Final Technical Report on NASA Sun-Earth-Connections Theory Grant NAG5-8136 "Comprehensive Quantitative Model of Inner-Magnetosphere Dynamics"

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Papers Completed

Garner, T. W., R. A. Wolf, R. W. Spiro, and M. F. Thomsen, First attempt at assimilating data to correct a magnetospheric model, *J. Geophys. Res.*, *104*, 25145-25152, 1999.

This project was the first instance of observational data being ingested into the time loop of a magnetospheric model, overriding theoretically computed values with observed ones. The corrections substantially affect model-calculated values for later times. Data from Los Alamos particle detectors on geosynchronous spacecraft were assimilated into the Magnetospheric Specification Model. The efficacy of the corrections was judged by comparing with data from another geosynchronous spacecraft, data that were not assimilated into the model. Data assimilation was modestly successful in improving model predictions.

Kim, H.-J. A. A. Chan, R. A. Wolf, and J. Birn, Can substorms produce relativistic outer belt electrons?, *J. Geophys. Res.*, *105*, 7721-7735, 2000.

This research quantitatively tested the idea that the strong induction electric fields that occur in the substorm expansion phase can accelerate some electrons from the high-energy tail of the plasma sheet to the killer-electron (MeV) range at synchronous orbit. Electrons were traced in electromagnetic fields from a Birn-Hesse MHD substorm simulation. We were able to identify a class of trajectories on which the substorm swept electrons from ~ 20 R_E geocentric to about 10 R_E, with magnetic moments in the killer-electron range. The number of electrons produced in a series of strong substorms seems on the borderline of adequacy for explaining killer-electron events.

Toffoletto, F.R., R.W. Spiro, R.A. Wolf, J. Birn, and M. Hesse, Computer experiments on substorm growth and expansion, in *Proceedings of The 5th International Conference on Substorms, St. Petersburg, Russia, 16-20 May 2000 (ESA SP-443)*, edited by A. Wilson, pp. 351-355, European Space Agency, Noordwijk, The Netherlands, 2000.

The central controversy of substorm physics concerns the nature of substorm onset. The Near-Earth X-Line model is based on the idea that the essential violation of the frozen-in-flux condition is the violation is the formation of an X-line about 25 R_E behind the Earth. The Tail-Current Disruption Model is based on the idea that the essential violation of frozen-in-flux occurs about 10 R_E behind the Earth, with the X-line a secondary effect that occurs further from the Earth at a slightly later time. Because of the small number of available spacecraft, timing studies have not yet convincingly resolved the controversy. With the RCM coupled to an equilibrium solver, we can make different assumptions about the violation of frozen-in-flux and derive quantitative consequences. The runs show that, if one assumes that violation of frozen-in-flux is confined to flux tubes that undergo reconnection at an X-line near 25 R_E, then one of two ionospheric phenomena must occur at lower altitudes:

1. Strong meridional electric fields must occur in the nightside auroral zone at substorm onset, with opposite signs on the two sides of the center of the substorm, on field lines that map to geocentric distances between about 10 R_E and 25 R_E.
2. There must be field-aligned potential drops on those field lines, strong enough to decouple rapid motion near the equatorial plane from the ionosphere.

Observers are being encouraged to look for these signatures at substorm expansion onset, but we are not aware of any observations of either signature.

Wolf, R.A., R.W. Spiro, T.W. Garner, and F.R. Toffoletto, Forecasting kilovolt electrons, in *Proceedings of the Chapman Conference on Space Weather*, edited by P. Song, G.L. Siscoe, and H.J. Singer, pp. 313-320, Am. Geophys. Un., Washington, D. C., 2001.

The paper reviewed Rice efforts at predicting fluxes of kilovolt electrons in the magnetosphere for space-weather purposes. The paper summarized results of testing the accuracy of the Magnetospheric Specification Model against geosynchronous particle data and discussed the prospects for improving model performance using data assimilation and by improved first-principles modeling.

Toffoletto, F.R., R.W. Spiro, R.A. Wolf, J. Birn, and M. Hesse, Modeling inner magnetospheric electrodynamics, in *Space Weather, Geophysical Monograph Series Volume 125*, edited by P. Song, H.J. Singer, and G.L. Siscoe, pp. 265-272, Am. Geophys. Un., Washington, D. C., 2001.

This paper displayed results of simulations of the substorm growth phase using the the new coupled RCM/Friction-Code, with the magnetic configuration adjusted for consistency with the evolving plasma. The runs assumed that dayside reconnection added new flux to the tail lobes and examined the consequences for the tail magnetic configuration and plasma sheet. The results were consistent with the main observed features of the growth phase. The tail lobe flux increased with time, B_z in the inner plasma sheet near local midnight decreased, as the field lines became more stretched, and the thickness of the inner plasma sheet decreased. Most of these results had been expected from earlier 2D magnetic-equilibrium calculations of Erickson and Hau, but this was the first time the growth phase was reproduced using full 3D equilibrium calculations that include the departures from MHD due to transport by gradient/curvature drift.

Data from polar-orbiting low-altitude spacecraft has, for many years, indicated that most of the nightside region-1 Birkeland current does not flow on antisunward-flowing boundary-layer field lines but rather on sunward-moving plasma-sheet field lines. This has long been a puzzle for our representation of the plasma sheet using the Rice Convection Model. The classical RCM could produce region-1 currents in the plasma sheet only if we assumed that the entropy invariant pV^γ was significantly higher on the flanks of the tail than near the center (*Yang et al.*, *JGR*, *99*, 223, 1994), but we could never think of any reason why Nature should choose to fill tail flux tubes that way. Runs with the new coupled RCM/Friction-Code, with the magnetic configuration adjusted for consistency with the evolving plasma, seem to resolve the problem. In times of strong convection, flow choking in the near-midnight inner plasma sheet caused the flow of high-pV^{γ} from the distant plasma sheet to divert around the flanks, automatically generating the required cross-tail gradient in pV^{γ}.

Wang, C.-P., L.R. Lyons, M.W. Chen, and R.A. Wolf, Modeling the quiet time inner plasma sheet protons, *J. Geophys. Res.*, *106*, 6161-6178, 2001.

This paper uses an upgraded version of the MSM and a procedure for enforcing force balance along the x-axis to derive a self-consistent model of the magnetotail for conditions of steady weak convection. The results are encouragingly consistent with average observations from a variety of spacecraft. Nearly all of this work was done at UCLA by Larry Lyons' graduate student Chih-Ping Wang (now a post-doc). The Rice contribution was limited to supplying the MSM code with documentation and occasional advice.

Wolf, R.A., F.R. Toffoletto, R.W. Spiro, M. Hesse, and J. Birn, Magnetospheric substorms: An inner-magnetospheric modeling perspective, in *Space Weather Study Using Multipoint Techniques*, edited by L.H. Lyu, pp. 221-229, Elsevier Science Ltd., Oxford, England, 2002.

This paper presented a vision of how ring-current injection results from convection and substorms, along with some supporting evidence from simulations performed with the coupled RCM/Friction-Code. If strong convection is enforced on the magnetotail, and the plasma undergoes only adiabatic gradient, curvature, and ExB drift, the lobe field strengthens, the nightside inner plasma sheet thins, and the flow chokes there. The simulated magnetotail takes a form that looks like the growth phase, but nothing happens that resembles an expansion phase or ring-current injection. We claim that the essence of the expansion phase is the creation of low-$pV^{5/3}$ flux tubes, which dipolarize as in the standard current-wedge picture. These low-$pV^{5/3}$ are the ones that can be injected into the inner magnetosphere to form the ring current.

The paper also compared the typical ion distribution function in the plasma sheet about 15 R_E from Earth with the typical fluxes observed at L = 6.6 and in the storm-time ring current at L = 4, assuming conservation of the isotropic invariant $\lambda = W_K V^{2/3}$, where W_K is the particle kinetic energy. Assuming adiabatic convection of typical plasma-sheet ions from 15 R_E to geosynchronous and L=4 would produce fluxes that are several times higher than those typically observed. This confirmed that some non-adiabatic process, presumably in the substorm expansion phase, reduces the distribution function and $pV^{5/3}$ to allow injection of fresh particles into the ring current.

Heinemann, M., and R.A. Wolf, Relationships of models of the inner magnetosphere to the Rice Convection Model, *J. Geophys. Res.*, *106* (8), 15545-15554, 2001.

Peymirat and others in France have developed a computer model of the inner magnetosphere that resembles the RCM but is not equivalent. Its formulation differs from the RCM in that it works in terms of a fluid velocity (momentum density/mass density), whereas the RCM works in terms of guiding-center-drift velocity. These two velocities are not approximately equal, and the relationship between the two formalisms is remarkably subtle. Building on the work of Heinemann (*JGR*, *104*, 28397, 1999), we have finally sorted the relationship out. The main conclusions are the following:

(i) To make Peymirat's fluid theory consistent with any guiding-center-drift formalism requires the inclusion of a substantial heat flux in the fluid formalism;
(ii) With that addition, Peymirat's theory is equivalent to the RCM if the latter is modified to make the additional assumption that the particles are always in thermal equilibrium, so that the distribution function is always Maxwellian;
(iii) A convection model built on that assumption would be considerably different from the RCM; in a simple test with a Maxwellian blob of plasma injected into a magnetic field with a gradient and assuming no electric field, the RCM predicts that the blob will disperse, with the most energetic particles in the distribution drifting away from the initial location fastest and the less energetic particles drifting more slowly. The density distribution continues to look vaguely gaussian, but with the width increasing linearly with time and the peak density correspondingly decreasing. In the fluid theory (with heat flux), the initial Maxwellian separates into two blobs, one hot and fast-drifting and the other cold and slow-drifting.

We had originally hoped to find a way to adapt ordinary MHD to provide a reasonable representation of the Earth's inner magnetosphere, by modifying the Ohm's law and adding the heat flux. The results of this study suggest that that will be difficult.

The paper also contains a new derivation of the RCM's equations for conservation of particles and energy from the Boltzmann equation.

S. Sazykin, R. A. Wolf, R. W. Spiro, T. I. Gombosi, D. L. De Zeeuw, and M. F. Thomsen, M. F., Interchange instability in the inner magnetosphere associated with geosynchronous particle flux decreases, *Geophys. Res. Lett.*, *28*, 10.1029/2001GL014416, 2002.

The inner magnetosphere was simulated for the magnetic storm of September 25, 1998, running the Rice Convection Model with boundary fluxes estimated from geosynchronous data. Model results indicate development of an interchange-like instability in the dusk-to-midnight sector, producing ripple structures in the plasma density, swirls in the subauroal ionospheric electric field pattern, and undulations near the equatorward edge of the diffuse aurora. We suggest that these disturbances might be observable whenever a strong main-phase ring-current injection is followed by a major, sustained decrease in the plasma energy density at geosynchronous orbit, a circumstance that will also produce rapid decay of the storm-time ring current.

Goldstein, J., R.W. Spiro, P.H. Reiff, R.A. Wolf, B.R. Sandel, J.W. Freeman, and R.L. Lambour, IMF-driven penetration electric field: An explanation for the plasmaspheric shoulder of May 24, 2000, *to be publ. in GRL*, 2001.

This research, which was supported mainly from IMAGE funds but partly by the SECTP grant, proposes an explanation for the "shoulder" feature that appears in EUV images of the plasmasphere in response to a northward turning of the IMF. Simulations run with the Magnetospheric Specification Model, which has an electric field model that imitates typical RCM results, produced a plasmaspheric shoulder very similar to the observed one, when run for the event of May 24, 2000. This agreement between theory and observation confirmed the existence of the overshielding phenomenon. Overshielding (Kelley et al., *GRL*, *6*, 301, 1979) is the name given to the antisunward (backwards) convection that is theoretically expected in the inner magnetosphere after a northward turning of the IMF. Overshielding has long been a feature of RCM simulations. The IMAGE observations also confirmed the RCM prediction that the penetration field is concentrated in the midnight-dawn quadrant.

Theses

Garner, T. W., Doctoral Thesis, "A Case Study of the June 4-5, 1991 Magnetic Storm Using the Rice Convection Model," Ph. D. thesis, Rice University, Houston, Texas, 2000.

This thesis centered on a large number of computer experiment simulations of the major magnetic storm of June 4-5, 1991. The thesis showed how the degree of penetration of magnetospheric electric fields depends on plasma sheet number density and temperature and on different elements of the magnetic field configuration. It showed that, in major-storm conditions, the convection electric field, rather than being shielded out of the inner magnetosphere, can actually be focused into that region. It also showed that the RCM predicts the fast westward flows in at low L that were observed by Rowland and Wygant (*JGR*, *103*, 14959, 1998) and Burke et al. (*JGR*, *103*, 29399, 1998). The ionospheric potential patterns also exhibited Subauroral Plasma Flows (discussed later in this report). Two papers based on the thesis are finally nearing completion.

Work Still in Progress, Continued Under Followon SECTP Grant

Fok, M.-C., T.E. Moore, G.R. Wilson, J.D. Perez, X. Zhang, P. C:son Brandt, D.G. Mitchell, J.-M. Jahn, C.J. Pollock, R.A. Wolf, and E.C. Roelof, Global ENA IMAGE simulations, *Space Sci. Rev.* (submitted), 2002.

This paper reviews comparisons between modeling results and ENA pictures from the IMAGE spacecraft. It was written primarily by Mei-Ching Fok (Goddard). Arguably the most interesting result discussed relates to the asymmetry of the ring current in the main phase of a magnetic storm.

Conventional wisdom in magnetospheric physics has long held that the main-phase ring current peaks near local dusk, for two reasons:

1. Simple convection models (uniform dawn-dusk or Stern-Volland) imply that plasma sheet ions come closest to Earth at local dusk. In the main phase of a storm, of course, the inner edge of the plasma sheet ions is presumably the inner edge of the ions being injected into the ring current.
2. Ground magnetograms show that low-latitude magnetic field on Earth has its maximum depression near local dusk, in the main phase of a storm, suggesting a partial ring current peaked near dusk.

Of course, direct measurements of ring-current asymmetry have generally not been available, since we have rarely had two well-instrumented spacecraft simultaneously in the ring current at different local times.

RCM results have long indicated that the inner edge of the ion plasma sheet is closest to Earth near local midnight, and it is this asymmetry that produces the region-2 Birkeland currents. The dawn-dusk asymmetry in low-latitude magnetograms was explained in RCM terms by the fact that the sum of region-1 and region-2 currents is down on the day side, up on the night side; the current is completed mainly by the eastward and westward electrojets flowing from the day side of the auroral ionosphere to the night side [*Harel et al., JGR, 86*, 2242, 1981; *Crooker and Siscoe, JGR, 86*, 11201, 1981; *Chen et al., JGR, 87*, 6137, 1982].

Results from IMAGE (left panel of Figure 1) indicate that the main phase ring current ion flux typically peaks in the midnight-dawn sector, in dramatic disagreement with conventional wisdom [*C:son Brandt et al.*, subm. to *GRL*, 2002]. Mei-Ching Fok (Goddard) ran the Comprehensive Ring Current Model (CRCM) for the IMAGE-observed magnetic storm of August 12, 2000 and found remarkably good agreement with the IMAGE data. (See right side of Figure 1.) The CRCM uses RCM procedures to calculate Birkeland currents and potentials. The ring current flux calculated by the CRCM peaks between midnight and dawn, because the westward electric fields that inject plasma-sheet ions into the inner magnetosphere peak near local dawn, not near midnight (Figure 2). In other words, the electric field pattern in the inner magnetosphere is twisted eastward relative to that in the outer magnetosphere.

Typical RCM storm simulations exhibit westward injection electric fields that peak in the midnight-dawn sector, and the inner edge of the plasma sheet ions (and thus peak fluxes) typically occur near midnight, or often a bit west of midnight. On the dawn side, equipotentials typically twist toward the east as they approach the Earth, as they do in Figure 2. However, the degree of equipotential twisting varies from run to run, and it is not clear why the CRCM simulation of the August 2000 storm showed greater-than-average twisting, causing the ring current to peak after midnight. We are continuing to investigate this matter. Nevertheless, it is clear that the RCM and CRCM are much more consistent with the striking new IMAGE observations than simple electric field models.

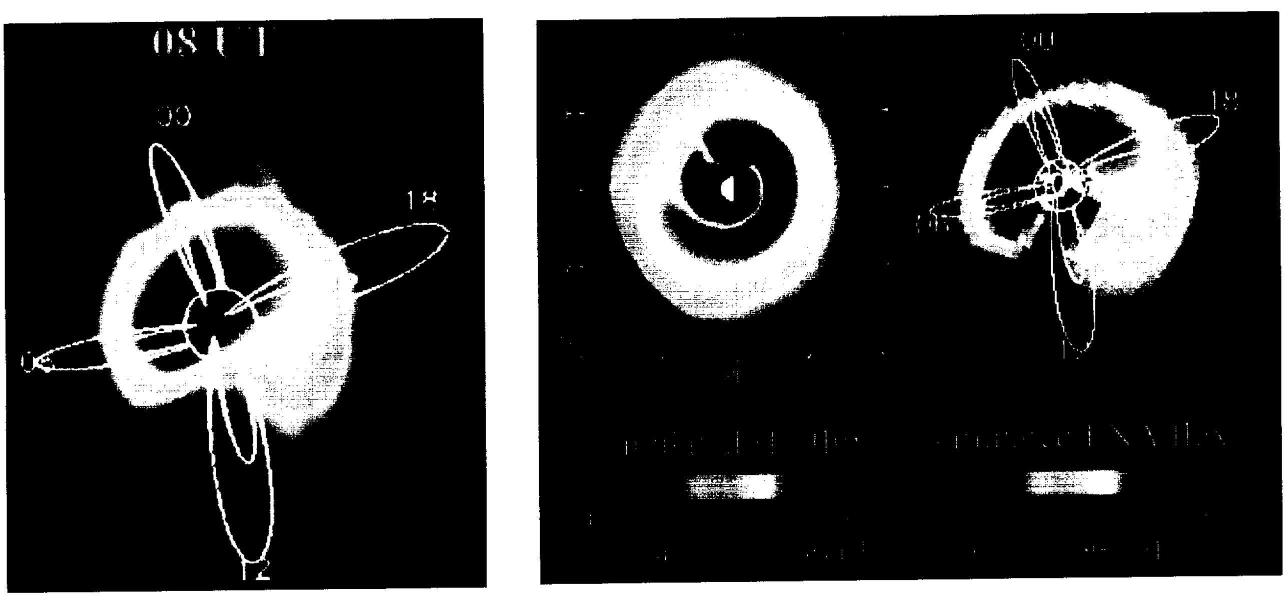

Figure 1. Observations and CRCM model fluxes for 12 August 2000, at the peak of the main phase of a storm. Ring current peaks between midnight and dawn in both observation and model. The middle image shows CRCM calculated H^+ flux in the equatorial plane, while the right diagram shows a simulated ENA image based on the same CRCM configuration. From Fok et al. (submitted to Space Sci. Rev., 2002)

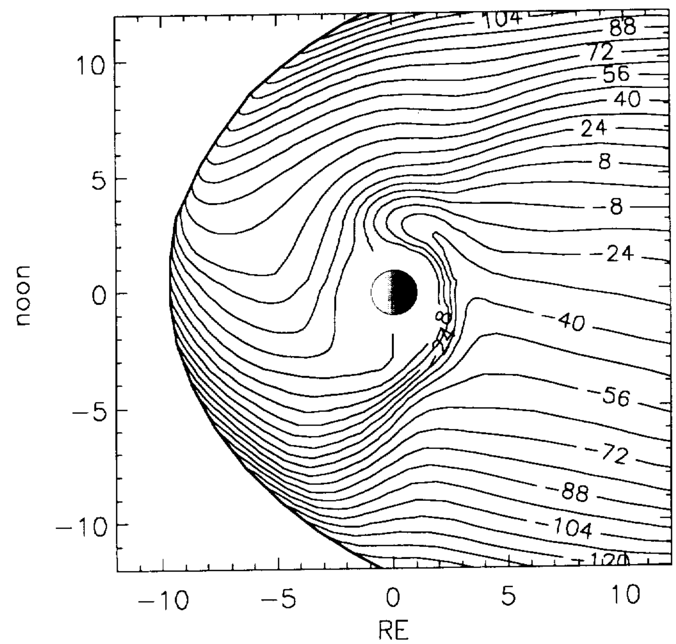

Figure 2. Equipotentials computed by the CRCM, shown in the magnetospheric equatorial plane, with the Sun to the left. This plot shows the convection electric field only. Corotation is included in the calculation, but not in the display. (From Fok et al., submitted to Space Sci. Rev., 2002)

Subauroral Polarization Streams

Recently John Foster has focused attention on streams of plasma that are observed drifting rapidly west, just equatorward of the nightside auroral ionosphere during major magnetic storms (Foster and Burke, submitted to *EOS*, 2002). These features, called Subauroral Polarization Streams (SAPS), are several degrees wide in latitude and seem distinct from the narrower SAID events (SubAuroral Ion Drift) that often accompany substorms.

Magnetic storm simulations with the RCM consistently show SAPS-type features. In Figure 2, a SAPS event is apparent in the closely spaced equipotentials on the night side at $L\sim3$. Stanislav Sazykin and Bob Spiro are using RCM simulations to investigate the detailed physics of these features.

General Comments on RCM Calculations of Subauroral Electric Fields

The plasmaspheric shoulder, the peaking of the main-phase ring current in the midnight-dawn sector, and subauroral plasma streams are all basically consistent with RCM calculations of the inner magnetospheric electric fields. These results, combined with the earlier work of Fejer and Scherliess (*JGR*, *102*, 24047, 1997), which showed convincing agreement between the radar-observed equatorial penetration electric field and RCM predictions, clearly indicate that first-principles calculations of inner magnetospheric electric fields are really working. RCM and CRCM calculations, which self-consistently include effects of magnetospheric pressure gradients and realistic ionospheric conductances, produce more realistic inner-magnetosphere electric fields than simple models. The theory seems to be working!

Modeling Bursty Bulk Flows

Graduate student Shuo Ji is pursuing a modeling effort that was started by Chen and Wolf (1999) and was aimed at computational representation of flow bursts in terms of thin MHD filaments moving through the plasma sheet. Chen and Wolf (1999) showed that rapid earthward motion of the near-equatorial region of a flow-burst flux tube generates an Alfvén wave and slow shock that propagate earthward.

Parks et al. (2001) pointed out that in fast-flow situations, the observed distribution function often shows two or three peaks, very different from the Maxwellian that one would normally associate with an ideal fluid. They properly questioned the applicability of ordinary MHD for describing this kind of situation.

Mr. Ji did a detailed analysis of a simple problem with a cold, collisionless gas in a pipe with one end closed and the other end defined by a piston that moves steadily toward the closed end. This simple problem resembles the flow-burst situation, where the equatorial end of the field line is rushing toward the strong-field region near the Earth. Mr. Ji solved the pipe problem exactly in terms of kinetic theory and also using ordinary MHD as well as double-adiabatic (Chew-Goldberger-Low) MHD. In double-adiabatic MHD, separate energy equations are used to calculate $P_{\parallel}$ and $P_{\perp}$. While the ordinary MHD solution differed substantially from kinetic theory, the double-adiabatic MHD gave a solution that was exactly consistent with kinetic theory.

Encouraged by these results, Mr. Ji developed a double-adiabatic-MHD theory of a thin filament and wrote a numerical code to solve the equations. Initial results indicate that the double-adiabatic filament behaves somewhat differently from the ordinary MHD solutions of Chen and Wolf (1999) in several respects:

1. $P_{\parallel}$ considerably exceeds $P_{\perp}$ in most of the flux tube.
2. The slow shock (a longitudinal wave) travels earthward considerably faster than the Alfvén (transverse) wave, because the latter is slowed down by the pressure anisotropy.
3. After the slow shock reflects from the near-Earth region and propagates again into the tail, a firehose instability develops, crinkling the filament.

Statistical Model of the Plasma Distribution Function in the Plasma Sheet

Post-doc Trevor Garner is developing a statistical model of the plasma sheet, in terms of the equatorial distribution function $f(x, y, \lambda)$, where λ is the isotropic energy invariant, which is related to the particle kinetic energy W_K by

$$W_K = \lambda\left(\int \frac{ds}{B}\right)^{-2/3}$$

The isotropic energy invariant should be well conserved in the presence of strong, elastic pitch-angle scattering, like that provided by chaotic ion motion in the tail plasma sheet. The drift equations imply that $f(x, y, \lambda)$ is constant along a drift path.

Dr. Garner has constructed the statistical model by combining a *Tsyganenko* (1989c) magnetic field model with statistical results from *Borovsky et al.* (*JGR*, *104*, 14613, 1999), *Paterson et al.* (*JGR*, *103*, 11811, 1998), *Christon et al.* (*JGR*, *94*, 13409, 1989; *96*, 1, 1991), and *Korth et al.* (*JGR*, *104*, 25047, 1999).

The distribution function $f(x, y, \lambda)$ is found to decrease earthward through the plasma sheet, in contradiction to the hypothesis of steady earthward convection. The discrepancy cannot be explained in terms of gradient/curvature drift across the tail. This is another manifestation of the pressure balance inconsistency.

One basic objective of this work is a better observation-based model of the plasma sheet, for use as initial and boundary conditions for the RCM and MSM.