the influences of the boundaries. The north-south asymmetry is caused by the different rates of particle penetrations due to the reconnection at the high latitude mantle.

4 Discussion

The results presented in Figures 1 through 4 show that even with the modest grid-size of 215 by 95 by 95 cells, our 3-D fully kinetic model is able to generate the complete magnetosphere with its basic characteristics with

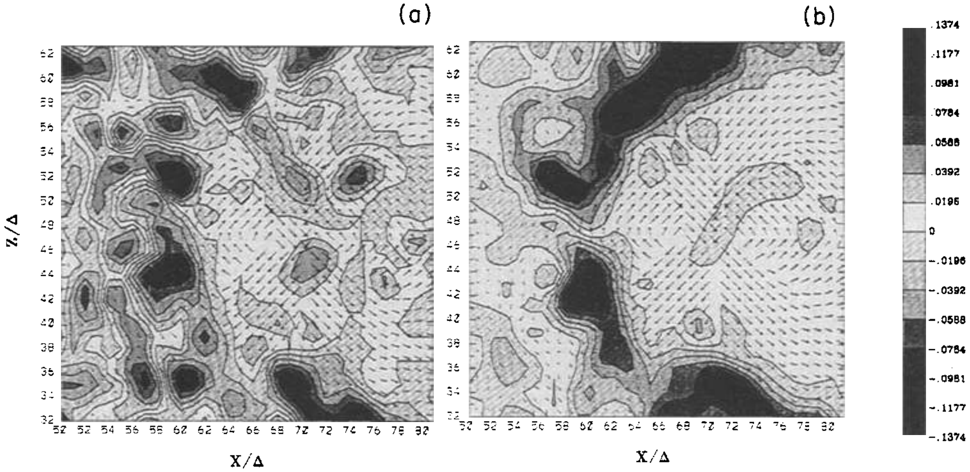

Fig. 3. Particle flux near the magnetopause with magnetic fields by the arrows at step 1152: (a) electron flux, (b) ion flux.

IMFs. The simulation with a southward interplanetary magnetic field (IMF) has been performed. After the solar wind with the IMF reaches the dayside magnetopause, more particles are diffused into the magnetosphere than without an IMF. The magnetosphere is shrunk and more particles are trapped in the nightside magnetosphere. This may be a manifestation of the magnetic reconnection at the magnetopause. In our 3-D EM particle simulations the resistivity in the magnetopause is self-consistently determined by the particles and the electric and magnetic fields. The detailed analysis with the close up diagnosis near the dayside magnetopause show the clear reconnection with jet-like flow from the x point.

On the contrary, in the case of solar wind with northward IMF, the magnetotail was shifted toward south and its length is shortened. This result is consistent with the occurrence of the magnetic reconnection at the high latitude mantle. Due to the more effective reconnection at the north side the more plasma move into from the north side, therefore, the distant magnetotail move toward south shortening its length.

These simulation results encourages us to continue our work using fin-

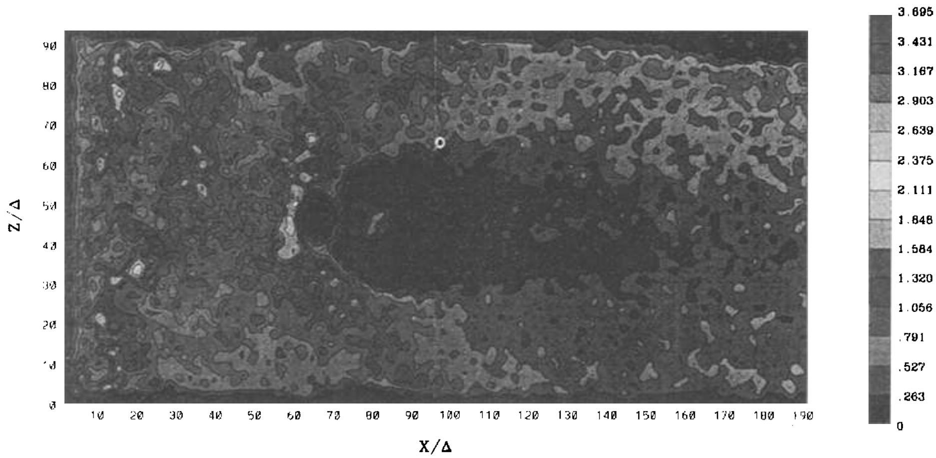

Fig. 4. Electron density in the center xz-layer containing the dipole center with a northward IMF at step 1408.

er grids (larger array sizes) and including such features as time-dependent IMFs, a tilt of the magnetic axis, and an inner conducting surface simulating the ionosphere. Larger dimensions will allow finer resolution of fields. The number of particles should also be increased. Longer runs would allow us to enhance realism by using smaller m_e/m_i and larger c/v_D. On presently available single processor computers the grid resolution could be increased by a factor of 2 in all dimensions. Multi-processor machines in the future will allow even greater improvement, since the code allows simultaneous updating of many cells.

Some important issues that with advantage can be addressed with a kinetic code are:

1. In MHD simulations reconnection phenomena are sometimes studied using artificial numerical dissipation to drive the process. Furthermore, artificially high diffusion coefficients are often used in order to achieve a stable solution. On the contrary a full kinetic code can handle reconnection processes self-consistently without such problems.

2. The motions of individual particles are tracked. In many regions of the magnetosphere, such as the magnetopause and the tail, gradients in the magnetic field are of such magnitude that the magnetic field changes significantly during a particle gyration. This gives rise to non-isotropic, non-Maxwellian distribution functions which drives the physics of those regions. The recent research into chaotic particle orbits in the magnetotail (Chen and Palmadesso, 1986; Burkhart and Chen, 1991; Ashour-Abdalla *et al.*, 1994) is examples. The complex particle motion gives rise to such phenomena as collisionless electron viscosity Dungey, 1988; Sonnerup, 1988; Lyons and Pridmore-Brown, 1990) and collisionless conductivity (Horton and Tajima, 1991). Furthermore, a particle code calculates the particle dynamics in self-consistent rather than model magnetic fields.

3. The complete wave dynamics from low frequency magnetohydrodynamic modes (Kelvin-Helmholtz instabilities at the magnetopause and ULF pulsations) to electron waves (Langmuir oscillations) is included. An example where electron kinetics is important is illustrated by recent studies of the dynamics of the magnetopause current layer (Berchem and Okuda, 1990; Okuda, 1991,1992,1993). It is thought that a generalized lower hybrid drift instability is generated, which in the case of the magnetopause has the effect of broadening the current layer and causing filamentation of the current.

4. Any complicated magnetic field configuration can be simulated by a simple modification of the source-current. This makes it straight-forward to simulate not only other planetary magnetospheres such as that of Uranus, but also the effect of the diurnal rotation of the Earth's dipole axis with respect to the direction to the sun.

However, some form of scaling is usually needed in particle simulations, even in one and two dimensions, and still such simulations are able to reveal much of the physics behind natural phenomena. Similar problems are also encountered, and to some degree overcome, in laboratory plasma simulations of macro-scale space plasma phenomena. Examples include the study of magnetic field line reconnection (Gekelman and Stenzel, 1984; Gekelman and Pfister, 1988), and the interaction of a magnetized plasma flow with a dipole magnetic field (Rahman *et al.*, 1991). We propose, therefore, that a kinetic particle model will be a useful tool for the study of the Earth's and other planetary magnetospheres in the solar wind, by supplementing present models that do not contain the complete particle dynamics.

5 Acknowledgements

Support for this work was provided by NASA contract NAS8-38772, NASA grant NAGW-2350, and NSF grants ATM-9106639, ATM-9119814, and ATM-9121116. The development of the simulation code was performed at the National Center for Supercomputing Applications, University of Illinois at Urbana-Champaign and test runs were performed at National Center for Atmospheric Research. Both centers are supported by the National Science Foundation.

References

Ashour-Abdalla. M. Zelenyi, L. M. Perroomian, V. and Richard, R. L.: 1991, "Consequences of magnetotail ion dynamics," *J. Geophys. Res.*, **Vol. 99**, pp. 14,891-14,916

Berchem, J. and Okuda, H.: 1990, "A two-dimensional particle simulation of the magnetopause current layer," *J. Geophys. Res.*, **Vol. 95**, pp. 8133-8147

Brecht S. H. and Ferrante, J. R.: 1991, "Global hybrid simulation of unmagnetized planets: Comparison of Venus and Mars," *J. Geophys Res.*, **Vol. 96**, pp. 11,209-11,220

Brecht, S. H. J. Lyon, S. H., Fedder, J. A. and Hain, K.: 1981, "A simulation study of East-West IMF effects on the magnetosphere," *Geophys. Res. Lett.*, **Vol. 8**, pp. 397-400

Brecht, S. H., Lyon, J. G. Fedder, J. A. and Hain, K.: 1982, "A time-dependent three-dimensional simulation of the Earth's magnetosphere: Reconnection events," *J. Geophys. Res.*, **Vol. 87**, pp. 6098-8108

Brecht, S. H. Ferrante, J. R. and Luhmann, J. G.: 1993, "Three-dimensional simulation of the solar wind interaction with Mars," *J. Geophys Res.*, **Vol. 98**, pp. 1345-1357

Buneman, O.: 1994, "TRISTAN: The 3-D, E-M Particle Code," *Computer Space Plasma Physics, Simulation Techniques and Software*, edited by H. Matsumoto and Y. Omura, Terra Scientific, Tokyo, pp. 67-84

Buneman, O., Barnes, C. W. Green, J. C. and Nielsen, D. E.: 1980, "Review: Principles and capabilities of 3-d, E-M particle simulations," *J. Comput. Phys.*, **Vol. 38**, pp. 1-44

Buneman, O. Neubert, T. and Nishikawa, K.-I.: 1992, "Solar wind-magnetosphere interaction as simulated by a 3D, EM particle code," *IEEE Trans. Plasma Sci.*, **Vol. 20**, pp. 810-816

Buneman, O. Nishikawa, K.-I. and Neubert, T.: 1994, "Solar wind-magnetosphere interaction as simulated by a 3D EM particle code," *Micro and Meso Scale Phenomena in Space Plasmas*, AGU Monograph, in press

Buneman, R. Barker, R. J., Peratt, A. L., Brecht, S. H., Langdon, A. B., Lewis, H. R.: 1994, "A Tribute to Oscar Buneman—Pioneer of Plasma Simulation," *IEEE Trans. Plasma Sci.*, **Vol. 22**, pp. 22-30

Burgess, D.: 1989, "Cyclic behavior of quasi-parallel collisionless shocks," *Geophys. Res. Lett.*, **Vol. 16**, pp. 345-348

Burkhart G. R. and Chen, J.: 1991, "Differential memory in the earth's magnetotail," *J. Geophys. Res.*, **Vol. 96**, pp. 14,033-14,049

Chen J. and Palmadesso, P.: 1986, "Chaos and non-linear dynamics of single particle orbits in a magnetotail-like magnetic field," *J. Geophys. Res.*, **Vol. 91**, pp. 1499-1508

Dungey, J. W.: 1988, "Noise-free neutral sheets," *Proceedings of an International Workshop in Space Plasma*, held in Potsdam, GDR, European Space Agency Special Report, *ESA SP-285* **Vol. II**, 15-

Elphic, R. C.: 1987, "The bowshock and magnetopause," *Rev. Geophys.*, **Vol. 25**, pp. 510-522

Fedder, J. A. and Lyon, J. G.: 1987, "The solar wind-magnetosphere-ionosphere current-voltage relationship," *Geophys. Res. Lett.*, **Vol. 14**, pp. 880-882

Fedder, J. A., Mobarry, C. M. and Lyon, J. G.: 1991, "Reconnection voltage as a function of IMF clock angle," *Geophys. Res. Lett.*, **Vol. 18**, pp. 1047-1050

Gary, S. and Sgro, A. G.: 1990, "The lower hybrid drift instability at the magnetopause," *Geophys. Res. Lett.*, **Vol. 17**, pp. 909-912

Gekelman, W. and Stenzel, R. L.: 1984, "Magnetic field line reconnection experiments 6. Magnetic turbulence," *J. Geophys. Res.*, **Vol. 89**, pp. 2715-2733

Gekelman, W. and Pfister, H.: 1988, "Experimental observations of the tearing of an electron current sheet," *Phys. Fluids*, **Vol. 31**, pp. 2017-2025

Haerendel G. and Paschmann, G.: 1982, "Interaction of the solar wind with the day-side magnetosphere," *Magnetospheric Plasma Physics*, edited by A. Nishida, Reidel Publishing Company, Dordrecht, Boston, London, pp. 49–142

Horton W. and Tajima, T.: 1991, "Collisionless conductivity and stochastic heating of the plasma sheet in the geomagnetic tail," *J. Geophys. Res.*, **Vol. 96**, pp. 15,811-15,829

Huang, C. Y.: 1987, "Quadrennial review of the magnetotail," *Rev. Geophys.*, **Vol. 25**, pp. 529-540

Leboeuf, J. N. Tajima, T. kennel, C. F. and Dawson, J. M.: 1981, "Global simulation of the three-dimensional magnetosphere," *Geophys. Res. Lett,*, **Vol. 8**, pp. 257-260

Lindman, E. L.: 1975, "Free-space boundary conditions for the time dependent wave equation," *J. Comp. Phys.*, **Vol. 18**, pp. 66-78

Lyons L. R. and Pridmore-Brown, D. C.: 1990, "Force balance near an X-line in a collisionless plasma," *J. Geophys. Res.*, **Vol. 95**, pp. 20,903-20,909

Mauk B. H. and Zanetti, L. J.: 1987, "Magnetospheric electric fields and currents," *Rev. Geophys.*, **Vol. 25**, pp. 541-554

Moore, K. R. Thomas, V. A. and McComas, D. J.: 1991, "Global hybrid simulation of the solar wind interaction with the dayside of Venus," *J. Geophys. Res.*, **Vol. 96**, pp. 7779-7791

Neubert, T. Miller, R. H. Buneman, O. and Nishikawa, K.-I.: 1992, "The dynamics of low-β plasma clouds as simulated by a 3-dimensional, electromagnetic particle code," *J. Geophys. Res.*, **Vol. 97**, pp. 12,057-12,072

Nishikawa, K.-I. Buneman, O. and Neubert, T.: 1994a, "New aspects of whistler waves driven by an electron beam as studied by a 3-D EM particle code," *Geophys. Res. Lett.*, **Vol. 21**, pp. 1019-1022

Nishikawa, K.-I. Sakai, J. I. Zhao, J. Neubert, T. and Buneman, O.: 1994b, "Coalescence of two current loops with a kink instability simulated by a 3-D EM particle code," *Ap. J.*, in press

Ogino, T.: 1986, "A three-dimensional simulation of the interaction of the solar wind with the Earth's magnetosphere: the generation of field-aligned currents," *J. Geophys. Res.*, **Vol. 91**, pp. 6791-6806

Ogino, T., Walker, R. J. Ashour-Abdalla, M. and Dawson, J. M.: 1985, "An MHD simulation of the By-dependant magnetospheric convection and field-aligned current during northward IMF," *J. Geophys. Res.*, **Vol. 90**, pp. 10,835-10,842

Ogino, T., Walker, R. J. Ashour-Abdalla, M. and Dawson, J. M.: 1986, "An MHD simulation of the effects of the interplanetary magnetic field By component on the interaction of the solar wind with the Earth's magnetosphere during southward interplanetary magnetic field," *J. Geophys. Res.*, **Vol. 91**, pp. 10,029-10,045

Ogino, T. Walker, R. J. and Ashour-Abdalla, M.: 1994, "A global magnetohydrodynamic simulation of the response of the magnetosphere to a northward turning of interplanetary magnetic field," *J. Geophys. Res.*, **Vol. 99**, pp. 11,027-11,042

Okuda, H.: 1991, "Numerical simulations on the magnetopause current layer," *Modeling Magnetospheric Plasma Processes*, American Geophysical Union, Geophysical Monograph 62, pp. 9-16

Okuda, H.: 1992, "Structure of the magnetopause current layer at the subsolar point," *J. Geophys. Res.*, **Vol. 97**, pp. 1389-1395

Okuda, H.: 1993, "Numerical simulation of the subsolar magnetopause current layer in the Sun-Earth meridian plane," *J. Geophys. Res.*, **Vol. 98**, pp. 3953-3962

Omidi, N., Quest, K. B. and Winske, D.: 1990, "Low Mach number parallel and quasi-parallel shocks," *J. Geophys. Res.*, **Vol. 95**, pp. 20,717-20,730

Peratt, A. L., Green, J. and Nielsen, D.: 1980, "Evolution of colliding plasmas," *Phys. Rev. Lett.*, **Vol. 44**, pp. 1767-1770

Peratt, A. L.: 1986, "Evolution of the plasma universe: II. The formation of systems of galaxies," *IEEE Trans. Plasma Sci.*, **Vol. PS-14**, pp. 763-778

Quest, K. B. 1988, "Theory and simulation of collisionless parallel shocks," *J. Geophys. Res.*, **Vol. 93**, pp. 9649-9680

Rahman, H. U., Yur, G. White, R. S. Birn, J. and Wessel, F. J.: 1991, "On the influence of the magnetization of a model solar wind on a laboratory magnetosphere," *J. Geophys. Res.*, **Vol. 96**, pp. 7823-7829

Sakai, J. I. Zhao, J. and Nishikawa, K.-I.: 1994, "Loops heating by D.C. electric current and electro- magnetic wave emissions simulated by a 3-D EM particle code," *Solar Phys.*, in press

Sato, T., Shimada, T. Tanaka, M. Hayashi, T. and Watanabe, K.: 1986, "Formation of twisting flux tubes on the magnetopause and solar wind particle entry into the magnetosphere," *Geophys. Res. Lett.*, **Vol. 13**, pp. 801-804

Sonnerup, B. U. O.: 1988, "On the theory of steady-state reconnection," *Comput. Phys. Commun.*, **Vol. 49**, 143-159

Thomas, V. A. and Winske, D.: 1990, "Two dimensional hybrid simulations of a curved bow shock," *Geophys. Res. Lett.*, **Vol. 17**, pp. 1247-1250

Thomas, V. A., Winske, D. and Omidi, N.: 1990, "Re-forming supercritical quasi-parallel shocks 1. One- and two-dimensional simulations," *J. Geophys. Res.*, **Vol. 95**, pp. 18,809-18,819

Villasenor J. and Buneman, O.: 1992, "Rigorous charge conservation for local electromagnetic field solvers," *Comp. Phys. Comm.*, **Vol. 69**, pp. 306-316

Walker, R. J., Ogino, T. and Ashour-Abdalla, M.: 1987, "A magnetohydrodynamic simulation of reconnection in the magnetotail during intervals of with southward interplanetary magnetic field," *Magnetotail Physics*, Edited by A. T. Y Lui, Johns Hopkins University Press, Baltimore, pp. 183-190

Walker, R. J., Ogino, T. Raeder, J., and Ashour-Abdalla, M.: 1993, "A global magnetohydrodynamic simulation of the magnetosphere when the interplanetary magnetic field is southward: The onset of magnetotail reconnection," *J. Geophys. Res.*, **Vol. 98**, pp. 17,235-17,249

Watanabe, K. and Sato, T.: 1988, "Self-excitation of auroral arcs in a three-dimensionally coupled magnetosphere-ionosphere system," *Geophys. Res. Lett.*, **Vol. 15**, pp. 717-720

Watanabe, K. and Sato, T.: 1990, "Global simulation of the solar wind-magneto- sphere interaction: The importance of its numerical validity," *J. Geophys. Res.*, **Vol. 95**, pp. 75-88

Winglee, R. W.: 1994, "Non-MHD influences on the magnetospheric current system," *J. Geophys. Res.*, **Vol. 99**, pp. 13,437-13,454

Winske, D., Omidi, N. Quest, K. B. and Thomas, V. A.: 1990, "Re-forming supercritical quasi-parallel shocks 2. Mechanism for wave generation and front re-formation," *J. Geophys. Res.*, **Vol. 95**, pp. 18,821-18,832

Wu, C. C. Walker, R. J. and Dawson, J. M.: 1981, "A three-dimensional MHD model of the Earth's magnetosphere," *Geophys. Res. Lett.*, **Vol. 8**, pp. 523-526

Zhao, J. Nishikawa, K.-I. Sakai, J. I. and Neubert, T.: 1994a, "Study of nonlinear Alfvén waves in an electron-positron plasma with 3-D EM particle code," *Phys. Plasmas*, **Vol. 1**, pp. 103-108

Zhao, J. Sakai, J. I. Nishikawa, K.-I. and Neubert, T.: 1994b, "Relativistic particle acceleration in an electron-positron plasma with a relativistic electron beam," *Phys. Plasmas*, in press