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Analysis and Visualization of Global Magnetospheric Processes

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Abstract

This is the final report of a three-year, Laboratory Directed Research and Development (LDRD) project at Los Alamos National Laboratory (LANL). The purpose of this project is to develop new computational and visualization tools to analyze particle dynamics in the Earth's magnetosphere. These tools allow the construction of a global picture of particle fluxes, which requires only a small number of in situ spacecraft measurements as input parameters. The methods developed in this project have led to a better understanding of particle dynamics in the Earth's magnetotail in the presence of turbulent wave fields. They have also been used to demonstrate how large electromagnetic pulses in the solar wind can interact with the magnetosphere to increase the population of energetic particles and even form new radiation belts.

Background and Research Objectives

The Earth, as well as other planets in the solar system, forms an obstacle to electromagnetic perturbations and particle flows that originate at the Sun. The stationary solar wind consists of energetic ionized particles, which are deflected by the magnetosphere, causing a time-independent deformation of the Earth's dipole magnetic field. In addition, solar eruptions, in the form of coronal mass ejections and solar flares, can cause large temporal modifications of the magnetospheric field. Similar changes occur in the electric field that is formed due to plasma convection across, or to temporal changes in, the magnetic field.

The source populations of electrons and ions in the magnetosphere originate from the ionospheric flows and from the penetration of the solar wind particles through the magnetopause. The curved geomagnetic field that envelops the magnetosphere can be described to the lowest order as a dipole. The modifications to this field due to a slowly changing solar wind pressure can be included via one of the well-known Tsyganenko models [1].

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During magnetic disturbances, satellite measurements are used to parameterize the time-dependent electric and magnetic fields. The motion of an ionized particle in such fields can be very complex. For example, charged particles in a stationary geosynchronous orbit with an energy of several keV perform three distinct motions. These orbital motions differ widely in their time periods: gyration around the local magnetic field, which takes milliseconds up to a fraction of a second; bounce along the magnetic field, which takes a fraction of a minute; and drift across the magnetic field, which takes several hours. For 10 MeV electrons at low altitudes ($L \sim 3$), these periods become a fraction of a millisecond, a fraction of a second, and 1-2 minutes, respectively.

Therefore, a complete phase space (position and velocity) description of the motion of an ionized particle in the magnetosphere needs to resolve time scales which differ by many orders of magnitude. Spatial resolution on the scale of the entire magnetosphere thus requires the calculation of the orbits of a very large number of particles. Some approximations to the full phase space dynamics may be considered for certain conditions. For example, when the scale lengths of the electric and the magnetic fields are much larger than the particles' gyroradii, one may average the equation of motion over the gyration period, which results in the guiding center approximation. In this description, the dynamic variables reduce to parallel velocity and position, perpendicular drift, and the (relativistic) total energy.

Changes in the dynamic pressure of the solar wind can affect the magnetosphere in several ways. First, the Kelvin-Helmholtz instability due to the shear in solar wind velocity results in long period geomagnetic pulsations (150-600 sec) with small azimuthal wave numbers [2,3]. Second, enhanced ring current intensity excites compressional Pc5 waves with large azimuthal wave numbers [4]. Third, strong dynamic pressure oscillations in the solar wind and upstream of the bow shock have been shown to correlate with large scale fluctuations of the magnetic field in the magnetosphere [5]. Finally, sudden impulses are able to change significantly the quiet time geomagnetic field [6]. For example, a recent sudden storm commencement (SSC) event [7, 8] created a new electron radiation belt at $L \sim 2.5$ with a mean energy of 15 MeV.

Ionized particles are an excellent tracer of plasma phenomena that occur in the magnetosphere. Any natural or artificially induced process that modifies the structure of the magnetic and electric field will immediately affect the motion of ionized particles. If a series of probes were placed at different locations in the magnetosphere during geomagnetically active times, they would record modifications in the fluxes of ions and electrons. Understanding this correlation between the electromagnetic phenomena (waves

or shocks) and the resulting inhomogeneous particle distributions is the basis of this project.

Importance to LANL's Science and Technology Base and National R&D Needs

The project deals with global behavior of ions and electrons taking into account the most realistic features of the geomagnetic field and the appropriate time-dependent electromagnetic phenomena. For instance, the evolution of the sudden injection of particles due to naturally-occurring phenomena, artificially ejected particles in controlled space experiments, or trajectory debris from spacecraft can be calculated with the same methods as those described hitherto. The innovation of on-line graphical presentation of results used in this project can be used in many other applications where correlation between a real-time event and its analysis is required. The interactive simulation device may also involve the transformation of images through a high-speed network, enabling a simultaneous analysis by researchers who are separated physically, and provides a powerful tool for visualization to give a quick analysis of the numerical results. This method renders unique multi-point measurements, which can never be accomplished by real probes (satellites), allowing one to test many theoretical models. The computational tools developed here are a major advance in space physics calculational capability and can be used to aid in the analysis and future development of spacecraft instrumentation.

We consider this project as a first step toward a more complete description of particle distributions in the magnetosphere, which includes a better modeling of the time-dependent electromagnetic phenomena and effects due to coupling with the ionosphere. At one end, the electromagnetic interaction between the solar wind and the magnetosphere is parameterized with the help of known accumulated satellite data and in the future will be improved due to better measurements. At the other end, the response of the ionosphere with modified ion flows can be considered as an enhanced particle source. Additional aspects of future research include the influence of geomagnetic plasma effects on global change, such as the formation of a long lasting radiation belt due to sudden commencements, as observed in 1991 aboard the CRRES satellite [9].

We also expect in the future to use the same computational tool for magnetospheres of the other planets. The modifications involve mainly a different stationary planetary magnetic field. For example, it will be interesting to correlate not just virtual probes in the Earth's magnetosphere, but also with similar probes at other planets, when a major disruption of solar origin affects the heliospheric space. The relation between Jovian

acceleration, motion along the spiral heliospheric field lines, and detection of accelerated electrons at the Earth's magnetosphere has been suggested by Baker et al. [10]. Therefore, future extensions of this study will include atmospheric as well as ionospheric and heliospheric applications.

Science Approach and Accomplishments

The goal of this research is to give researchers a new, efficient computational tool and an on-line visualization system for an analysis of charged-particle distribution functions at virtual probes in the magnetosphere. The main scientific objective is to predict the particle fluxes at any desired location in the Earth's environment during a given magnetic perturbation. Available satellite observations are used to confirm the validity of the simulations. An important feature of the interactive simulation system is the instantaneous verification of the computed results by visual images. Additionally, the graphical images allow quick modification of the main simulation code, adding a degree of control to the input. The research involves the calculation of the orbits of a very large number of particles in phase space, in the presence of a realistic curved geomagnetic field, electromagnetic wave fields and strong shocks, on a global magnetospheric scale. The collection and processing of data at virtual probes located in the magnetosphere necessitates the use of new methods of computation with new graphics facilities.

Under this project, new tools for magnetospheric research involving the numerical modeling of a large number of particles in realistic magnetospheric environments have been constructed. Two different approaches for the numerical analysis have been developed: (a) a code that solves the full Lorentz equations of motion of particles in the geomagnetic field with an improved Tsyganenko field model [1], and (b) an efficient guiding center code, which is particularly appropriate for an investigation of geomagnetic perturbations. Both codes are connected to visualization modules, which are based on the IDL and AVS interactive software languages. The post-processing and the visualization of the simulation data has been upgraded for automated user requirements of virtual probes, and new features for the processing and monitoring of the simulation have been added [11].

Using these tools, two different applications have been studied. The first application involves an analysis of particle trajectories in the Earth's magnetotail with realistic wave turbulent fields. Even in the presence of small amplitude waves, we observe dramatic changes between adiabatic and non-adiabatic particle behavior. It has been shown that initial conditions that result in adiabatic orbits in the absence of waves are often non-adiabatic when the waves are included [12].

Figure 1 shows an example of the effect on the trajectory of a 100 eV proton by one single wave that was present for 100 sec. The upper set of plots illustrates the particle trajectory in the absence of waves; the bottom panels include the effect of the single wave. The upper plot in each set shows the projection of the particle trajectory on the x-z plane, while the lower plot in each set describes the x-y projections (x denotes the anti-solar direction, z is perpendicular to the ecliptic plane, and y is in dawn-dusk direction). This basic trajectory simulation in the full six-dimensional phase space enables us to monitor and visualize a whole distribution function of particles that are subjected to electromagnetic perturbations. Studies of this type show the importance of including realistic wave fields to accurately model particle energization processes in the magnetotail and hence eventually to understand how the central plasma sheet is populated.

A second application involves particle dynamics in the magnetosphere that are disturbed by the passage of a large disturbance in the solar wind [8]. Such disturbances have a major effect on charged particles throughout the magnetosphere, which can be studied in a very efficient manner with the computer models developed in this project. An example of one such calculation [13] is shown in Figure 2. Shown are contours of proton flux that result due to one of the large sudden storm commencement (SSC) impulses as observed by an Earth-orbiting satellite. The plot shows the flux intensity (white is most intense, dark is less intense) as a function of energy (in MeV) and the L shell (in units of Earth radius). One observes the formation of new proton radiation belts at high energies, which were formed at different phases of the interaction between the pulse and the drifting protons. The basic mechanism involves an increase in ion population due to solar protons that were accelerated by coronal mass ejection shocks. These protons drift at a given L-shell and interact with an SSC, which, over a short but finite time, has a similar drift. As a result of this interaction, a subset of ions is accelerated to energy of tens of MeV and forms an isolated radiation belt. Recurrent revolution of the fast ions allows formation of additional subsets of temporary radiation belts. The newly created radiation belts survive until ring current buildup starts as a result of a substorm, which disrupts trapping by violation of the adiabatic trapping criterion or by the generation of waves with frequency comparable to periodic particle motion.

In the future the new numerical tools constructed as part of this project will allow us to investigate the subsequent evolution of particle distribution functions due to substorms, the formation of nonthermal distribution functions in the interplanetary medium, and interactions between particles and electromagnetic waves at different planetary magnetospheres.

Publications

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2. Hudson, M.K., A.D. Kotelnikov, X. Li, J.G. Lyon, I. Roth, M. Temerin, J.R. Wygant, J.B. Blake, M.S. Gussenhoven, K. Yumoto, and K. Shiokawa, "Modeling formation of new radiation belts and response to ULF oscillations following March 24, 1991 SSC," *Proceeding of Taos Workshop on Energetic Particles in the Magnetosphere*, in press (1995).
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Figure 1. Trajectory of a 100 eV proton in the magnetotail showing the effect of the presence of one single wave. The upper set of plots illustrates the particle trajectory in the absence of waves; the bottom panels include the effect of the single wave. The upper plot in each set shows the projection of the particle trajectory on the x-z plane, while the lower plot in each set describes the x-y projections. The small figures to the left show the orientation of the magnetic field.

Figure 2. Calculation of the proton flux that results due to a large sudden storm commencement (SSC) impulse. The plot shows the flux intensity (where white is the most intense while dark is the least intense) as a function of energy (in MeV) and the L shell (in units of Earth radius).