Magnetospheric electric fields and plasma sheet injections to low-L shells during the June 4-5, 1991 magnetic storm: Comparison between the Rice Convection Model and observations

T. W. Garner
R. A. Wolf
R. W. Spiro
W. J. Burke
Bela G. Fejer, Utah State University, et al.
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1. Introduction

Geomagnetic storms are periods of strong ring current activity mainly caused by the injection of plasma sheet particles to low L-shells. These injections are caused by an intensification of the solar-wind-driven convection electric field. The convection electric field interacts with the ionosphere and its nonzero impedance to generate electric fields that are significantly more complex than the simple dawn-to-dusk field that is often assumed. In particular, various studies have reported large electric fields equatorward of the auroral oval ([Evans, 1978; Carpenter et al., 1979; Wand and Evans, 1981; Maynard et al., 1983; Rowland and Wygant, 1998; Burke et al., 1998, 2000]. The most intense electric fields are associated with narrow (~1° latitude) strips of rapid, westward \( \mathbf{E} \times \mathbf{B} \) flows [Galperin et al., 1974; Spiro et al., 1979; Anderson et al., 1991; Karlsson et al., 1998], commonly referred to as polarization jets or subauroral ion drift (SAID) events. In addition to these narrow features, broader scale features (~5° wide), called subauroral polarization streams (SAPS), have also been observed in the evening sector of the subauroral ionosphere during geomagnetically disturbed periods [Yeh et al., 1991; Foster and Burke, 2002; Foster and Vo, 2002]. SAPS may...
have important consequences for magnetospheric and ionospheric physics. For example, Liemohn et al. [2002] discussed their relationship to ring current injection, and Foster et al. [2002] have suggested that they play an important role in the formation of plasmaspheric drainage tails and corresponding plumes of enhanced total electron content.

[1] A statistical study of the electric fields in the inner magnetosphere [Rowland and Wygant, 1998] showed that the field strength in the dusk sector increases with increasing L, during periods of weak to moderate geomagnetic activity. However, they found that intensities peak at L ~ 5 during times of high activity. Burke et al. [1998] reported sustained, strong fields at L ~ 4 throughout the 4–5 June 1991 magnetic storm. These strong fields, observed near the magnetospheric equatorial plane, are presumably conjugate to SAPS structures detected in the ionosphere.

[4] This paper compares electric field distributions predicted by the Rice Convection Model (RCM) with observations by the Combined Release Radiation Effects Satellite (CRRES) in the inner magnetosphere and Defense Meteorological Satellite Program (DMSP) satellites in the middle-to-low latitude ionosphere during the magnetic storm of 4–5 June 1991. In RCM calculations, the electric field distribution evolves through a feedback between the plasma sheet particle distributions and the ionospheric impedance [Vasyliunas, 1970]. The electric field distribution in the inner magnetosphere is controlled by ionospheric responses to Birkeland currents. These currents are generated in the magnetosphere by the component of the plasma pressure gradient perpendicular to the gradient of the magnetic flux tube volume. To complete the Birkeland current loop, a horizontal closure current flows across the ionosphere with its finite conductivity. The ionospheric potential distributions produced by this horizontal current are mapped into the magnetosphere along magnetic field lines.

[5] During periods of magnetic activity, the two main large-scale field-aligned current systems, called Region 1 and Region 2, electrically couple the ionosphere to the magnetosphere. The Region 1 currents flow near the high-latitude boundary of auroral precipitation, into and out of the ionosphere on the morningside and eveningside, respectively. Region 2 currents develop in and near the equatorward part of the auroral oval with polarities opposite to the Region 1 currents. Nopper and Carovillano [1978] showed that ionospheric potential patterns needed for Region 1 current closure correspond to two large convection cells, whose sense of rotation is clockwise/counterclockwise in the evening/morning sectors of the northern ionosphere. When mapped out to the magnetic equatorial plane, these potential cells correspond to dawn-to-dusk electric fields in the magnetospheric interior. The potential distribution needed for Region 2 current closure corresponds to convection cells with the opposite sense of rotation. In the magnetospheric equatorial plane, these currents correspond to dusk-to-dawn electric fields Earthward of the Region 2 currents and dawn-to-dusk electric fields further out. The instantaneous electric field in the inner magnetosphere/ionosphere is a superposition of electric fields generated by the two sets of Birkeland currents. The reduction of the total inner-magnetospheric electric field by Region 2 current effects is called “shielding.” When the Region 2 currents are too weak to shield the inner magnetosphere effectively, part of the convection electric field (called the “penetration field”) penetrates into the inner magnetosphere.

[6] During periods of high activity, strong poleward directed electric fields are frequently generated in the evening sector equatorward of the auroral electron boundary and poleward of the inner edge of ion plasma sheet. Plasma sheet ions, which drive most of the Region 2 currents and carry most of the storm-time ring current, commonly follow trajectories that carry them closer to the Earth than plasma sheet electrons, particularly on the dusk side. Particles on these trajectories generate Region 2 currents that flow into the ionosphere equatorward of the auroral oval, a region that on the nightside, has very low conductance. Southwood and Wolf [1978] suggested that polarization jets result from Region 2 currents that flow down into the subauroral duskside ionosphere, causing a strong poleward electric field across the low-conductance region between the downward current and the diffuse aura. Such electric fields have been seen in RCM simulations [e.g., Harel et al., 1981b] of strong convection, but none of the previous simulations depicted a major storm.

[7] Because of this inherent feedback, the dynamics of the ring-current particles must be considered along with the physics that governs the inner-magnetospheric electric field. It is clear that enhanced convection in the storm main phase injects plasma sheet ions into the inner magnetosphere, contributing to the storm-time ring current, but the physical picture is not entirely clear. Lyons and Williams [1980] suggested that the majority of ions that form the storm-time ring current did not come from the plasma sheet during the main phase but rather consist of previously trapped ions that are injected closer to the Earth during the main phase, with the attendant acceleration. Composition is a further complicating factor. Much of the storm-time ring current consists of atomic oxygen ions of ionospheric origin. The upward transport from ionosphere to magnetosphere mainly occurs in the cleft ion fountain, plasma-sheet boundary layer, and central plasma sheet, and the attendant inner-magnetospheric effects can be represented as a boundary condition. It is not clear whether substantial upward transport occurs on inner-plasma-sheet/ring-current field lines. (For a review of ring-current physics, see Daglis et al. [1999].)

[8] This paper centers on quantitative observational tests of self-consistent calculations of the particle distributions and electric field in the inner magnetosphere (the magnetic field is not treated self-consistently). The RCM-calculated inner magnetospheric electric fields and particle distributions reproduce the CRRES and DMSP observations reasonably well. The model results suggest that the injection of plasma sheet particles deep into the inner magnetosphere is largely responsible for generating the storm-time ring current and the subauroral polarization streams in the ionosphere.

2. Overview of the 4–5 June 1991 Magnetic Storm

[9] Figure 1 shows the solar wind speed and density, and Figure 2 shows the IMF conditions during this storm period. While the solar wind reaches speeds of 700 km/s, this storm is characterized by an extremely dense solar wind with a
peak density that is 10 times the average value. A significant increase in the ram pressure occurred about 1600 UT on 4 June, and the IMF $B_z$ turned sharply southward about the same time, initiating strong convection. The IMF turns northward shortly after 1800 UT and remains weak until about 2100 UT when it becomes strongly northward. At 2700 UT (0300 UT on 5 June), the IMF turns southward again until shortly after 3500 UT. A third southward turning occurs near 3800 UT. Each southward turning corresponds to a ring current injection as indicated by the Dst index, which is shown in Figure 3 along with the Kp index, the stand-off distance (calculated by balancing the solar wind ram pressure and the Earth’s dipole magnetic pressure), and the auroral boundary index (ABI). The ABI, which is the latitude of the equatorward edge of the auroral oval at midnight [Gussenhoven et al., 1983], provides a measure of the amount of magnetic flux in the tail [Hilmer and Voigt, 1995]. The storm recovery begins after 4500 UT.

As merits a storm of this strength, several studies of the 4–5 June 1991 storm have been published. These include observational analysis of inner magnetospheric electric fields [Burke et al., 1998], SAID events [Burke et al., 2000], and ion injections into the ring current [Daglis et al., 2000] and modeling studies of the ring current development [Liemohn et al., 2002; Kozyra et al., 2002].

3. Observations

Three Defense Meteorological Satellite Program (DMSP) spacecraft took ionospheric measurements during the storm. These spacecraft, designated as Flights 8 (F8), 9 (F9), and 10 (F10), were in circular, Sun-synchronous polar orbits with an inclination of 97.8°, an altitude of about 840 km, and a period of 100 min. The ascending nodes of F8 and F9 were on the dawnside, while the ascending node of F10 occurred on the duskside. Each spacecraft crossed the polar cap at a different local time; F8 along the 0600–1800 meridian, F9 along 1030–2230, and F10 along 2000–0800.

While there are many different instruments on the DMSP spacecraft, only measurements taken by the ion drift meter (IDM) and the electron spectrometer are used in this study. Use of the electron spectrometer data is limited to determining the equatorward edge of the diffuse aurora. The IDM [Rich and Hairston, 1994] measures the components of the ion velocity perpendicular to the spacecraft velocity vector, from which the electric field $E_k$ can be derived. The indefinite integral $\int E_k ds$ gives the potential along the track, and the difference between the maximum and minimum potentials encountered in either a northern or southern half-orbit provides an estimate for the total potential drop across the polar cap (PCP). Since the spacecraft do not necessarily cross the maximum and minimum potentials, the DMSP-calculated PCP is a lower-limit.

Figure 4 shows the individual values of PCP calculated for each DMSP spacecraft orbit during the 4–5 June 1991 storm. The solid line, an upper envelope of the DMSP values, provides the polar-cap potential drop used as input for the RCM. The scatter in the DMSP-PCP measurements is caused by the sensitivity of the DMSP-calculated PCP to the different ways in which the various spacecraft cross the potential pattern at different times of day. As can be seen in Figure 4, the convection electric field, while fluctuating throughout the storm, increases dramatically around 1300 UT and remains strong through most of 5 June.

Augmenting DMSP, the Combined Release and Radiation Effects satellite (CRRES) provides a large amount of data from 350 km out to an apogee of 6.3 $R_E$ in a nearly equatorial orbit (18.2° inclination). On 4–5 June 1991, the CRRES apogee was in the evening sector, with an orbital period of approximately 10 hours, so only three orbits occurred during this storm.

The electric field instrument (EFI), low-energy plasma analyzer (LEPA), and the magnetospheric ion composition spectrometer (MICS) on CRRES are used in this study. The EFI [Wygant et al., 1992] is a biased, double floating probe with cylindrical and spherical sensors on 100 m tip-to-tip antennas. A bias current flows to nullify...
photoemission currents. The EFI measures the electric field in the Y and Z solar ecliptic coordinates. The third component can be inferred by assuming \( \mathbf{E} \cdot \mathbf{B} = 0 \). The electric field data presented here are spin-averaged over a sampling rate of 32/s using a least squares fit to a sine wave over each satellite rotation. LEPA [Hardy et al., 1993] consisted of two electrostatic analyzers, which measured both the electron and ion fluxes for particles in the 10 eV to 30 keV range. LEPA measurements are used in this study to determine the location of the inner edge of the electron plasma sheet. MICS [Wilken et al., 1992] measured proton, He\(^+\), He\(^{++}\), and O\(^+\) fluxes over an energy range from 1 to 426 keV/e. The MICS particle fluxes are averaged over a pitch angle band that includes all pitch angles under most magnetic conditions. The MICS flux measurements are averaged in 10-min bins.

4. Rice Convection Model

4.1. Model Description

[16] The Rice Convection Model (RCM) self-consistently calculates the inner magnetospheric particle distribution, the Region 2 Birkeland currents, and resulting electric field patterns. Magnetic field variations caused by changes in the Region 2 currents and the particle distribution are not presently calculated, but this treatment is presently being developed. The RCM solves the fundamental equation of magnetospheric-ionosphere coupling [Vasyliunas, 1970; Wolf, 1983]

\[
\nabla_H \cdot \left( \Sigma \mathbf{i}_H \right) = \frac{\sin(I)B_i}{2B_{eq}} \delta_{eq} \cdot \nabla_{eq} \rho \times \nabla_{eq} V,
\]

where \( \nabla_H \) is the horizontal gradient in the ionosphere, \( \Sigma \) is a tensor representing the field-line-integrated ionospheric conductance (one hemisphere), \( \Phi \) is the electric potential in the solar frame with the corotation field removed, \( I \) is the magnetic dip angle, \( B_i \) and \( B_{eq} \) represent the magnetic field strengths in the ionosphere and equatorial plane, \( \delta_{eq} \) is the unit vector of the magnetic field direction in the equatorial plane, \( \rho \) is the pressure, and \( V = \int ds/B \) is the volume of a magnetic flux tube with one unit of magnetic flux.

[17] Assuming strong, elastic pitch-angle scattering, the energy invariant

\[
\lambda = EP^{2/3}
\]

is conserved, where \( E \) is particle energy. The energy spectrum is divided into a discrete set of energy invariants \( \lambda_i \). The number of particles per unit magnetic flux of a given energy invariant \( \lambda_i \) is denoted \( n_i \). Here \( n_i \) is called the

Figure 2. The interplanetary magnetic field measured by the IMP 8 satellite on 4–5 June 1991. The measurements have been time shifted to the magnetopause and are in GSM coordinates. These data were provided courtesy of the NSSDC/OMNIWeb data center (available at http://nssdc.gsfc.nasa.gov/omniweb).
density invariant and is conserved along a drift path, except for the effects of loss:

\[
\frac{\partial}{\partial t} + \mathbf{\bar{v}}_{\text{drift},s} \cdot \nabla \eta_s = -\frac{\eta_s}{\tau_s},
\]

where \(\mathbf{\bar{v}}_{\text{drift},s}\) is bounce-averaged drift velocity and \(\tau_s\) is the loss lifetime. Particle sources are neglected in the runs described in this paper. Ion losses are neglected but effects of electron precipitation are included. The ideal monatomic-gas adiabatic invariant \(pV^{5/3}\) is related to the drift invariants by

\[
pV^{5/3} = \frac{2}{3} \sum_s \lambda_s \eta_s.
\]

The drift velocity is given by

\[
\mathbf{\bar{v}}_{\text{drift},s} = \frac{\mathbf{E} \times \mathbf{B}}{B^2} + \frac{\mathbf{b}_{\text{eq}} \times \mathbf{B} \cdot \mathbf{V}}{q_s B} \nabla V^{\text{surf}}^{-2/3}.
\]

[18] This RCM run includes two chemical species, electrons and singly charged ions. Since \(H^+\) and \(O^+\) ions of given energy drift the same and we are neglecting ion loss, there is no need to keep separate track of \(H^+\) and \(O^+\). The distributions of electrons and ions are each divided into 20 separate energy invariant species.

[19] The code represents the ion population in terms of contours of constant \(\eta_s\). Since \(\eta_s\) is constant along an ion drift path, the contours move at the drift velocity given by equation (5). Each contour is therefore defined by a set of drifting test particles. For each chemical species and each invariant energy level, ten contours levels are used. Nine levels define the initial trapped plasma distribution. The tenth level, representative of the central plasma sheet, is set to correspond with the plasma outer-boundary condition, which is uniform on the boundary and constant in time. This contour-based representation is used because it produces no numerical diffusion and allows a clean separation between particles that were in the original trapped distribution and those that came from the plasma sheet during the storm.

[20] Plasma sheet electrons are considered differently than ions. The electron population is specified in terms of \(\eta_s\) values at grid points rather than a series of test particles. The use of this grid-based representation allows the RCM to incorporate electron loss. Kilovolt electrons have lifetimes of only a few hours, so loss cannot be neglected [Axford, 1969]. As the electron plasma sheet convects Earthward, electron density decreases due to loss. In this RCM run, the electrons are lost by strong pitch-angle scattering, reduced by a factor of 2/3 for high \(Kp\) (greater than 4+) or a factor of 1/3 for lower \(Kp\) [Schumaker et al., 1989].

[21] The electric field has a potential part, which is derived by mapping the ionospheric potential out along magnetic field lines and correcting for the rotation of the Earth. The Earth’s dipole is assumed to be parallel to the rotation axis and perpendicular to the solar wind velocity. Since our model magnetic field changes with time during the storm, the electric field also has an inductive part, which is \(-\mathbf{v}_{\text{map}} \times \mathbf{B}\), where \(\mathbf{v}_{\text{map}}\) is the equatorial velocity of a magnetospheric field line with fixed ionospheric footprint [Fejer et al., 1990; Garner, 2003].

[22] The basic logic of the RCM (shown in Figure 5) is a modification of the Vasyliunas logic loop [Vasyliunas, 1970]. In the RCM logic diagram, rounded boxes designate RCM inputs, while square boxes indicate RCM calculations. The Rice Convection Model has been described in...
4.2. Model Inputs

[23] The basic inputs to the RCM are the initial and boundary plasma distributions, the magnetic field, the background and auroral zone ionospheric conductances, and the potential on the poleward boundary. The total strength of the imposed large-scale convection is given by the polar cap potential drop, and is distributed along the ionospheric poleward boundary as \( \sin(\pi MLT/12) \). For this study, we used the maximum DMSP-calculated potential drop in a given hour (shown in Figure 4). The magnetic field at a given time step is interpolated between Hilmer-Voigt magnetic field models [Hilmer and Voigt, 1995] specified every 15 min according to the calculated standoff distances and the Dst and ABI indices (shown in Figure 3). The dipole tilt is assumed to be zero.

[24] The initial ion distribution is perhaps the most complex input for this run. The preexisting ion population is inferred from MICS observations at different L-shells prior to the storm. The measured differential particle flux \( j \) is converted into the density invariant \( \eta \) by

\[
\eta_j = \frac{\pi \sqrt{8} m_j \left( \lambda_e V^2 \right) V^2 \Delta \lambda_p}{\sqrt{\lambda_j}},
\]

where \( \Delta \lambda \) is the separation between energy invariant channels. A piecewise logarithmic interpolation between the MICS energies is used to specify the fluxes at the RCM energy invariants. The upper bound of the RCM energy invariant range is approximately 100 keV at geosynchronous orbit.

[25] In treating the initial trapped magnetospheric particle distribution, we consider only ions. Of course, electrons must be present in the initial distribution to balance the ion charge, however these electrons are assumed to have sufficiently low energies that they do not contribute significantly to the pressure gradients that drive the Birkeland currents; thus they need not be included explicitly in the RCM.

[26] The plasma sheet population, which enters the model as a boundary condition, is based upon published plasma sheet statistics. Borovsky et al. [1998a] found that plasma sheet conditions (denoted \( ps \)) are related to solar wind (denoted \( sw \)) conditions at the magnetopause. In particular, the number density of ions in the plasma sheet between 17.5 and 22.5 \( R_E \) downtail is given by

\[
n_{ps} = 0.0785 n_{sw}^{0.62},
\]

where the number densities are in \( \text{cm}^{-3} \). The ion temperature is given by

\[
T_{ps} = -3.65 + 0.0190 v_{sw}^{2},
\]

where the plasma sheet temperature is in keV and the solar wind velocity is in kilometers per second. In this run, the plasma distribution \( \eta(\lambda) \) is assumed to be independent of time and position on the tailbound boundary of the RCM. To set this distribution, the boundary plasma moments are set to \( n_e = n_i = 0.148 \text{ cm}^{-3} \), \( T_i = 8.32 \text{ keV} \), and \( p_i = 0.2 \text{ nPa} \) at about 20 \( R_E \). The 8.32 keV value was estimated from equation (7b) and the solar wind velocity measured at 0600 UT on 5 June (630 km/s), during the largest ring current injection. Use of the measured solar wind density (37.6 \( \text{cm}^{-3} \)) leads to a plasma sheet density of 0.74 \( \text{cm}^{-3} \), but that leads to unrealistically high flux levels at geosynchronous orbit. For that reason, we divide the plasma sheet density derived from equation (7a) by five (a rough factor determined from a series of model runs) in setting our outer boundary condition. This is a symptom of the pressure balance inconsistency [e.g., Erickson and Wolf, 1980; Spence et al., 1989; Borovsky et al., 1998b]. Standard magnetic field models imply that the adiabatic quantity \( p V^{5/3} \) decreases Earthward between about 20 \( R_E \) and 6.6 \( R_E \), by processes that are not yet known and are not included in the RCM.

[27] The total electron density in the plasma sheet is set equal to the total ion density. The electron temperature is by \( T_i/T_e = 7.2 \) to agree with Baumjohann et al. [1989]. The density and temperature are converted into an density invariant-energy invariant spectrum using a Kappa function of the order of 6 [Vasyliunas, 1968; Christon et al., 1989, 1991] where the density invariant is given by

\[
\eta(\lambda) = \frac{2}{\sqrt{\pi}} (akT)^{3/2} \Gamma(\kappa + 1) \Gamma(\kappa - 1/2) \left( 1 + \frac{V^2 + \lambda^2}{a k T} \right)^{\kappa + 1/2} n \sqrt{\lambda \Delta \lambda}.
\]
Here, \( m \) is the particle mass, \( k \) is the Boltzmann’s constant, \( \kappa = 6 \) is the exponent of the high energy differential flux, and \( a = \kappa - 1.5 \). The inner edge of the plasma sheet is initially placed so that it just touches the modeling boundary at 1200 MLT and follows a contour of constant flux tube volume; thus the initial inner edge produces no Birkeland current.

[28] The final RCM inputs are the background conductance (produced by solar EUV ionization) and auroral enhancement (produced by particle precipitation). To compute the field-line-integrated background conductance, electron and ion densities and temperatures are taken from the International Reference Ionosphere (IRI) [Bilitza, 1997] and neutral densities from the Mass-Spectrometer Incoherent Scatter (MSIS) [Hedin, 1991] models. The background conductance is assumed not to change during the RCM simulation. In contrast, the auroral conductance changes during the RCM run, reflecting the RCM-computed electron distribution. The auroral conductances are adjusted at each time step to agree with the location and concentration of the electron plasma sheet. The precipitating electron flux is adjusted so that the integral of the electron precipitation flux over the RCM’s magnetic latitude range agrees with the corresponding integral from the Hardy et al. [1985] model at each magnetic local time. Thus the latitudinal distribution of electron precipitation is forced to line up with the computed electron plasma sheet, and the total precipitation rate at each local time is realistic. The conductance algorithms have been discussed in more detail by Suzykin [2000].

5. RCM Results for 4–5 June 1991

5.1. Overview of the Model Electric Field Results

[28] Figures 6, 7, and 8 show the time development of the RCM electric potential (with the corotation potential removed) in the S-M reference frame. One obvious and perhaps surprising feature of these figures is that the shielding is never strong during this event. There is always substantial penetration to the Earth’s equatorial region. The situation is different from past RCM simulations, such as Spiro et al. [1988], where the strong shielding developed.
after steady conditions were maintained for an hour or more. The major differences between these two runs are the model inputs: the plasma sheet pressure, the ionospheric conductance, and the magnetic field. Spiro et al. [1988] set the pressure to balance the lobe pressure at $X \approx -17 R_E$, whereas we have divided central-plasma-sheet pressure by five to produce realistic ion fluxes at geosynchronous orbit (section 4.2). The resultant $p V^{5/3}$ is only a 36% of the value in the Spiro et al. [1988] runs. In addition, the ionospheric conductance was higher in this solar maximum study than in the Spiro et al. [1988] study of solar minimum conditions. In addition, Spiro et al. [1988] used a constant Voigt [1981] magnetic field. This study used time-varying Hilmer and Voigt [1995] magnetic field models. Both changes significantly affect the inner magnetospheric electric field [Garner, 2003]. The electric field is significantly enhanced between $L \sim 3$ and $L \sim 5$ on the dusk side during most of the storm. This enhanced electric field, termed a subauroral polarization stream (SAPS), results from the deep penetration of ions from the plasma sheet [Southwood and Wolf, 1978]. When plasma sheet ions penetrate Earthward of the plasma sheet electrons, a strong electric field is generated in the ionosphere as the Region 2 Birkeland current closes in the low conductivity subauroral ionosphere. The SAPS develops slowly as the inner edges of the ion and electron plasma sheet separate, becoming quite strong late in the storm. The physical reason for the SAPS is essentially the same as suggested by Southwood and Wolf [1978] to explain SAID events. However, in this storm, the ion and electron edges separate more than in quiet times, mainly because the electron inner edge is strongly eroded by precipitation. In any case, it is interesting that the model storm’s strongest equatorial electric fields occur in the inner magnetosphere, far from the driving source of the convection.

5.2. Comparison With Electric Field Observations

[30] The RCM electric field agrees very well with the statistical study of the magnetospheric electric fields by Rowland and Wygant [1998], which examined CRRES-EFI measurements in magnetic local times from 1400 to 0400 and L-values from 2.5 to 8.3 during the January to October 1991 period. Rowland and Wygant [1998] found that the SM-Y component of the electric field is enhanced between

Figure 7. Continued time evolution of the electric potential distribution (same format as Figure 6).
L = 3.5 and L = 5 for moderate and high Kp. This is the magnetospheric signature of the SAPS.

The RCM electric field agrees well with observations from the CRRES-EFI and DMSP-IDM instruments for 4–5 June 1991. The first set of measurements is rather limited but provides a direct comparison between the RCM and the observed electric field. Figure 9 compares the electric field observed by the EFI for the three CRRES orbits during the storm with the RCM electric field. The corotation electric field has been subtracted from the measurements so that it does not dominate the field (especially at low L). The observed (solid line) Y component of the electric field in the geocentric solar ecliptic (GSE) coordinate system is compared with the GSE-Y electric field predicted by the RCM (dashed line). The top panel compares CRRES orbit 765 which occurred near the beginning of the storm. The second and strongest plasma sheet injection begins during orbit 766 (middle panel), while orbit 767 occurred during a steady period between the second and third injections (bottom panel). The RCM does very well in predicting the average dusk electric field along the three CRRES orbits during this storm, although the RCM underpredicts the amount of shielding seen by CRRES during orbit 766 for L < 4. The quasi-static assumption of the RCM and smoothed inputs preclude calculation of the rapid (≤5 min), wave-like variability observed throughout these orbits.

Figures 10, 11, and 12 show comparisons between RCM results and the DMSP-IDM cross-track ion drifts, as well as the orbit-averaged RCM ionospheric potential pattern, for different DMSP orbits during the storm. The spacecraft trajectory is shown across the potential pattern with an arrow indicating the direction and the starting and ending points of the half-orbit at the endpoints of the trajectory. The three DMSP spacecraft observed a total of 151 half-orbits (from the equator, over a pole, and back to the equator) during 4–5 June 1991, but only nine representative half-orbit comparisons are presented here. These half-orbits were chosen to give a good sampling of SAPS observations. In the DMSP data, SAPS are large sunward, cross-track velocities at subauroral latitudes. Typically, they are the lower latitude of two sunward velocity peaks.
Figures 10 through 12 only compare the RCM with data taken by DMSP F8 and F10 because these spacecraft cross the ionosphere in the dusk-dawn sector. F9 crosses the ionosphere on a morning-premidnight line, which is less interesting because the spacecraft moves more nearly parallel to the ion motion. Poleward of the RCM's modeling region, where the field lines map into the solar wind or to the deep magnetotail beyond the RCM's modeling region, the RCM ion drifts are arbitrarily set to zero. The cross-track ion drift is given in a satellite centered coordinate system in which positive drift flows to the left of the satellite track. Thus while all of the SAPS shown in Figures 10–12 are sunward flows, the ion drift may be positive or negative depending upon the direction of the satellite's motion.

Comparisons between RCM results and IDM measurements (taken in the ionosphere at ~800 km) are more subtle than comparisons between the RCM and EFI observations. There are several problems that can result in discrepancy between the observed and predicted ion drifts. First, the RCM cannot predict ion velocity along the magnetic field, only perpendicular to the magnetic field. In calculating the component of the ion drift along the spacecraft orbit, we assume that there are no vertical drifts and the ion drift is driven entirely by an imposed electric field. Another source of discrepancy is the magnetic field model. One of the conclusions in the Burke et al. [1998] paper is that the inner magnetospheric magnetic field during the 4–5 June 1991 storm was more inflated than magnetic field models indicate, invalidating the mapping between the magnetic equator and the ionosphere. This means that the model field line crosses the equatorial plane closer to the Earth than the actual field line and that a given point in the magnetic equatorial plane maps to higher latitudes in the model than it does in reality. An additional discrepancy arises from the boundary potential distribution, which is specified as a sine function on the ionospheric model boundary. The polar cap potential pattern has been observed to rotate in magnetic local time as a function of the solar wind magnetic field [e.g., Boyle et al., 1997]. A minor rotation of the boundary potential pattern would affect the predicted ion drifts by aligning the RCM potential gradient with the satellite track. Despite these problems, the RCM results compare fairly well with the IDM observations.

SAPS features are clearly observed by the DMSP-IDM instrument and well represented by the RCM again confirming the physical mechanism of SAPS formation. In the DMSP half-orbits presented here, SAPS are clearly seen at 2188, 3162, 3656, 4204, and 4370 hours UT. The RCM clearly predicts the occurrence of all but one of the observed SAPS (3162 UT), and that case is questionable (see below). The RCM also usually gets the peak magnitude right within a factor of two, which is remarkable considering that the DMSP drifts may be affected by offset errors and the ionospheric conductance (not self-consistently calculated) may be off by a factor of two.

Figures 10–12 make it clear that the RCM often places its SAPS poleward of the observed SAPS, consistent with use of an underinflated magnetic field model as previously explained by Burke et al. [1998]. As an indication of this under-inflation, we have indicated the location of the equatorward edge of the diffuse auroral oval as observed by the DMSP-F8 spacecraft (shown as a black line) and as predicted by the RCM (grey line). Note that the predicted SAPS is at the correct physical location (i.e., just equatorward of the electron aurora). Note also that the small predicted RCM peak at about 3158 UT (Figure 11) should perhaps be interpreted as a weak SAPS, since it lies just equatorward of the auroral boundary.

### 5.3. Overview of the Plasma Sheet Injection

Figure 13 shows the location of the inner edge of the ion plasma sheet at the three Dst minimums (corresponding to three plasma sheet injections) on 4 and 5 June: 2100 UT, 3130 UT, and 4330 UT. For comparison, the location of the test particles that began at \( L = 3.62 \) are also shown. Three different energy invariants are shown to demonstrate the thickness of the plasma sheet edge. The three rows correspond to ions with energy invariants of 819, 1803, and 2346 \( \mathrm{eV} (R/nT)^{2/3} \). These energy invariants correspond to different energies at different locations in the magnetosphere and under different magnetic field conditions. Table 1 shows the \( L \)-values of the inner edges for these three energy invariants, at the end of the first and third injections.

Figure 13 demonstrates three important aspects of the storm-time ring current development:
Figure 10. Comparison between the observed (+) and predicted (solid line) ion drifts measured perpendicular to the DMSP orbit after the first injection. Also shown is the orbit-averaged potential distribution in the ionosphere and the path of the spacecraft (the arrow indicates the direction of the orbit) across the ionosphere. Negative potentials are shown with dashed lines, while positive potentials are shown with solid lines. Poleward of the RCM modeling region, the RCM ion drifts are set to zero. The location of the equatorward edge of the diffuse aurora as observed by F8 (black line) and predicted by the RCM (gray line) are shown to indicate the level of magnetic field inflation. In the lower left-hand panel, the grey and black lines overlap.
1. The prestorm ring current particles get swept out of the magnetosphere through the dayside magnetopause very early in the storm. Through most of the main phase, the model ring current was composed almost entirely of fresh particles from the plasma sheet.

2. The plasma sheet ions convect far enough Earthward (to \( L = 2.8 \)) at appropriate energies \((E \sim 50–100 \text{ keV})\) to explain most of the storm-time ring current. However, the model presently does not include ionospheric upwelling, which may be a significant source of the storm-time ring current particles. Our results suggest that the Lyons and Williams [1980] hypothesis is not applicable to the 4–5 June 1991 storm but may be more applicable for weaker or single-injection storms. In addition, these results

Figure 11. Comparison between the ion drifts measured perpendicular to the DMSP orbit and those calculated by the RCM near the second injection. The format is the same as Figure 10.
indicate that large-scale convection is capable of injecting plasma sheet particles into the ring current without substorm injections. However, these results overpredict the ion fluxes at ring current locations (see below) which may be a symptom of the pressure-balance inconsistency. Substorm particle injection is a suggested solution to the pressure-balance inconsistency.

Finally, Figure 13 confirms conventional wisdom [e.g., Liemohn et al., 2001] concerning the symmetry of the ring current. Specifically, the ring current is highly asym-
metric in the first injection but more nearly symmetric by the third injection. However, the early-main-phase asymmetry is better described as a night-day asymmetry than a dusk-dawn asymmetry, in rough agreement with the IMAGE observations of C. Son Brandt et al. [2002].

5.4. Comparison Between the RCM Fluxes and Observations

[41] Since the inner magnetospheric electric field is sensitive to the location and magnitude of the pressure gradients, and hence the ion particle distribution, it is important to compare model fluxes with observations. During the 4–5 June 1991 storm, the CRRES spacecraft crossed $L = 5$ and $L = 4$ nine different times, providing a view of the development of the storm-time ring current. Figure 14 compares the RCM-calculated fluxes with observations from the MICS instrument onboard CRRES at $L = 5$, while Figure 15 compares the RCM fluxes with MICS observations at $L = 4$.

[42] The RCM fluxes early in the simulation (top rows of Figures 14 and 15) agree reasonably well with the observed fluxes, probably because most particles have been on

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**Figure 13.** Locations of the test particle contour for three different energy invariants at each $Dst$ minimum in the 4–5 June 1991 storm. In each case, the inner contour corresponds to particles that began the storm at $L = 3.62$, while the outer contour is the inner edge of the ion plasma sheet.
trapped orbits since the beginning of the run, when the initial condition was set to ensure that the model fluxes agreed with observations. Fluxes of $1 \rightarrow 100$ keV$^+$ particles increased during the main phase, in both the model and the observations, but the model fluxes increased considerably more, in the regions where fresh plasma sheet particles are present. The computed electric fields are clearly sufficient to inject a storm-time ring current. The problem is that the RCM predicts fluxes that are considerably higher than the observed fluxes, by an order of magnitude at some locations and energies.

43 A number of shortcomings in this RCM run probably contribute to this quantitative discrepancy:

44 1. This run does not include ion loss by charge exchange or precipitation.

45 2. In converting from the density invariant to flux, we have assumed that all ions are protons, which is undoubtedly incorrect [Lennartsson, 1989]. Assuming that all of the ions were $O^+$ would reduce predicted fluxes by a factor of four, eliminating much of the discrepancy. The study highlights the need for a more realistic ring current composition.

46 3. As discussed by Burke et al. [1998] and in section 5.2 above, there is considerable evidence that the real magnetic field was considerably more inflated than the Hilmer-Voigt model. In a region where fresh plasma sheet ions are present in the model storm-time ring current, overestimating the magnetic field leads to underestimated flux-tube volume, and overestimating particle energy (equation (2)) and flux (equation (6)).

47 4. The edge-based version of the RCM was used for these runs, because it tracks the motions of particles precisely, without numerical diffusion. It has the limitation that the plasma boundary condition must be held constant in both space and time. The actual particle distribution in the plasma sheet undoubtedly varies substantially with both position and time [e.g., Paterson et al., 1998; Borovsky et al., 1998a, 1998b]. Because of the interchange instability, lightly populated flux tubes (bubbles) systematically make their way Earthward, while heavily populated tubes (blobs) stay further out from Earth. This physical tendency toward stratification, which reduces fluxes in the inner region, is not included in these RCM runs. (For a discussion of a simple example of ring-current interchange, see Sazykin et al. [2002].)

5. The RCM does not include ion upflow from the ionosphere within the modeling region. Of course, correcting that deficiency would increase RCM-predicted fluxes and thus increase the discrepancy.

Efforts are underway to correct deficiencies 1–4.

5.5. Inner Edge of the Electron Plasma Sheet Comparison

56 In addition to predicting the ion fluxes, it is also useful to compare the observed location of the inner edge of the electron plasma sheet with the values predicted by the RCM. Burke et al. [1998] discussed in detail the observations of the inner edge of the electron plasma sheet. We compare the inner edge locations rather than the electron fluxes since the electron fluxes are strongly affected by the input precipitation model. Figure 16 compares the location of the electron inner edge observed in the magnetosphere by CRRES (top panel) and in the ionosphere by DMSP-F8 (bottom panel) with the location predicted by the RCM. These comparisons are made at the magnetic local time of the CRRES satellite and the longitude of the DMSP-F8 spacecraft, respectively. In general, the RCM agrees well with the CRRES observations late in the storm and the DMSP-F8 observations early in the storm. Later in the storm, the RCM predicts a more poleward location for electron inner edge than is observed by DMSP. Since the RCM’s predicted location agrees well with the CRRES observations, the discrepancy between the RCM prediction and the DMSP observation is further evidence of an underinflated magnetic field model, as discussed above and noted by Burke et al. [1998].

6. Conclusions

51 This paper reports the most complete case study done to date of a magnetic storm using the Rice Convection Model. The picture of the 4–5 June 1991 magnetic storm thus developed begins with strong convection rapidly driving the plasma sheet Earthward. In the process, the Region 2 current system becomes stronger and moves equatorward. As it does so, the inner magnetospheric electric field is weakened Earthward of the Region 2 currents (i.e., Earthward of the inner edge of the ion plasma sheet). However, the Region 2 currents never become strong enough to fully shield the lowest $L$ shells from the convection electric field. As convection drives the ion plasma sheet Earthward of the electron plasma sheet (or equally, the Region 2 currents equatorward of the diffuse electron aurora), subauroral polarization streams develop. The plasma sheet ions are driven deep into the ring current (where they reach $L \sim 3$).

52 This study suggests that SAPS are generated by the penetration of the ion plasma sheet Earthward of the electron plasma sheet. The RCM predicts the duskside penetration of plasma sheet ions Earthward of the electron plasma sheet. These predictions agree well with CRRES observations of the ion and electron plasma sheet locations. Additionally, the RCM predicts both the location and the approximate magnitude of electric field peaks seen by CRRES. The electric field peak observed by CRRES in $L = 4$ region is the magnetospheric signature of a SAPS. Furthermore, the observed by the equatorward of the diffuse aurora are correctly predicted by the model.
Figure 14. A comparison of RCM-predicted fluxes (solid line) to proton fluxes observed (+) by the CRRES-MICS instrument for the nine periods when CRRES was near $L = 5$ on 4–5 June 1991.
Figure 15. A comparison of RCM-predicted fluxes (solid line) to proton fluxes observed (+) by the CRRES-MICS instrument for the nine periods when CRRES was near $L = 4$ on 4–5 June 1991.
These results indicate that strong storm-time electric fields can inject plasma-sheet particles inside $L = 3$. The RCM-predicted ion fluxes, however, are higher than MICS observations, sometimes by as much as a factor of 10. We attribute this discrepancy partly to our assumption that all ions are protons in calculating particle fluxes, partly to our neglect of ion charge exchange and precipitation, and partly to bubbling/interchange effects that are not yet included in the model.

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W. J. Burke, Air Force Research Laboratory, 29 Randolph Road, Hanscom AFB, MA 01731-3010, USA. (burke@phl.af.mil)

B. G. Fejer, Center for Atmospheric and Space Sciences, Utah State University, Logan, UT 84322-4405, USA. (bfjejer@cc.usu.edu)

T. W. Garner, Center for Ionospheric Research, Applied Physics Laboratory, University of Texas, 10000 Burnet Road, F0252, Austin, TX 78758-4423, USA. (garner@arl.utexas.edu)

M. R. Hairston, Center for Space Science, University of Texas at Dallas, P.O. Box 830685 F022, Richardson, TX 75083-0685, USA. (hairston@utdallas.edu)

J. L. Roeder, Aerospace Corporation, Mail Stop MS2-260, P. O. Box 92957, Los Angeles, CA 90009-2957, USA. (james.l.roeder@aero.org)

S. Sazykin, R. W. Spiro, and R. A. Wolf, Rice Space Institute, Department of Physics and Astronomy, Rice University, 6100 S. Main, MS-108, Houston, TX 77005, USA. (sazykin@rice.edu; spiro@rice.edu; rawolf@rice.edu)