NASA/CR-97- 205949

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Final Report NASA Grant NAGW-4539
and Progress Report NASA Grant NAG5-4453

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Grant Periods: May 1, 1995 to June 30, 1997 (NAGW-4539)
May 1, 1997 to April 30, 1998 (NAG5-4453)

Most of the work carried out to date on this project is summarized in the enclosed reprints of two papers that were just published. The earlier paper that is also enclosed, Structure of the Magnetotail, J. Geophys. Res., *101*, 21,447, 1996 by D. L. Larson and R. L. Kaufmann, was primarily intended to describe our consistent orbit tracing (COT) technique and to show that the resulting magnetotail models were in good agreement with published experimental observations. The following are the most important results from the two new papers.

Force Balance and Substorm Effects in the Magnetotail (JGR *102*, 22,141, 1997)

This and the companion paper both used results from COT analyses. A model of the middle magnetotail ($-20\ R_E < x < -14\ R_E$, $0 < |z| < 2\ R_E$ in geocentric solar magnetospheric coordinates) was generated by first tracing orbits of many groups of ions. Each group in this study consisted of 1000 particles. The groups were picked so they would be dominated by particles that followed a particular type of orbit, and therefore carried a particular cross-tail current distribution. For example, some groups were dominated by particles that were trapped near the neutral sheet. Such particles meander back and forth across the equatorial plane, $z = 0$. Trapped particles with 5 keV of energy, which is characteristic of the region modeled, carry current in the $-y$ direction at $z = 0$, in the $+y$ direction at $0.25\ R_E < |z| < 0.5\ R_E$, and little current beyond $|z| = 0.5\ R_E$. The consistent model plasma sheet was made by including a percentage from each group. The fractions used were adjusted by a least squares routine so that the current carried by ions and electrons in the model plasma sheet equalled the current needed to generate the model magnetic field.

The output from a COT analysis was a full ion distribution function for each of the spatial boxes used in the run. The studies described in the attached papers used 120 boxes. Each box was $1\ R_E$ wide in the x direction, $0.1\ R_E$ wide in the z direction, and wide enough to contain all ions in the y direction. The distribution functions were integrated to evaluate all fluid parameters of interest such as the density, bulk velocity, and pressure tensor.

The purpose of the Force Balance paper was to see what we could learn about the magnetotail using the momentum equation. All the required fluid parameters were calculated during the COT analysis. Plasma is decelerated as it moves earthward in the region studied, but the net force needed to produce this steady state deceleration is much smaller than the $\mathbf{j} \times \mathbf{B}$ and pressure forces. The earthward $\mathbf{j} \times \mathbf{B}$ force therefore nearly cancels the tailward pressure force during quiet times. Relatively large force imbalances are needed to produce bursty bulk flow and substorm injection events.

Two features of the required occasional substantial force imbalances were noted that may be important to substorm processes. The first was that the diversion of cross-tail current to the ionosphere results in a much larger net earthward force than would a simple decrease of the entire cross-tail current system. This is because diversion involves field-aligned currents while the steady cross-tail current closes over the magnetopause. The perturbation magnetic fields produced by these two current systems are substantially different. It was shown that a 10-fold increase in the net earthward force is easily obtained inside a current diversion loop. This may produce some of the observed rapid earthward flows.

The other feature associated with occasional substantial force imbalances involved substorms with multiple expansions. The initiation of a current diversion loop causes a tailward force on plasma outside the loop, so this external region becomes more stretched. If substorm expansions require thin current sheets, then regions adjacent to the original diversion loop would become susceptible to new expansion onsets. For example, assume the loop labeled $\nabla \mathbf{j}_1$ in Figure 6 of the Force Balance paper is the initial current diversion loop. The thinning of adjacent regions may then cause the subsequent initiation of the diversion loops labeled $\nabla \mathbf{j}_2$ and $\nabla \mathbf{j}_3$ in Figure 6, resulting in multiple onsets.

Nonguiding Center Motion and Substorm Effects in the Magnetotail
(JGR *102*, 22,155, 1997)

Effects of nonguiding center motion in the region near $z = 0$, where field lines are sharply curved, were studied in this paper. One result that may be useful when examining satellite data is that the magnetic field can become so weak that the pressure tensor is not field-aligned near $z = 0$. Characteristic patterns were seen in the calculated distribution functions within a distance $2z_o$ of the neutral sheet. The location $z = z_o$ is defined as the point at which a particle's distance from the neutral sheet is equal to the particle's gyroradius. If such features can be identified in data, they will help determine the instantaneous location of the satellite relative to the neutral sheet.

A feature of nonguiding center motion was identified that may be important to substorm onset. This feature depends on the resonant and chaotic nature of certain orbits. For a Maxwellian plasma, certain regions exist in which most orbits are resonant and other regions exist in which most orbits are chaotic. The magnetic moment of a particle on a resonant orbit is almost the same after a current sheet interaction as it was before, even though the magnetic moment temporarily fluctuates while the particle is at the neutral sheet. The magnetic moment of a chaotic particle after a current sheet interaction is almost unrelated to the particle's magnetic moment before the interaction. There is a series of resonant and a series of chaotic regions. The lowest altitude regions are most important because this is where a Maxwellian plasma is dominated by particles on one type of orbit.

The feature that was emphasized in the Nonguiding Center Motion paper is that it was not possible to find particles near the lowest altitude chaotic region which can form a thin current sheet. It was suggested that if convection reduces the plasma density in such a region so that the plasma sheet becomes too thin, then the particles will not be able to carry the current needed to keep the tail lobes separated. This is one mechanism that could induce current disruption and diversion to the ionosphere. A related mechanism also was identified at the lowest altitude resonant region. Here particles are drifting across the tail at their maximum possible average speed. Since the average cross-tail drift speed of these particles cannot increase, any further thinning of the tail again can produce a region in which the existing particles cannot carry the necessary cross-tail current. In either case, the tail must respond, perhaps by collapsing, to bring in more current carrying particles or to change the orbital characteristics of the existing particles. This evolution could not be studied with a COT analysis, but it was possible to predict observable properties of a current sheet that is near each of these limiting states.

Ongoing and Future Work

We are now working on several projects. One is to study the energy and pressure equations in the tail. This project is a natural extension of the study of the momentum equation that was described above. The energy and pressure equations involve higher order moments of the distribution function, so the effects of fluctuations in our COT results are more severe. It appears that we will be able to draw meaningful conclusions by averaging our results over spatial boxes. A reasonable x-dependence is obtained when the results are averaged over all z-boxes, and a reasonable z-dependence is obtained when the results are averaged over all x-boxes. These results are preliminary at this time and must be checked by repeating the calculations to see if the results are reproducible.

Another project that has been started involves making detailed comparisons between the COT distribution functions and measured distribution functions. We have developed data handling and plotting routines so the experimental data and the COT output can be treated in the same manner. Fluctuations in the calculated distribution functions and low count rates in the observations present the biggest problems. Interesting features are fairly easy to identify and understand in the calculated results. So far it has been harder to find consistent anisotropic features in the data. The low count rates have required the use of relatively long sampling periods, so it is hard to find features that last long enough to be accepted as reliable. It is also unlikely that a satellite will be located inside a thin current sheet for an extended time period.

The inner part of the magnetotail current sheet is particularly interesting for two reasons. One reason is that substorm onsets are believed to take place in this region. A second reason is that detector count rates increase substantially as the altitude decreases. This provides better statistics and better time resolution in the experimental measurements. Finally, fluctuations observed in the plasma sheet decrease at lower altitudes, so the plasma sheet more nearly resembles a sheet modeled by the COT method. For all these reasons, we have been trying to extend our calculations to lower altitudes.

The biggest problems involved in extending the COT analysis to and earthward of 10 R_E are the need for a complex electric field model and the importance of three-dimensional (3-D) aspects of the problem. The COT calculations are fully 3-D, but the magnetic field models that were used are nearly 2-D near midnight in the middle tail. This permits the use of a minimal number of spatial boxes. Several times more boxes are needed for a study at lower altitudes. This primarily increases the amount of work needed to carry out each COT analysis. We have been working for most of the past year on a realistic electric field model for use at low altitudes. A procedure that appears to be adequate has been developed. This involves projecting electric potentials up from an empirical model (the Weimer 1996 model) that provides these potentials in the ionosphere. Projections are made to an extensive array of grids that cover the entire magnetosphere region of interest. This step needs to be done only once for a given magnetic and electric field model. Many groups of particles then can be traced in the resulting fields. Projections have only been done for one test case. Details involved in implementing this method turned out to be much more lengthy than we anticipated, so the work has progressed slowly. If no new major problems arise, I believe it will be possible to carry out a full run in the next six to twelve months.