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Tutorial Lecture

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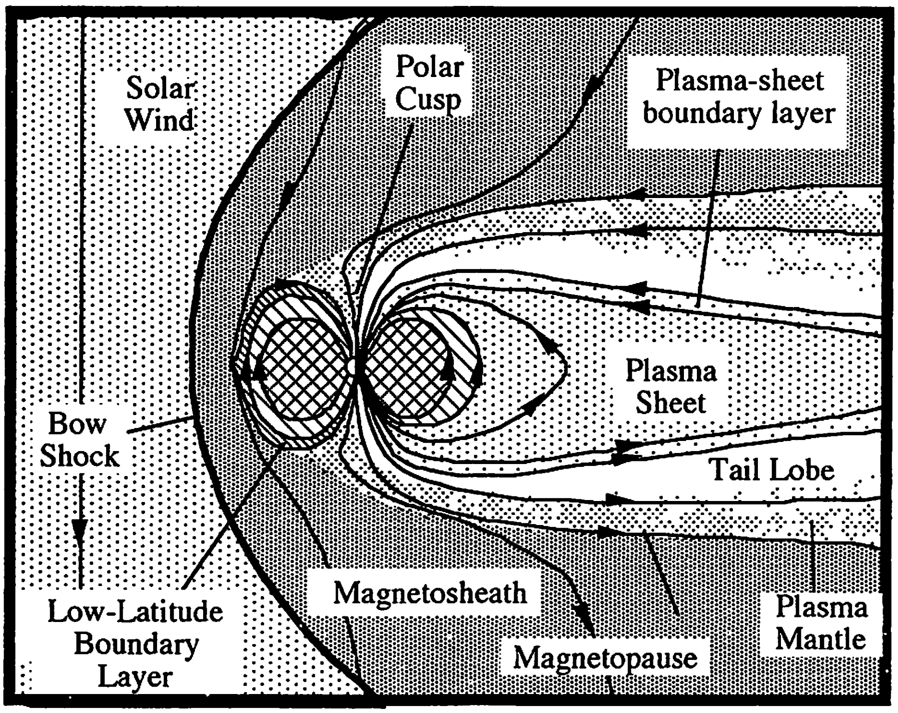
Use of Magnetospheric Models to Represent Space Weather and Provide Inputs to Ionosphere/Thermosphere Models

Use of Magnetospheric Models to Represent Space Weather and Provide Inputs to Ionosphere/Thermosphere Models

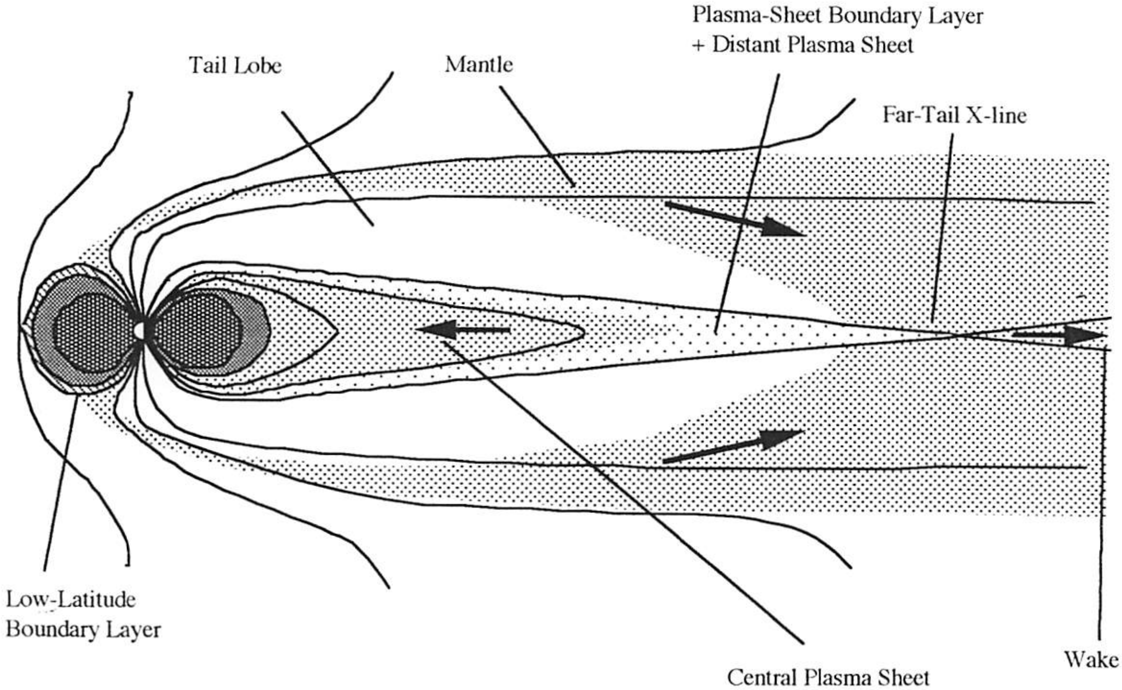
- Introduction/Outline
- How the Magnetosphere Works
- Space Weather: Operational Needs
  - Magnetospheric Conditions
  - Input to Ionosphere/Thermosphere
- Space Weather: Present Capabilities
  - List of Existing Operational Magnetospheric Models
  - Magnetospheric Specification and Forecast Model
    - Relationship to RCM, MSM
    - Objectives, modeling region, basic equations
    - B-field model
    - E-field model – How it works, How well it works, Other models
    - Initial & boundary conditions, loss algorithms...
    - Precipitation model – How it works, How well it works, Other models
    - Simulation of Ring-Current Injection
    - How Accurately Does MSFM Calculate Magnetospheric Fluxes?
    - Plasmasphere simulation
- Next-Generation Operational Magnetospheric Models?
- Concluding Comments

How the Magnetosphere Works: Coupling to the Solar Wind



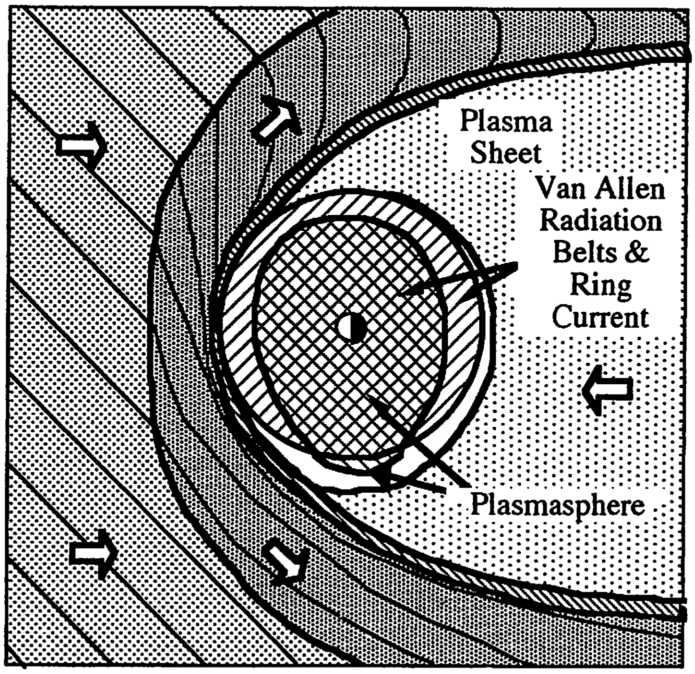
- In ideal MHD, no transport of particles, shear stress,energy, magnetic flux, or electric field through magnetopause.
- Actual transport efficiencies:
  - ~0.4% for capturing solar wind ions into plasma sheet
  - ~3% of energy
  - ~20% of magnetic flux
  - ~20% of solar-wind electric field

Coupling to the Solar Wind



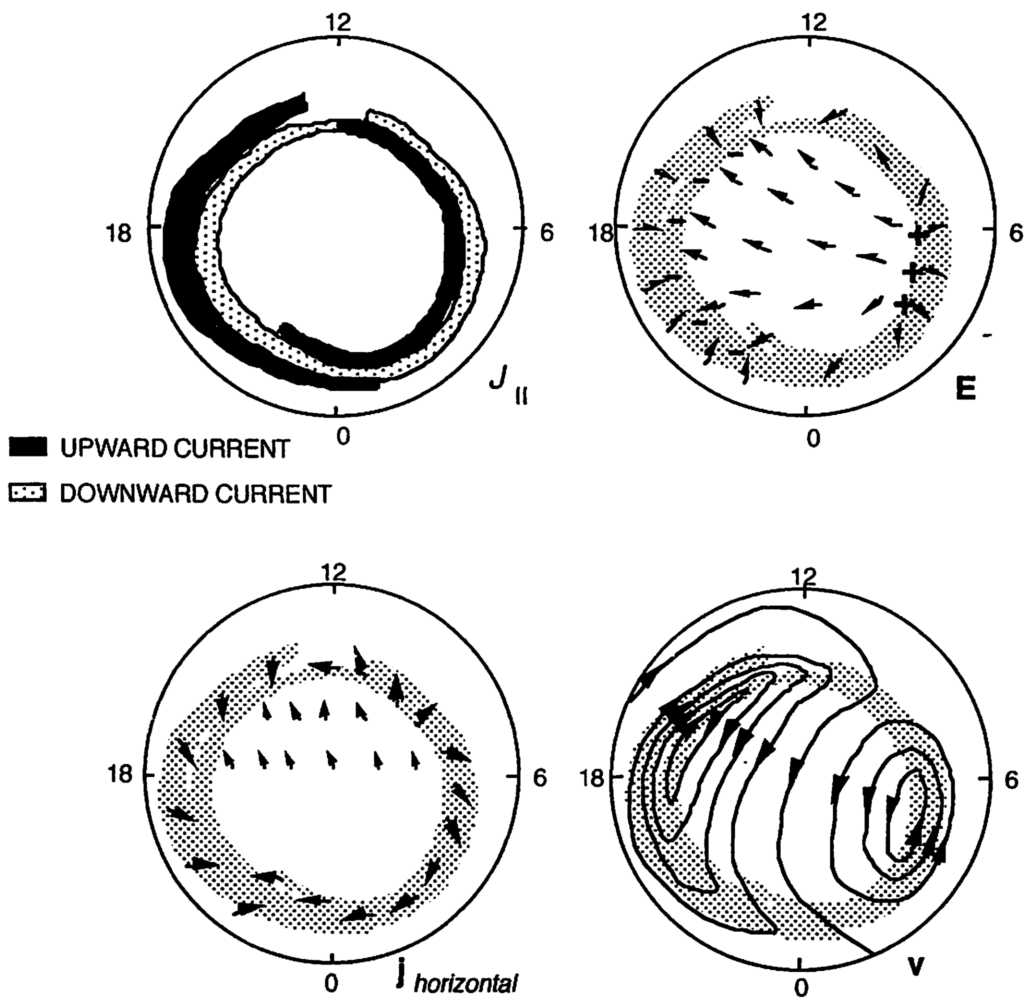
- Primary transport mechanism is magnetic reconnection.
- Coupling correlates strongly with southward component of interplanetary magnetic field. (Polar-cap potential drop, magnetic indices...)
- Particles enter magnetosphere directly in polar cusp.
- Polar-cap electric field pattern correlates strongly with *y*-component of interplanetary magnetic field.
- Lots of empirical information on magnetopause reconnection.
- Lots of confusion on how reconnection occurs in the tail.

Internal Magnetospheric Processes



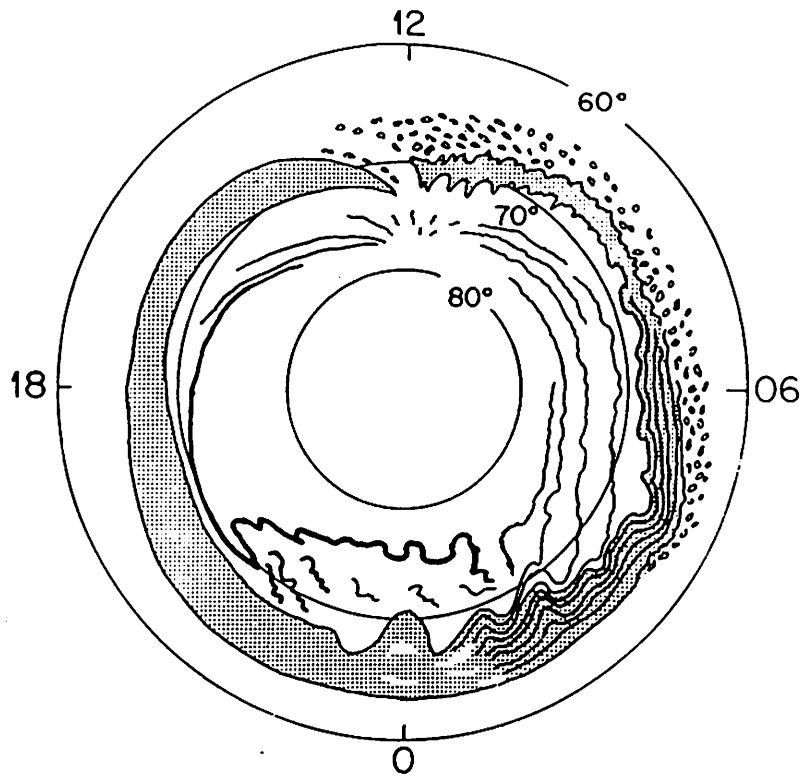
- Sunward convection through the plasma sheet.
- Plasma sheet maps to most of auroral zone.
- Substorms, which are sort of like bursts of convection, disrupt the plasma sheet, auroral ionosphere, and geosynchronous-orbit region.
- In magnetic storms, fresh ions are injected from the plasma sheet into the trapped-particle region near the Earth, to form the storm-time ring current.

Coupling to Ionosphere/Thermosphere – Electrodynamics



- Polar cap (connected to open field lines) convects antisunward. Complicated for northward IMF.
- Auroral zone convects sunward.

Coupling to Ionosphere/Thermosphere – Particle Transport



(From Akasofu, in *Physics of Auroral Arc Formation*)

- Auroral particle precipitation – mostly keV electrons.
  - Highly structured discrete aurora
  - Less dramatically structured diffuse aurora
- Upward magnetic-field-aligned electric fields accelerate electrons down to form bright features.
- Upward $E_{\parallel}$ also causes upflowing keV ions.
- Ion precipitation slower, less structured.

Space Weather: Operational Needs – Magnetosphere

- Outer-belt MeV electrons
  - Kill spacecraft by deep dielectric charging
  - Highly variable
  - Consistent observational relationship to high-speed streams near solar minimum.
  - Decrease in main phase of storm
  - Increase ~ 2 days after peak of storm
  - Very little is understood about the dynamics of these particles.
- Spacecraft surface charging
  - Due mainly to > 10 keV electrons
  - Important at synchronous orbit and earthward of that.
  - This is what the Magnetospheric Specification Model was primarily aimed at.
- Magnetopause location
  - Spacecraft operators need to know if they are in the magnetosheath.
- Radiation dose

Inputs to Ionosphere and Thermosphere Space-Weather Models

- High-latitude electric field pattern
- Precipitating particle fluxes.
- Basic questions:
  - Can index-driven statistical potential and precipitation patterns be made consistent with each other?
  - For specification, are magnetospheric models "ever" likely to outperform the observation-driven AIMIE approach to specifying electric fields and precipitation patterns?
  - For forecasts, can magnetospheric models predict patterns more accurately than index-driven statistical **E**-fields and precipitation patterns?
- Low-latitude ionospheric electric fields:
  - Observations are complex and sparse.
  - AIMIE approach hasn't been applied to this problem yet.
  - Three driving mechanisms:
    - Winds driven by solar heating
    - Winds driven by magnetospheric inputs at high latitudes
    - Prompt penetration of magnetospheric heating and **E** at high latitudes.
  - Quantitative understanding of dynamics will require coupled magnetosphere/ionosphere/thermosphere models
    - Can't trivialize magnetosphere, ionosphere, or thermosphere and represent the dynamics of low-latitude E correctly.

Space Weather: Present Capabilities – Operational Magnetospheric Models

- Radiation belts
  - NASA statistical models
  - Koons-Gorney neural-network model
    (> 3 MeV geosynchronous electrons)
    (part of MSM)
  - CRRES statistical models
    - CRRESRAD – dose rate
    - CRRESPRO – 1-100 MeV protons
    - CRRESEL – 0.5 - 7 MeV electrons
- Magnetosheath
  - (Gasdynamic Convected Field Model)
- Magnetospheric Specification Model

RCM, MSM, and MSFM

- Rice Convection Model (RCM)
  - Longstanding basic research model of inner and middle magnetosphere.
  - Calculates Birkeland currents, ionospheric electric fields, magnetospheric particle populations by solving partial differential equations.
- Magnetospheric Specification Model (MSM)
  - U. S. Air Force effort.
  - Scaled-down version of RCM. Does not calculate Birkeland currents. Uses data-adjusted fitting formula for E-field. Calculates particle distributions in detail.
  - Development started 1987.
  - First version delivered 1990.
  - Most recent update delivered Fall 1994.
  - Became fully operational at 50th Weather Squadron, Falcon AFB in early 1996.
- Magnetospheric Specification and Forecast Model (MSFM)
  - Adds neural networks for forecasting main MSM driving parameters from solar-wind parameters and also correction procedures
  - Development started 1991.
  - First version delivered 1994.
  - Transition process about to start.

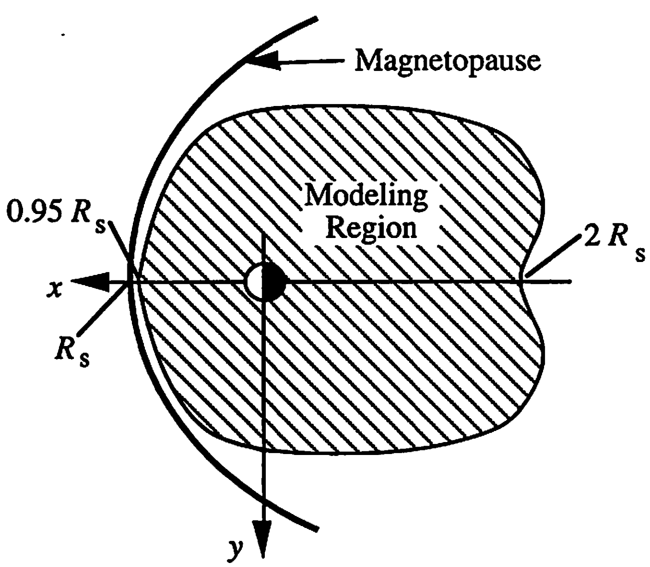
Magnetospheric Specification and Forecast Model – Contributors

- Rice
  - J. Freeman (PI), Bob Spiro, B. Bales, D. Brown, K. Braaten, A. Chan, K. Costello, B. Hausman, J. Williams
- Phillips Lab
  - W. Denig, D. Hardy, M. Heinemann, R. Hilmer, R. Lambour, N. Maynard (now at MRC), F. Rich
- Los Alamos
  - R. Belian, T. Cayton, D. McComas, M. Thomsen
- Computational Physics
  - J. Bishop
- University of Texas at Dallas
  - R. Heelis, M. Hairston
- Le Tourneau University
  - G. Andrews

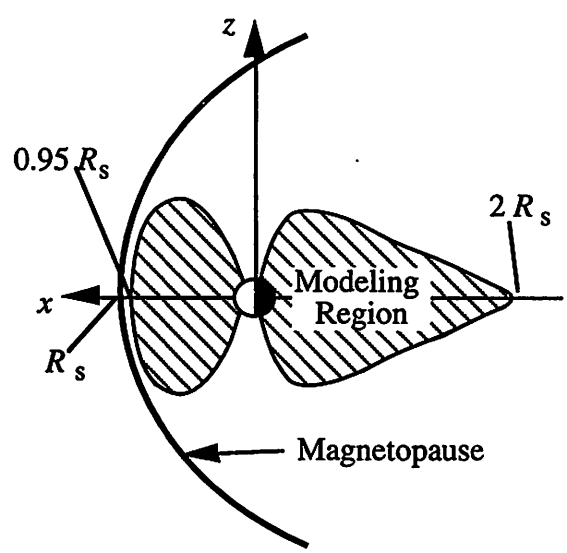
MSFM Objectives and Modeling Region

- Objective
  - To provide specifications and short-term forecasts of:
    - Magnetospheric particle fluxes (~100 eV to ~ 100 keV).
    - Precipitating electron fluxes
    - Ionospheric electric fields
    - Magnetospheric magnetic fields

- Modeling Region



Equatorial Plane

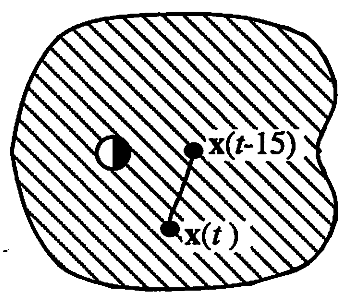


Noon-Midnight Meridian Plane

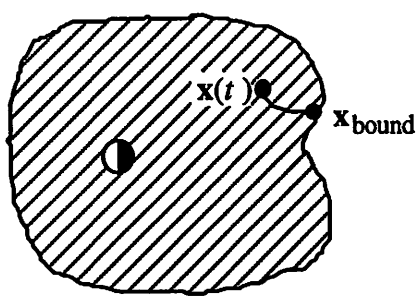
MSFM Basic Equations

- General Idea:
  - Use state-of-the-art **E** and **B** models to follow drifting particles backwards in time to initial or boundary condition.

particles/unit flux



$$\eta_s\left(\mathbf{x}(t), t\right) = \eta_s\left(\mathbf{x}(t-15\ \mathrm{mn}), t-15\ \mathrm{mn}\right) - \int_{t-15\ \mathrm{mn}}^{t} L_s\left(\mathbf{x}(t'), t'\right) dt'$$



$$\eta_s\left(\mathbf{x}, t\right) = \eta_s\left(\mathbf{x}_{\mathrm{bound}}, t_{\mathrm{bound}}\right) - \int_{t_{bound}}^{t} L_s\left(\mathbf{x}(t'), t'\right) dt'$$

loss rate

Assume isotropic pitch angles

$$\mathbf{v}_s = \frac{\mathbf{B} \times \nabla\left[V + \frac{\lambda_s}{q_s}\left(\int ds / B\right)^{-2/3}\right]}{B^2}$$

Particle energy Energy invariant

$$W_s = \lambda_s\left(\int ds / B\right)^{-2/3}$$

Hilmer-Voigt **B**-Field Model

(Hilmer and Voigt, *JGR*, *100*, 5613, 1995)

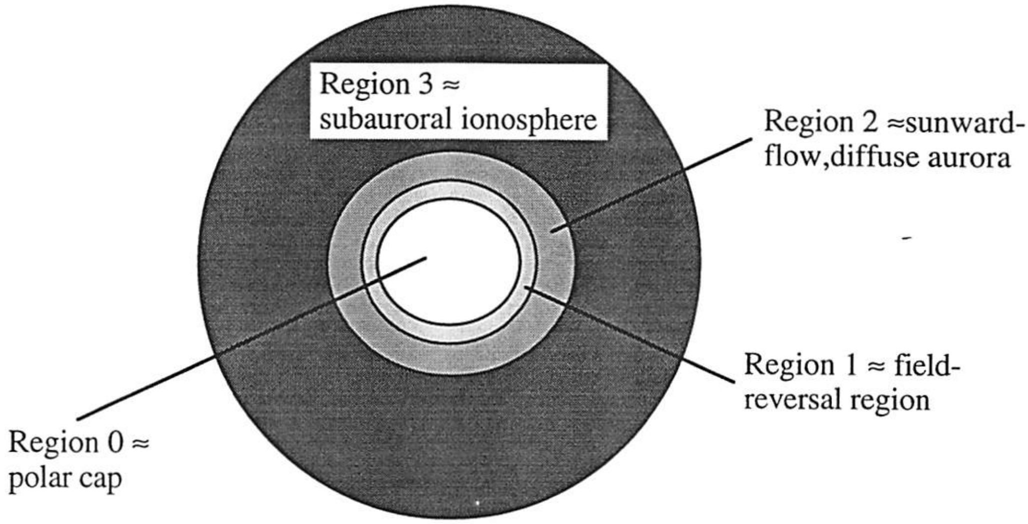
Magnetopause current	Cylinder with spherical cap
Ring current	Blended
Tail current	Generalized Tsyganenko type

- Built to respond to several different real-time inputs
- B-fields are pre-computed. Mapping information is stored.
- **Inputs:**

Standoff distance	Estimated from ρv_{sw}^2 or *Kp*
Dst	Low-latitude magnetograms
Auroral boundary index	Data from DMSP J/4 instrument and Gussenhoven algorithm. A mapping requirement is enforced at the plasma-sheet inner edge..
Collapse parameter*	Geosynchronous particle fluxes
Tilt	Not used in MSFM.

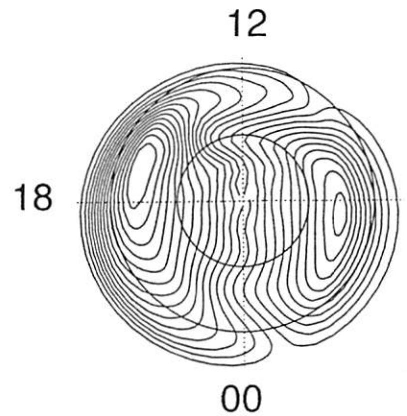
* MSFM only

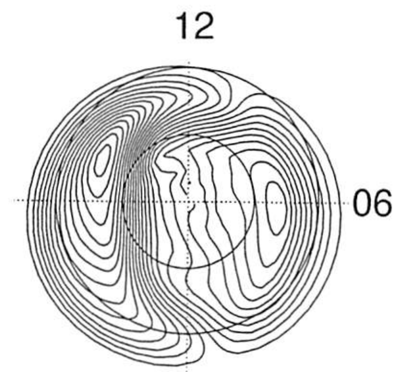
Electric-Field Model



- Region 0: Heppner-Maynard patterns for southward IMF, scaled for size and potential drop. Pattern type estimated from DMSP (UTD alg.)
- Region 3: Penetration driven by rate of change of auroral boundary index.
- Region 2: Analytic formula for classic sunward convection, Harang discontinuity; merges smoothly to subauroral region.
- Region 1: Power-law in latitude – smoothly joins regions 0 and 2.

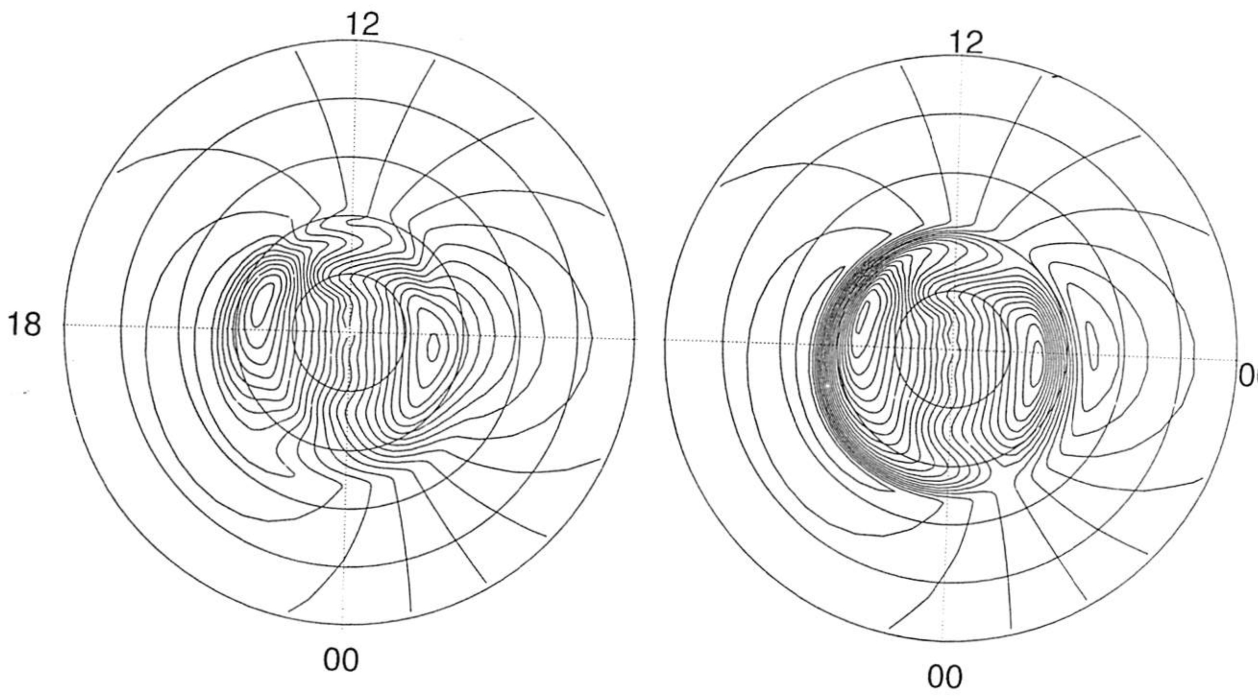
Sample MSFM Equipotential Patterns





- Three Heppner-Maynard pattern types, no penetration.

Sample MSFM Equipotential Patterns

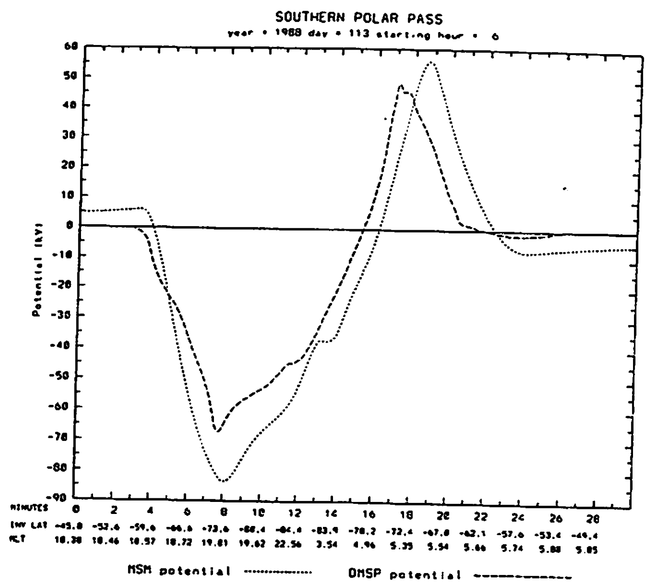


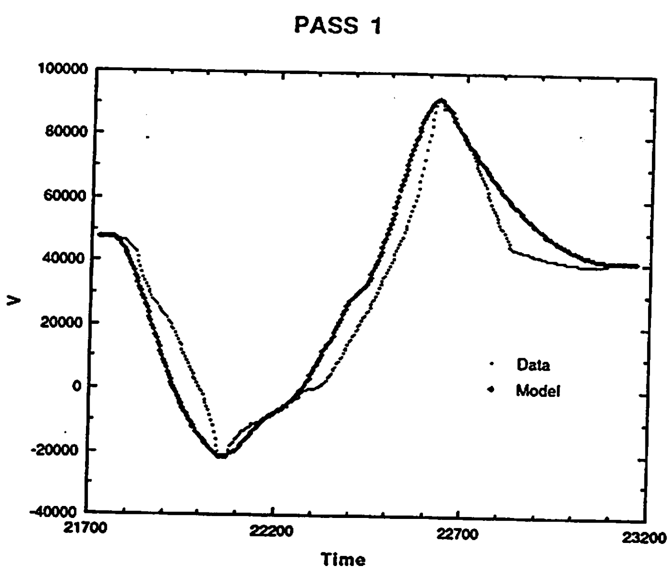
- Penetration pattern for increasing convection, decreasing convection.

E-Field Model –
MSFM Correction Machinery*

- If DMSP ion-drift-meter data are available, the ionospheric potential pattern is adjusted to ensure model correctness on
  - total potential drop
  - potential drop across dawn and dusk-side sunward flow regions
  - locations of field reversals

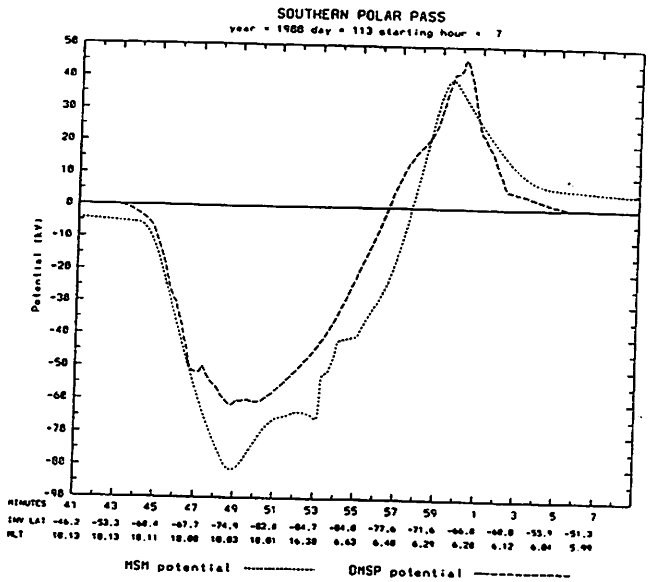
MSFM Ionospheric Electric Fields – How Good Are They?

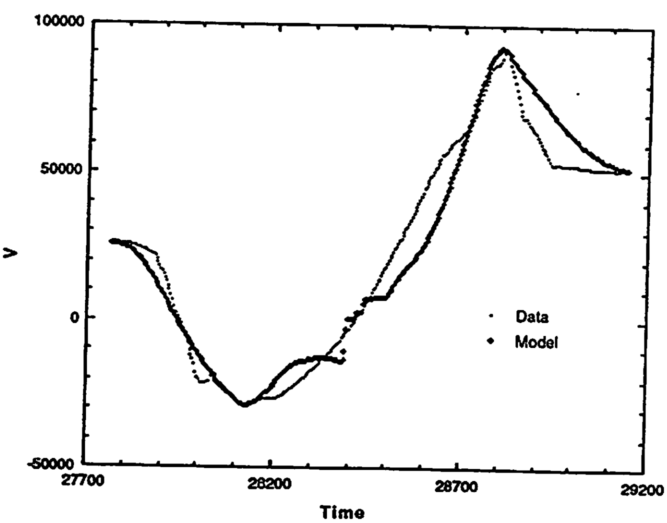




Comparison with DMSP data for pass starting 6:00UT on day 113, 1988. Only total potential drop and pattern type were used as input for top panel. Full corrections were applied to bottom panel.

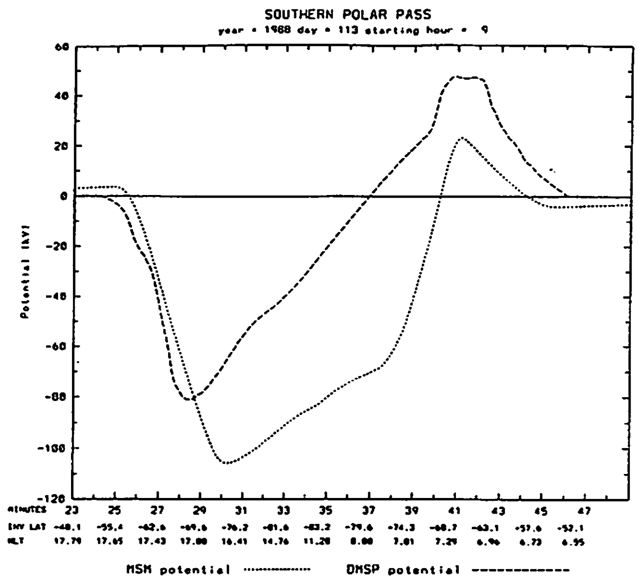
MSFM Ionospheric Electric Fields – How Good Are They?

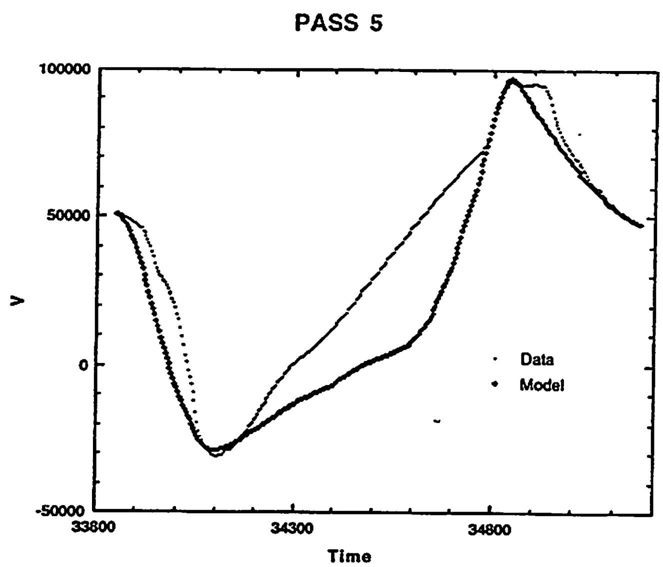




Comparison with DMSP data for pass starting 0740 UT on day 113, 1988. Only total potential drop and pattern type were used as input for top panel. Full corrections were applied to bottom panel.

MSFM Ionospheric Electric Fields – How Good Are They?

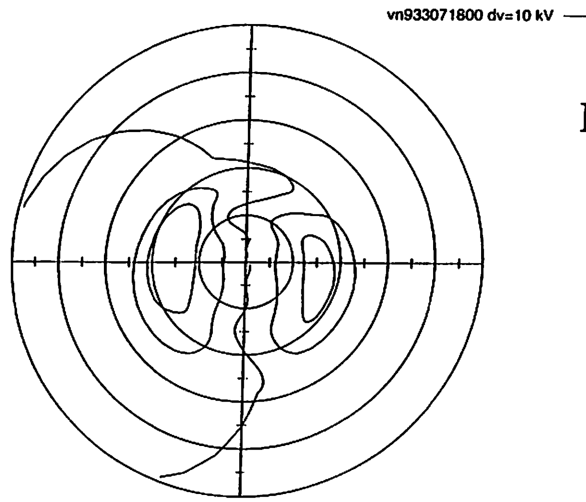




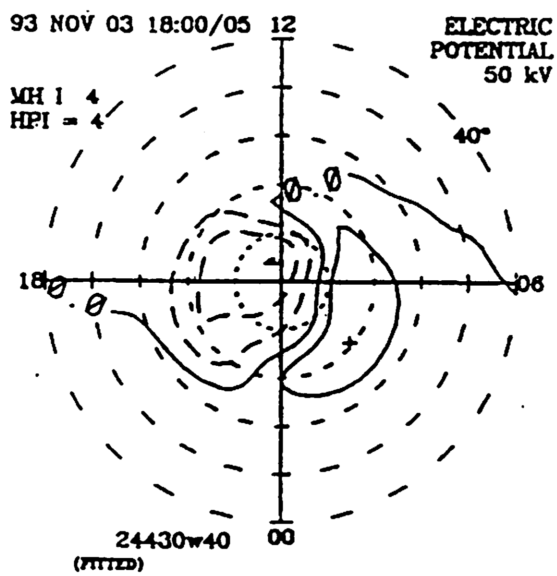
Comparison with DMSP data for pass starting 0923 UT on day 112, 1988. Only total potential drop and pattern type were used as input for top panel. Full corrections were applied to bottom panel.

Comparison of MSFM and AIMIE Models for November 1993 Storm

November 3, 1993
18 UT



MSFM

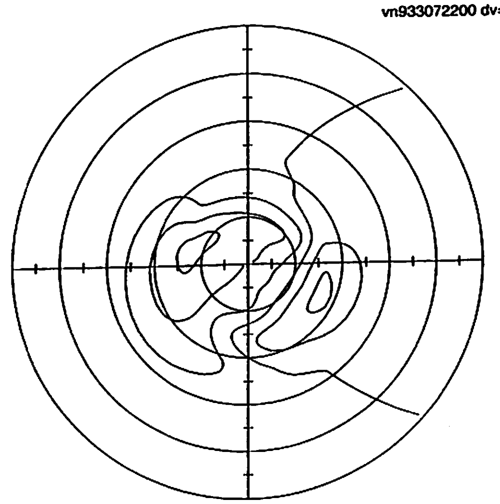


AIMIE

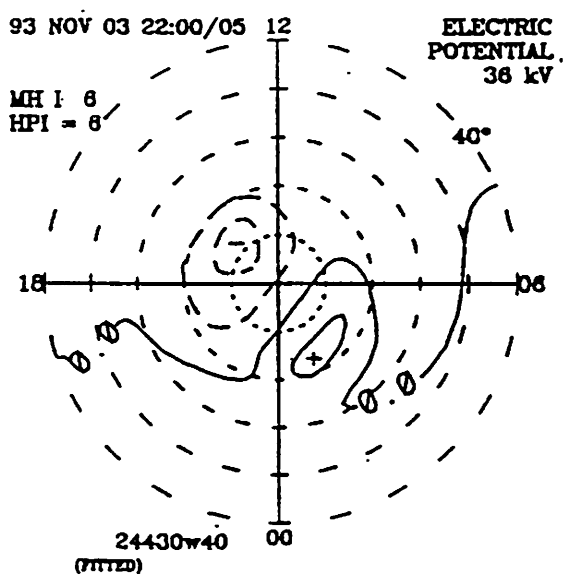
Plots prepared by J. Freeman/R. Spiro and B. Emery/D. Knipp for the National Space Weather Pilot Study.

Comparison of MSFM and AIMIE Models for November 1993 Storm

November 3, 1993
22 UT



MSFM

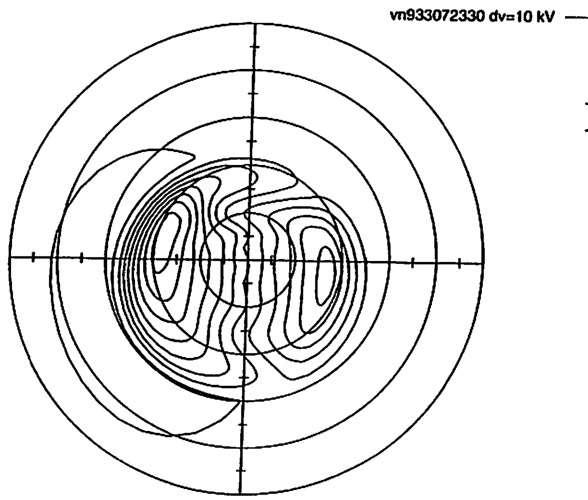


AIMIE

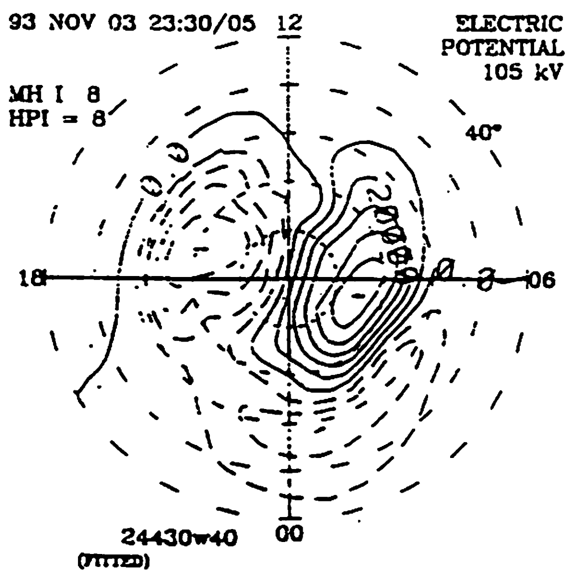
Plots prepared by J. Freeman/R. Spiro and B. Emery/D. Knipp for the National Space Weather Pilot Study.

Comparison of MSFM and AIMIE Models for November 1993 Storm

November 3, 1993
23:30 UT



MSFM

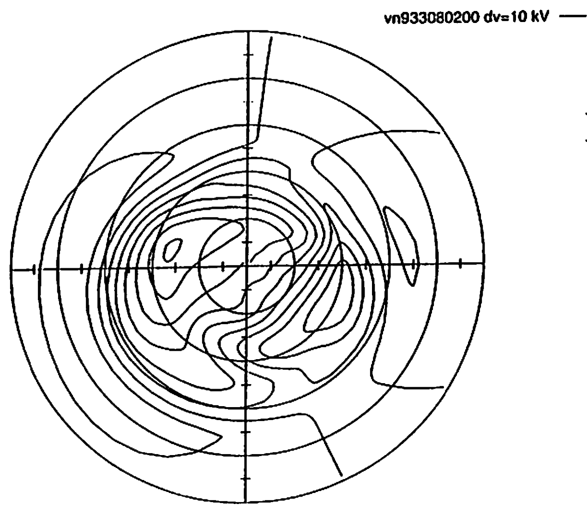


AIMIE

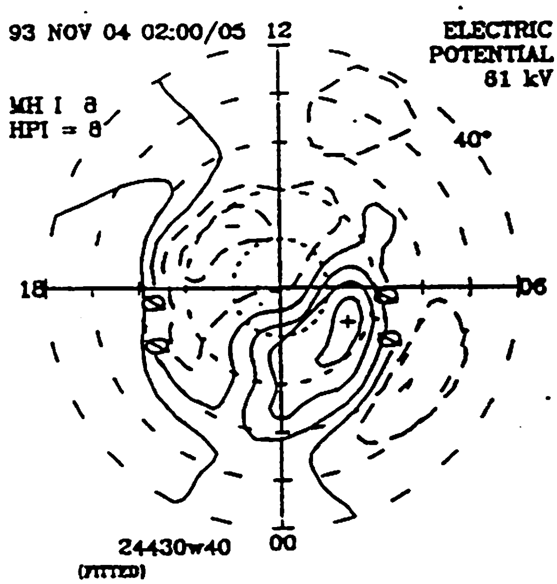
Plots prepared by J. Freeman/R. Spiro and B. Emery/D. Knipp for the National Space Weather Pilot Study.

Comparison of MSFM and AIMIE Models for November 1993 Storm

November 4, 1993
02 UT



MSFM

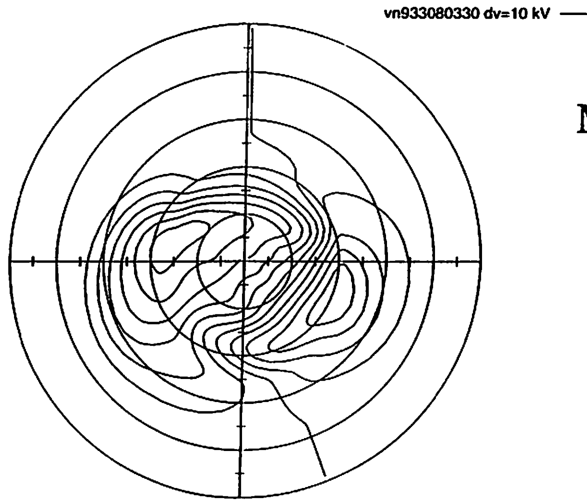


AIMIE

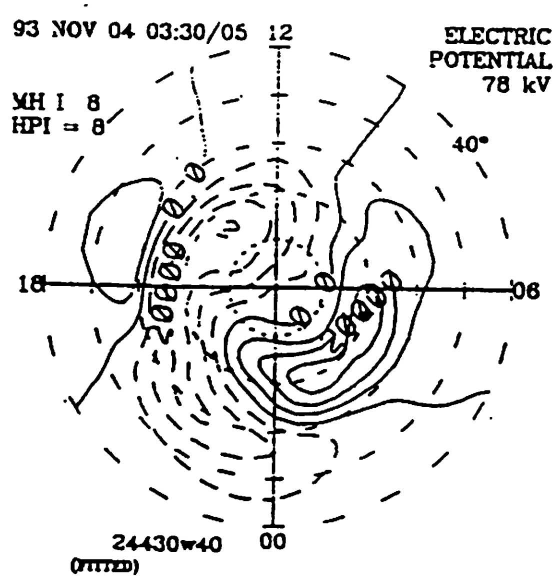
Plots prepared by J. Freeman/R. Spiro and B. Emery/D. Knipp for the National Space Weather Pilot Study.

Comparison of MSFM and AIMIE Models for November 1993 Storm

November 4, 1993
03:30 UT



MSFM

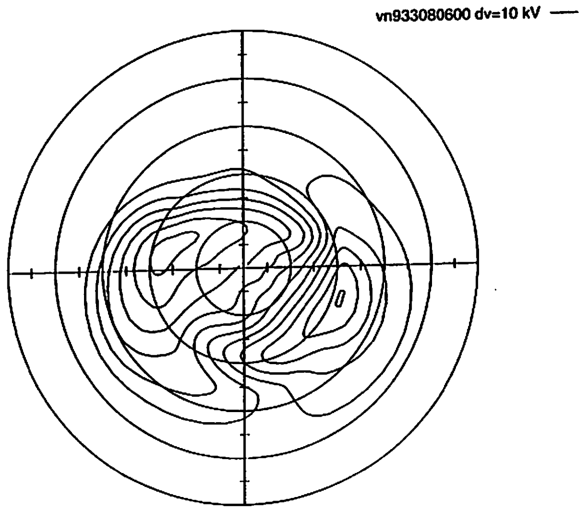


AIMIE

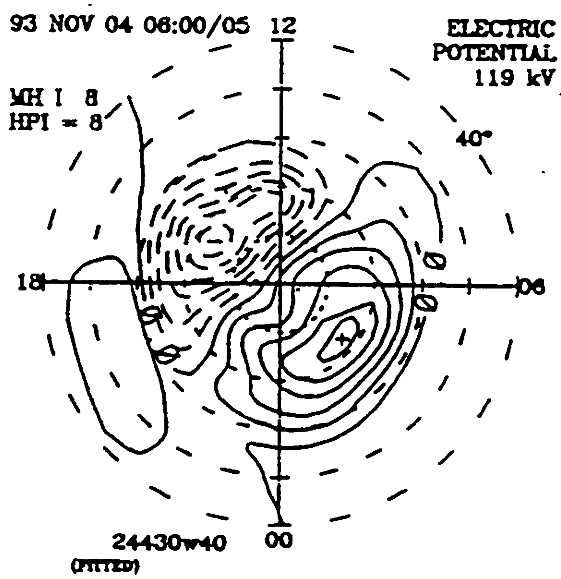
Plots prepared by J. Freeman/R. Spiro and B. Emery/D. Knipp for the National Space Weather Pilot Study.

Comparison of MSFM and AIMIE Models for November 1993 Storm

November 4, 1993
06 UT



MSFM

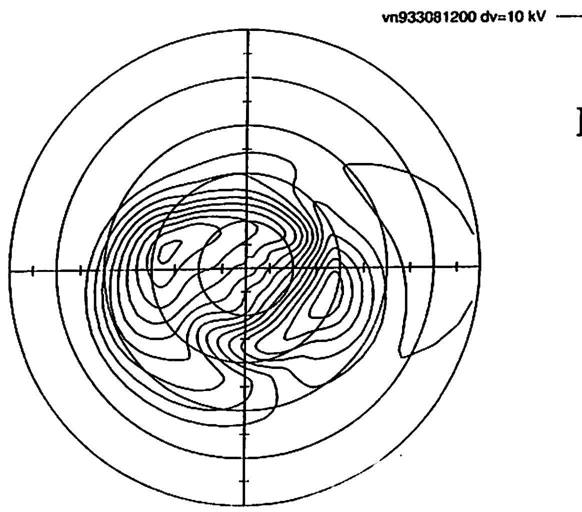


AIMIE

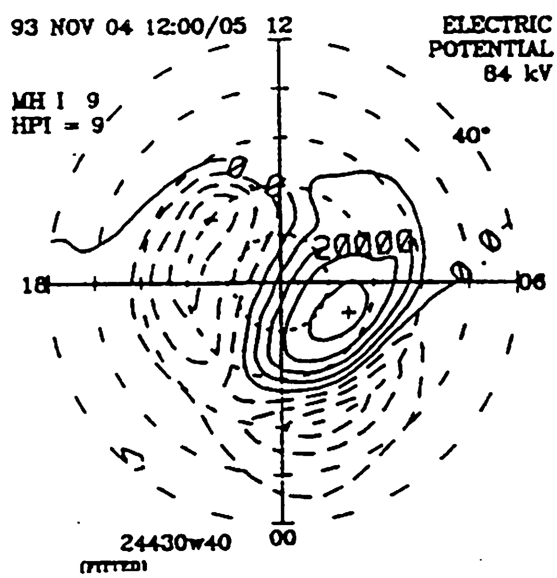
Plots prepared by J. Freeman/R. Spiro and B. Emery/D. Knipp for the National Space Weather Pilot Study.

Comparison of MSFM and AIMIE Models for November 1993 Storm

November 4, 1993
12 UT



MSFM



AIMIE

Plots prepared by J. Freeman/R. Spiro and B. Emery/D. Knipp for the National Space Weather Pilot Study.

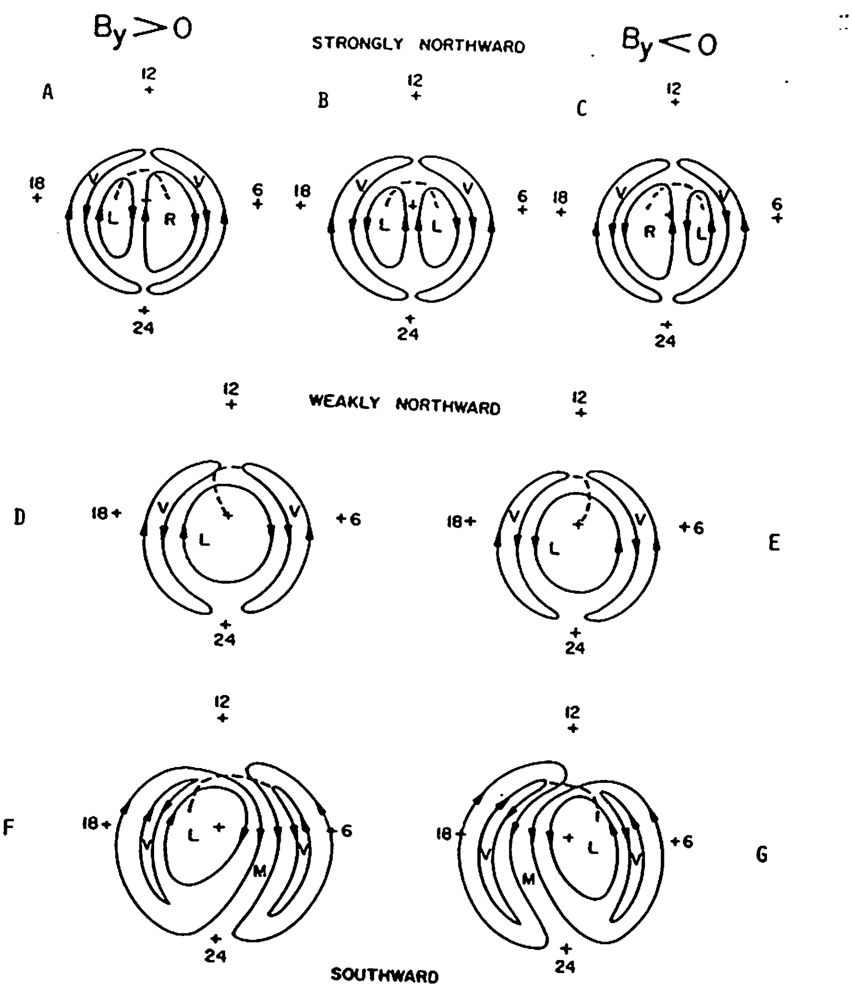
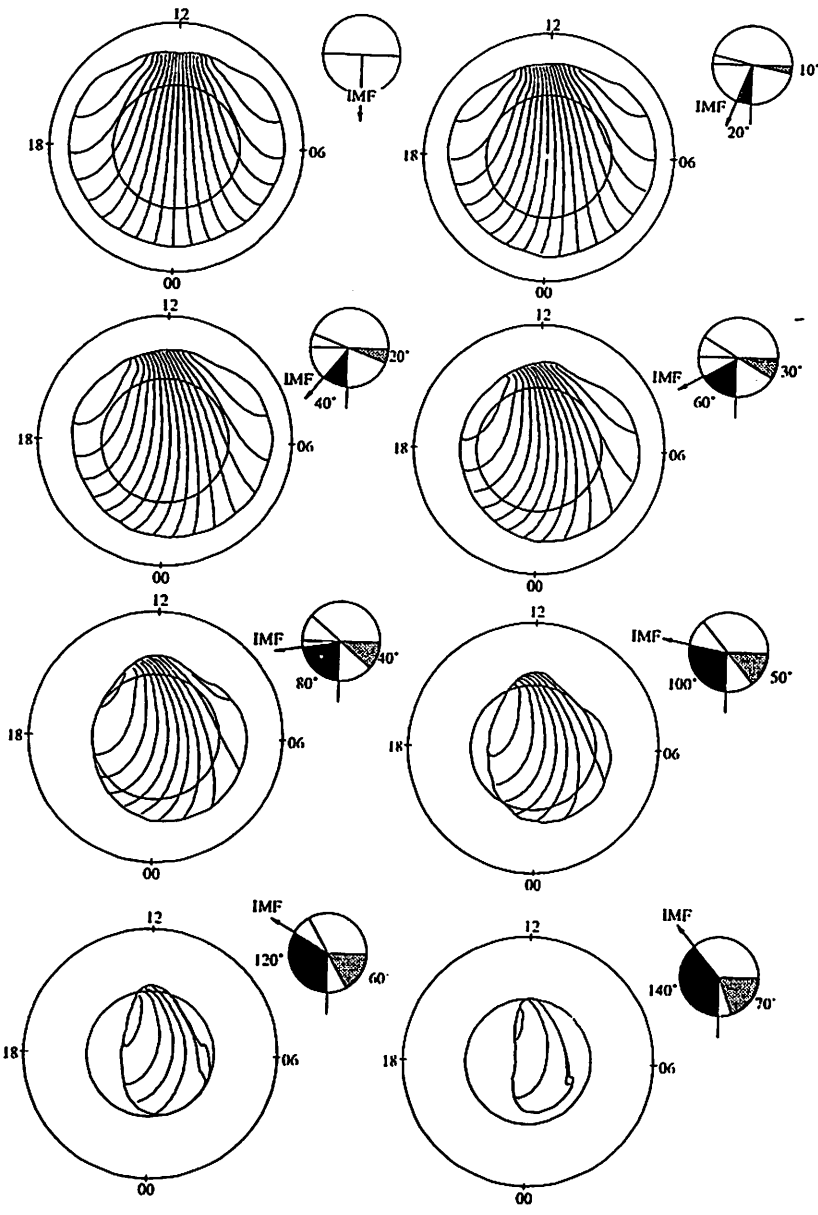


Figure 4.7.1. Schematic northern-hemisphere polar-cap convection patterns for various orientations of the IMF. The left column (i.e., *a, d,* and *f*) is for $B_y > 0$, the center column (i.e., *b*) has $B_y \approx 0$, and the right column (i.e., *c, e,* and *g*) is for $B_y < 0$. The top row (i.e., *a, b,* and *c*) is for strongly northward IMF (B_z>0); the middle row (i.e., *d* and *e*) for weakly northward IMF, and the bottom row (i.e., *f* and *g*) for southward IMF. Viscous cells are marked with a "V", merging cells are marked with an "M", and lobe cells with an "L". The "L" cells in diagram *b* are driven by reconnection at the dayside magnetopause between tail-lobe field lines and northward magnetosheath field lines, as suggested by Russell. The cells marked with an "R" are "reclosure cells", with the sunward-flowing portion on closed field lines. The southern-hemisphere convection pattern is almost the mirror image (reflect through the 1100-2300 MLT line). From Reiff and Burch (*J. Geophys. Res.*, *90*, 1595-1609, 1985).

Possibility for Improving Ionospheric E-Fields: Toffoletto-Hill Model

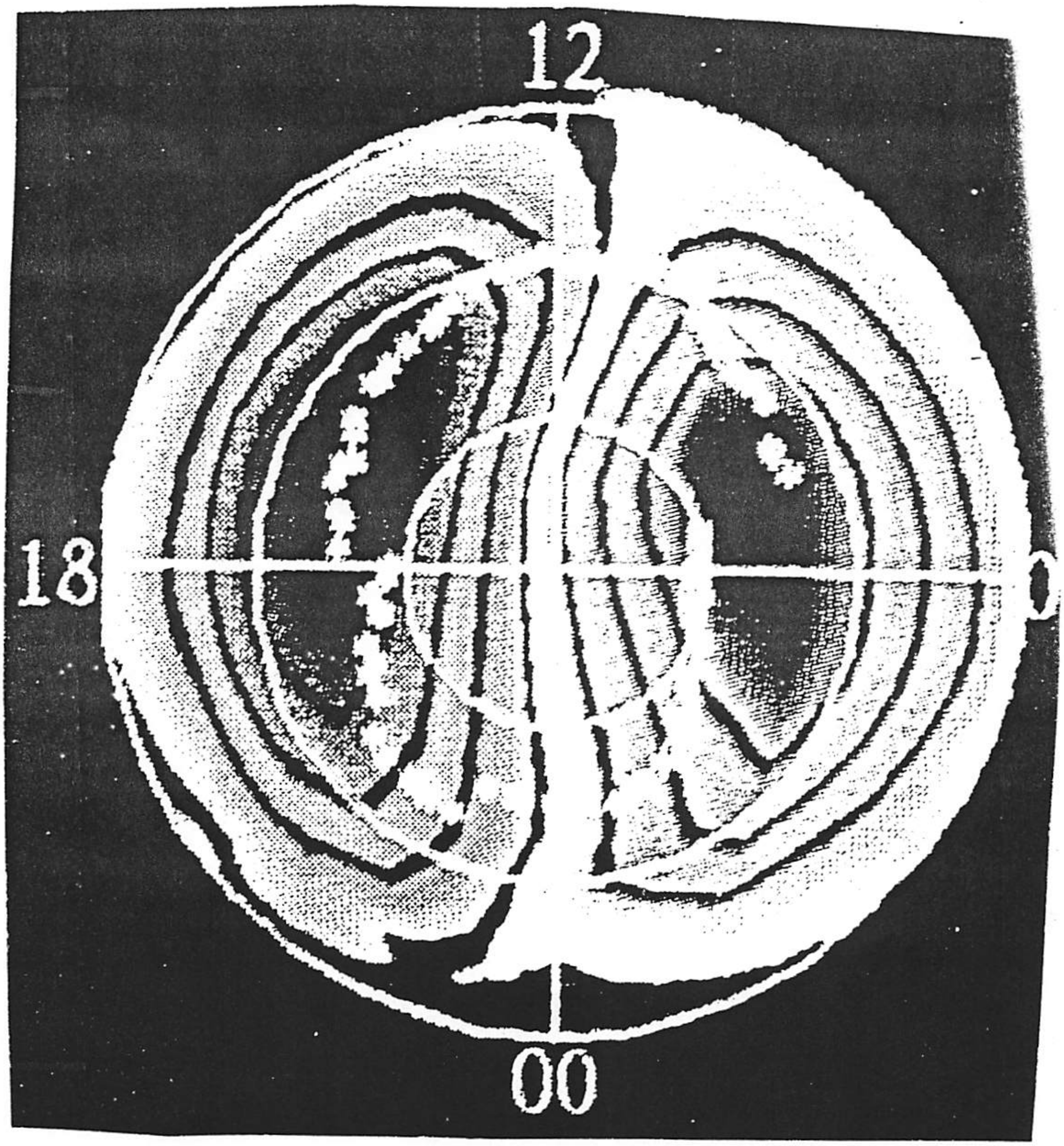
- Approach:
  - Assume distribution of B_{normal} on magnetopause and map magnetosheath electric field along field lines to polar cap.
  - Mixes theory and empiricism.

Toffoletto-Hill Model –
Sample Polar-Cap Patterns



From Toffoletto + Hill, *JGR*, *98*, 1339, 1993.

Possibility for Improving Ionospheric E-Fields: 3D Global MHD Model



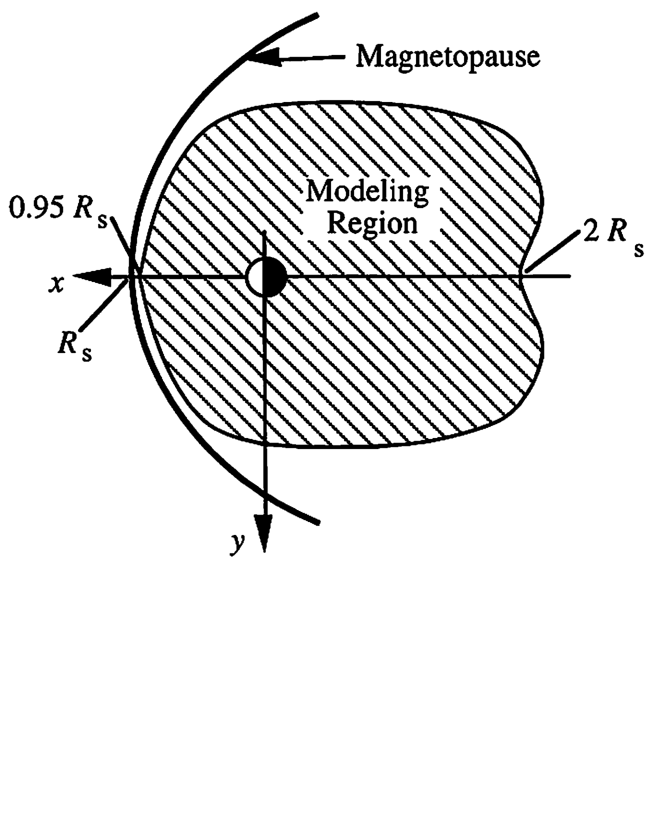
Equipotential pattern in the northern ionosphere, for 1135 UT on October 19, 1986, as computed by global MHD simulation of the event. (Fedder et al., *JGR*, *100*, 19083, 1995)

MSFM Electric Fields – Summary Discussion

- Strong Points:
  - Based on input data that are already available in real time
  - Sensible, reliable, conservative
  - Makes an intelligent effort at estimating the penetration of the electric field to low ionospheric latitude
- Weak Points:
  - Only uses three polar-cap pattern types
  - Cannot represent most event-specific peculiarities.
- Possibilities for Improvement of High-Latitude **E**:
  - Use physical model of the polar cap (Toffoletto-Hill or 3D global MHD)
  - Substitute model that uses more input data. AIMIE? IZMEM? Weimer?
  - Systematic comparison tests would be illuminating.
- Possibilities for Improvement of Low-Latitude **E**:
  - Add model of wind-generated electric fields
  - Improve understanding

Initial- and Boundary-Condition Fluxes

- Based on $j_{\mathrm{Kp}}^{\mathrm{equatorial}}(r_e, E, Kp)$ for H^+, O^+, e^-.
- Compiled from
  - Huang-Frank plasma-sheet statistics
  - Garrett synchronous-orbit statistics + Baker et al. published observations of 40-keV electrons
  - Published ring-current observations (mostly AMPTE)
  - NASA radiation-belt models



Loss Algorithms

$$\frac{D\eta_s}{Dt} = -\max\left[\frac{\left(\eta_s - \eta_{strong,s}\right)}{\tau_{strong,s}}, 0\right] - \max\left[\frac{\left(\eta_s - \eta_{weak,s}\right)}{\tau_{weak,\,s}}, 0\right]$$

- Plasma-sheet electrons:

  $\eta_{strong} = \eta_{min}$

  $\tau_{strong} = \left(\frac{1}{3} - \frac{2}{3}\right) \times \left(\text{strong pitch–angle scattering}\right)$

  $\tau_{weak} = \infty$

- > 40 keV electrons in plasmasphere

  $\eta_{weak} = \eta_{min}$

  Use Lyons' formulas, based on precipitation being due to pitch-angle scattering in plasmaspheric hiss.

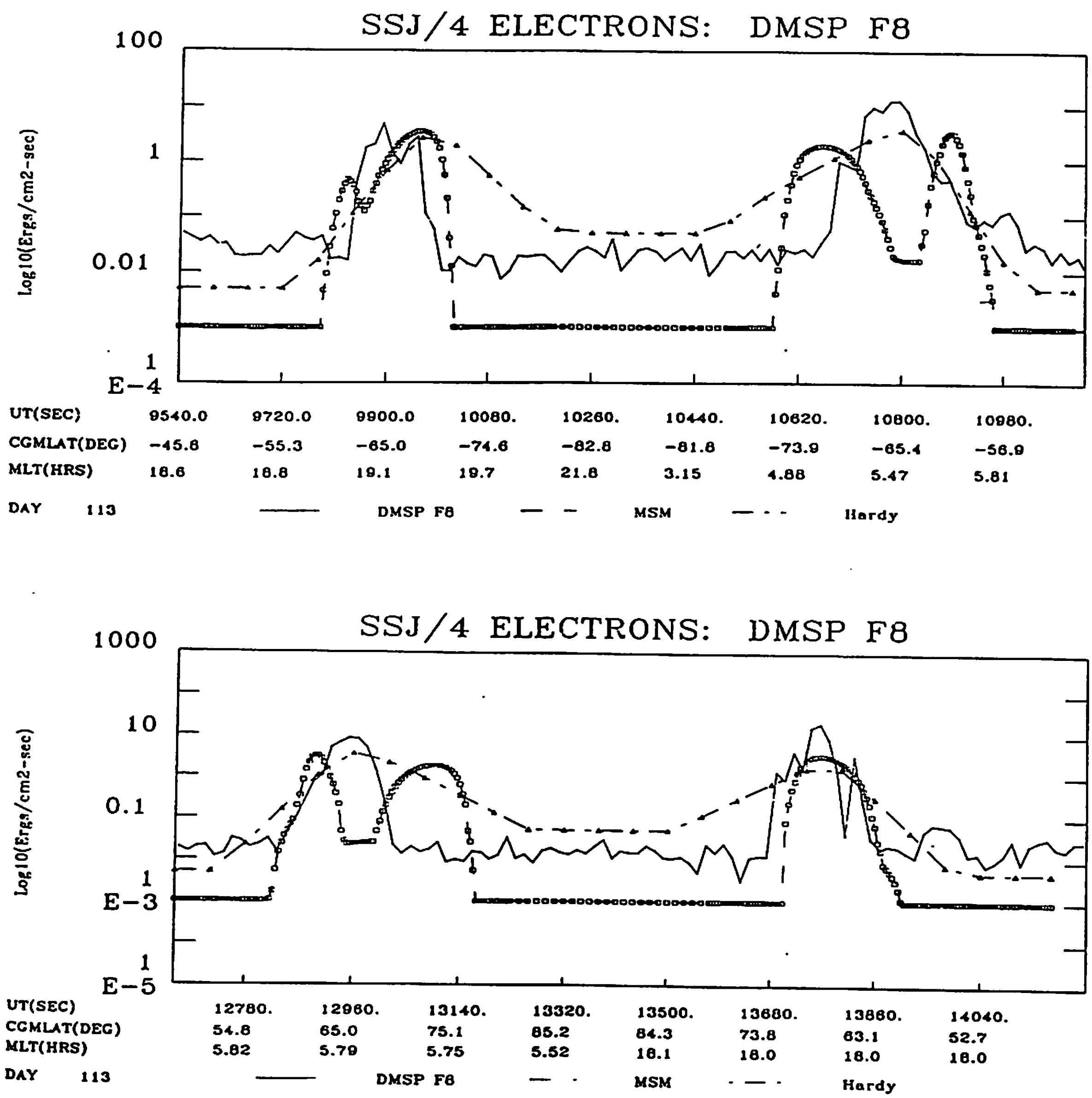
- Ions

  Consider charge exchange only. Use routine by James Bishop.

Electron-Precipitation Model

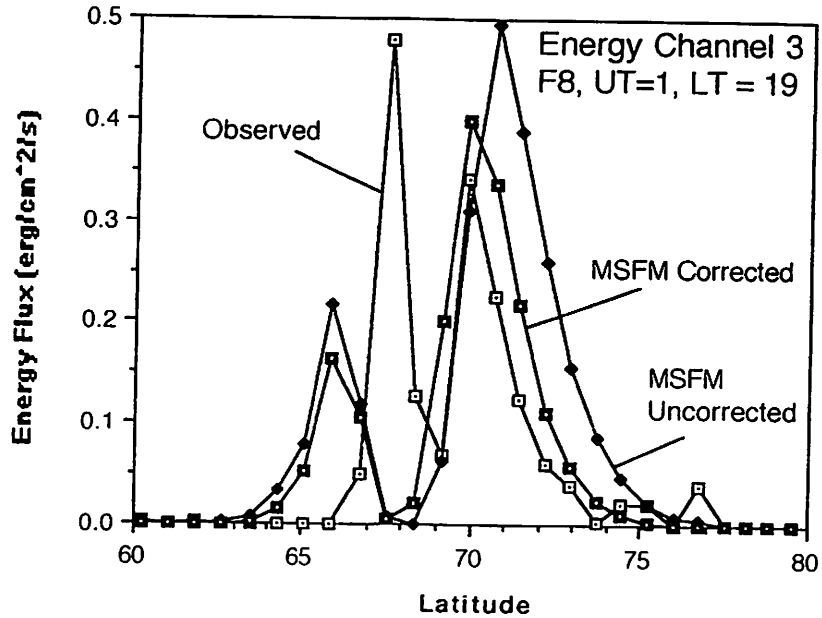
- Set equal to electron loss from model plasma sheet, with no field-aligned potential drop.
- Fluxes specified in four energy bins.
- If detailed data are available from DMSP J/4 electron detector, model profiles are corrected to agree with observations in
  - latitude-integrated flux
  - centroid latitude
  - width of auroral zone

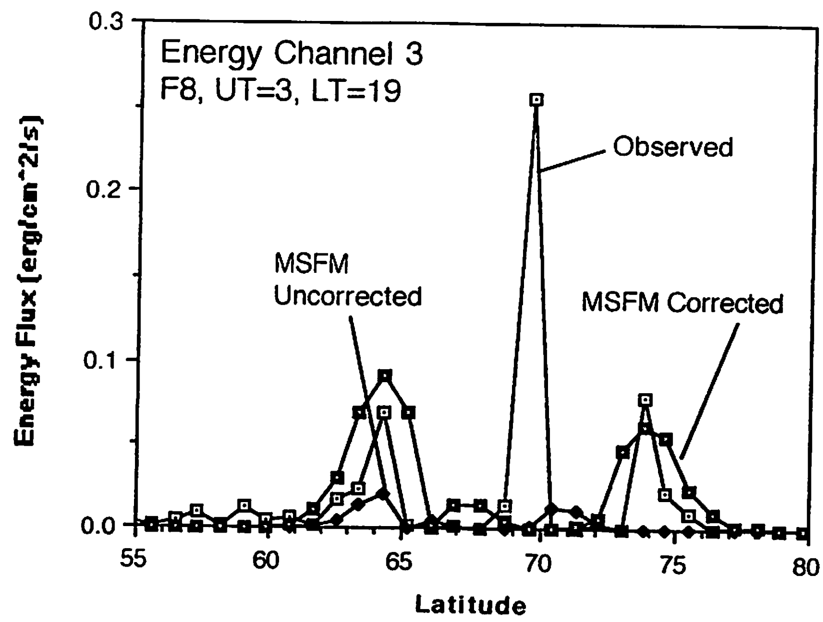
MSFM Precipitating Electron Fluxes – How Good Are They?



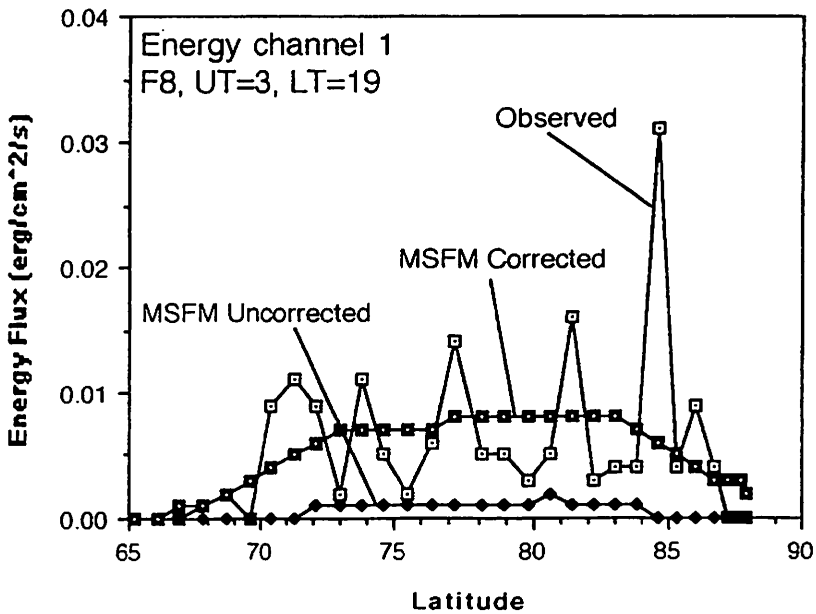
Sample comparisons of precipitating electron flux from MSFM compared with observations and with Hardy model.

Sample Results of MSFM Post-Corrections to Precipitating Fluxes in 5-15 keV Channel

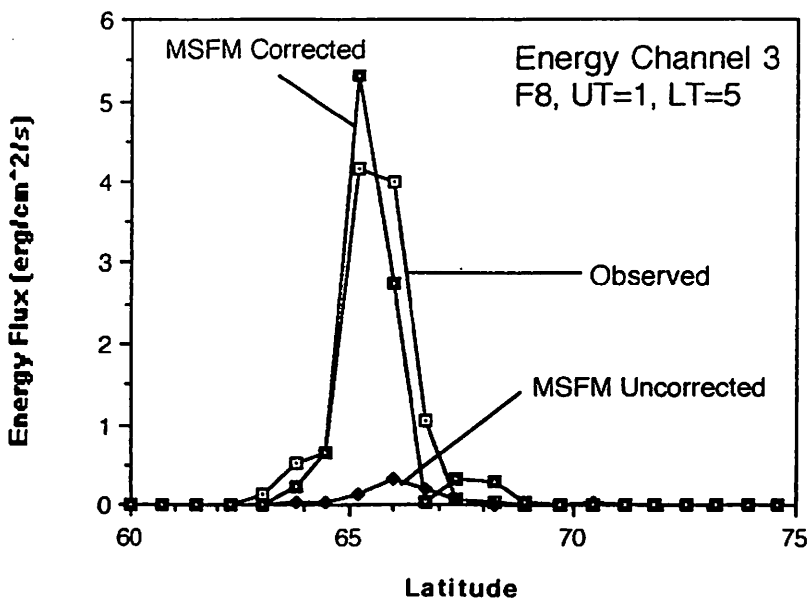




Sample Results of MSFM Post-Corrections to Precipitating Fluxes in Various Energy Channels



Uncorrected MSFM frequently underestimates flux in lowest channel (100-500 eV), probably because model does not include secondary electrons. Correction helps.



Correction procedure worked well in 5-15 keV channel in this case, even though correction was large.

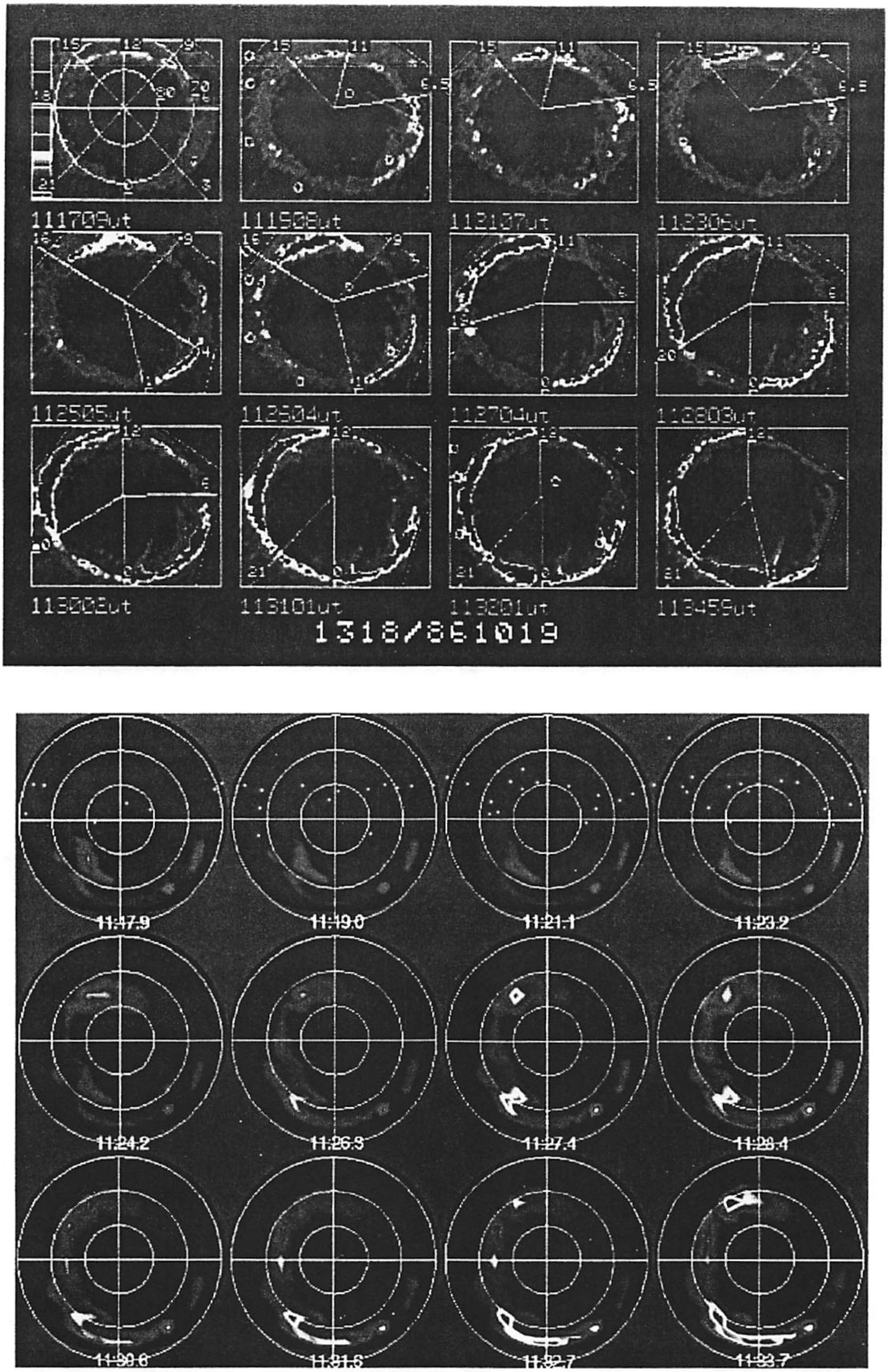


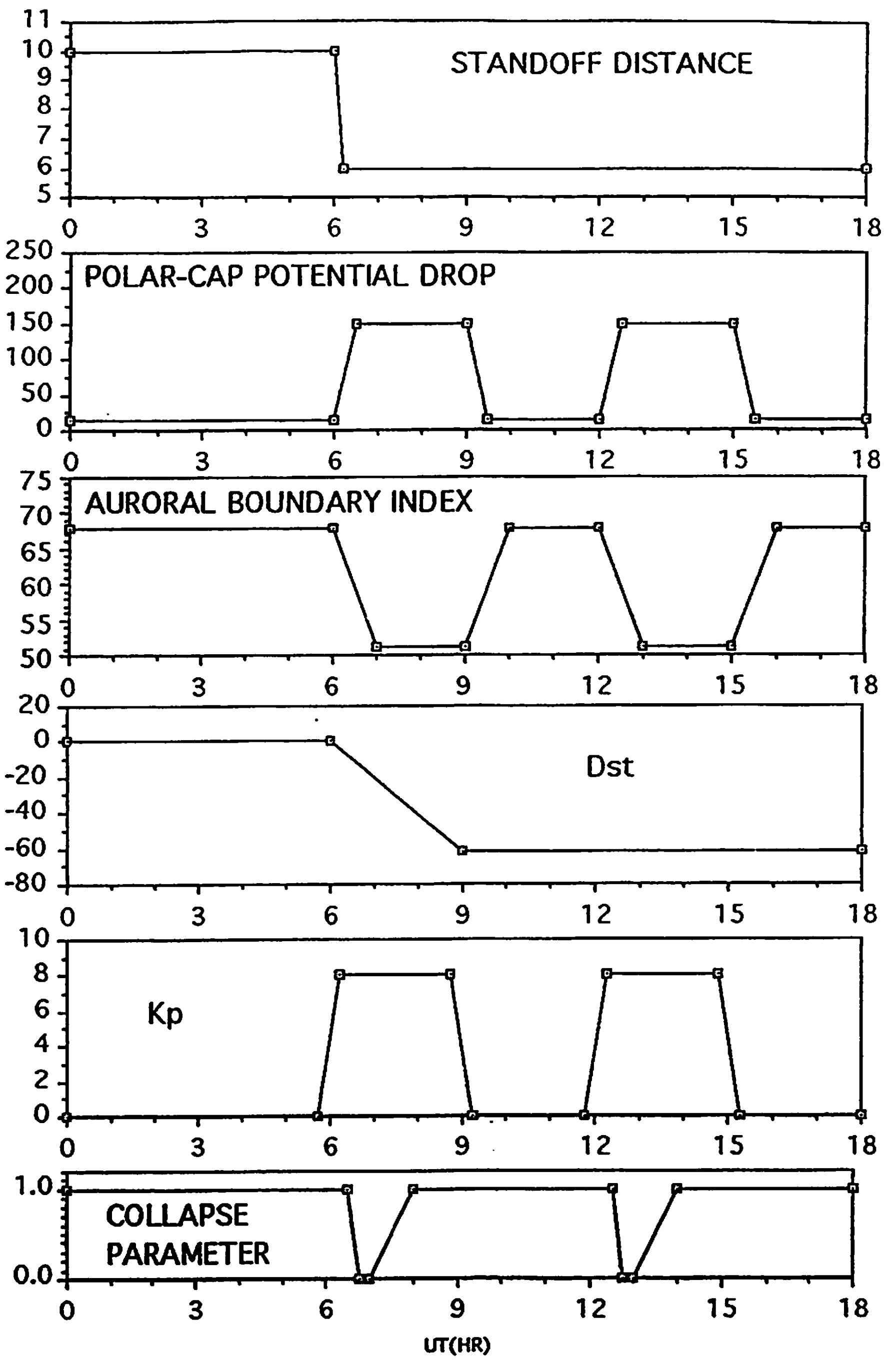
Figure 1. A comparison between the Viking ultraviolet auroral images for October 19, 1986 and synthetic aurora produced from a global MHD simulation: The actual images are the top panel and the bottom the simulations. The image resolution of the Viking images is about 50 km, while the numerical resolution of the simulations is about 400 km.

37.5

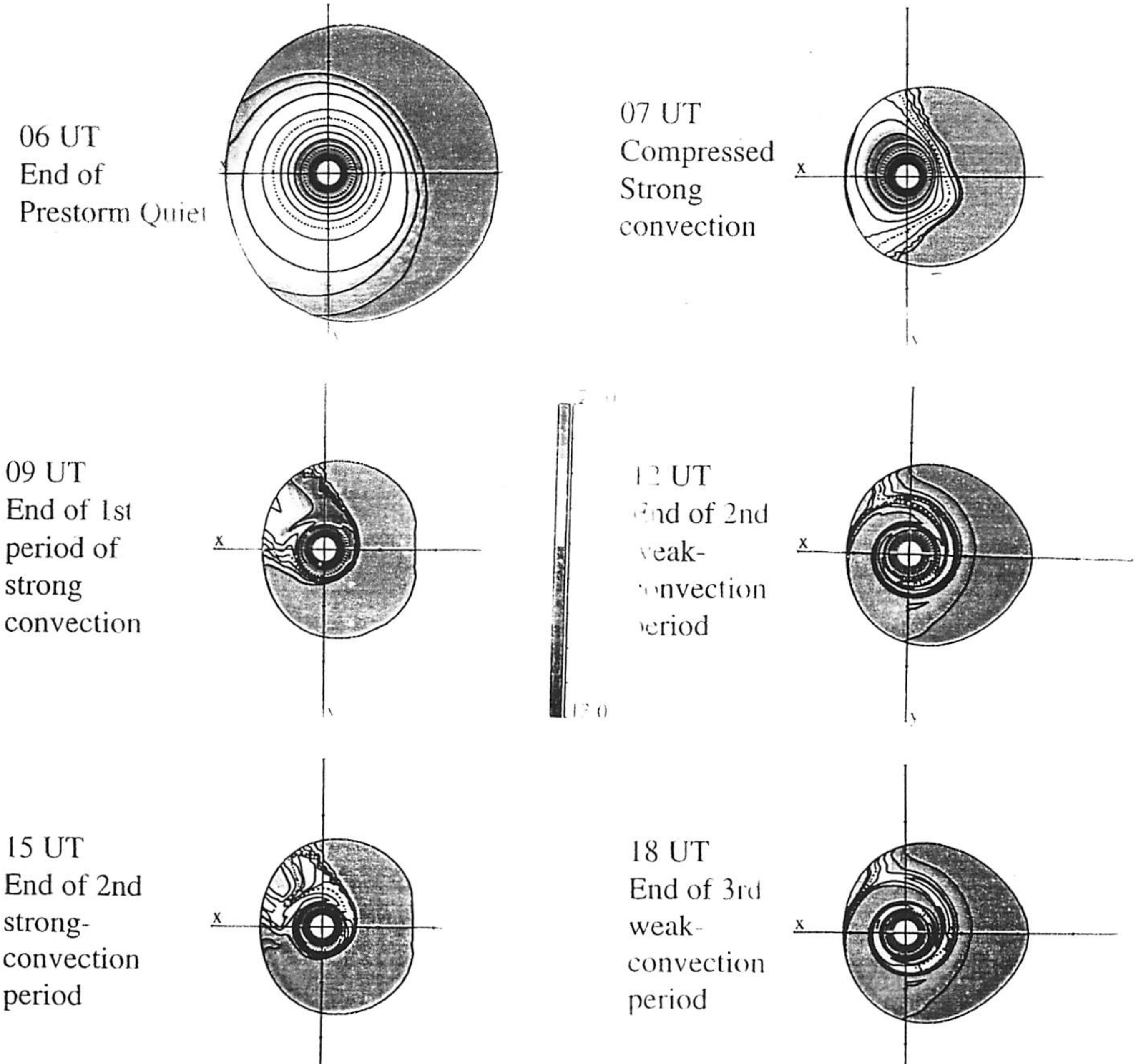
MSFM Precipitating Fluxes: Discussion

- Strong Points
  - Conservative algorithm that gives sensible values
  - MSFM fluxes don't have the artificially diffuse structure that characterize the statistical models
  - MSFM tries to align the equatorward precipitation boundary with the equatorward edge of the auroral flow.
- Weak Points
  - Field-aligned potential drops are not included.
  - Misses most detailed structure
- Possibilities for Improvement
  - Systematic contests between different empirical models would be helpful.
  - Develop an algorithm that adjusts the pattern to fit real-time auroral images.
  - Global 3D MHD model?
  - Understand the aurora better.

Portrait of Ring-Current Injection-Model Inputs for Idealized Storm

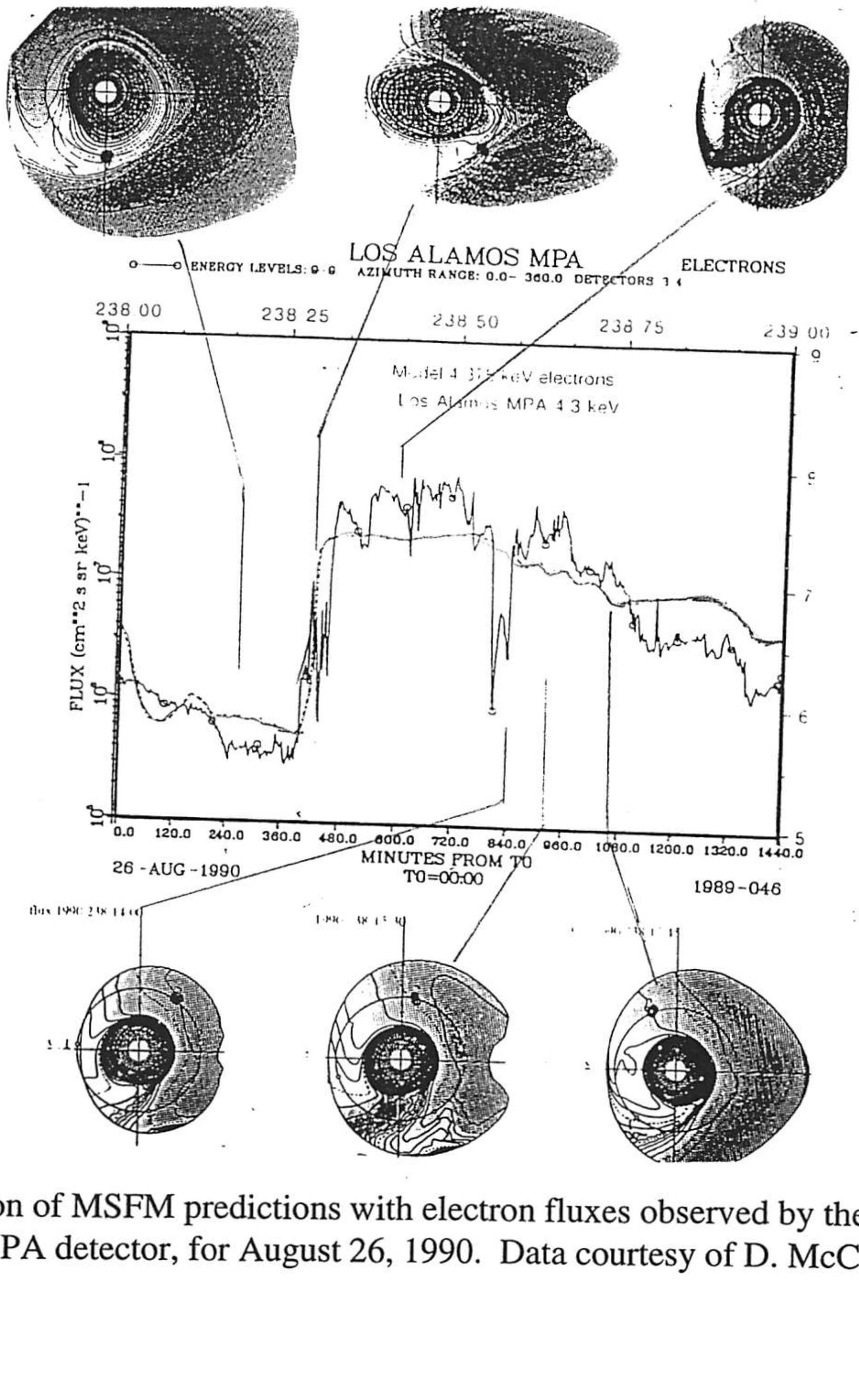


Portrait of Ring-Current Injection-
Equatorial Plots of MSFM Results



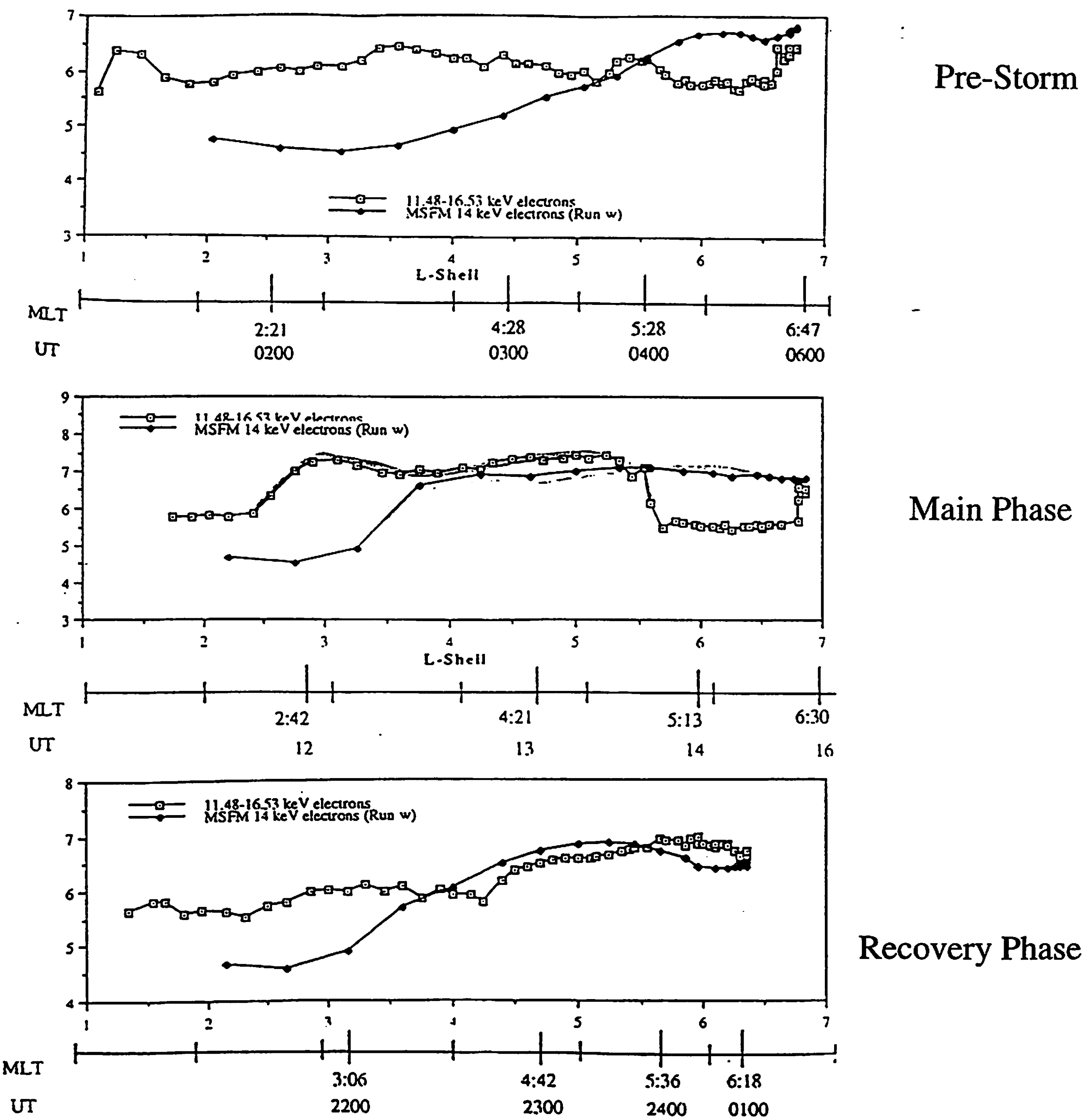
Equatorial plots of $\log_{10}(\eta)$ for H^+ ions with 8.6 keV at GEO,70 keV at $L = 3$.

Comparison with Observed 40-keV Geosynchronous Electrons



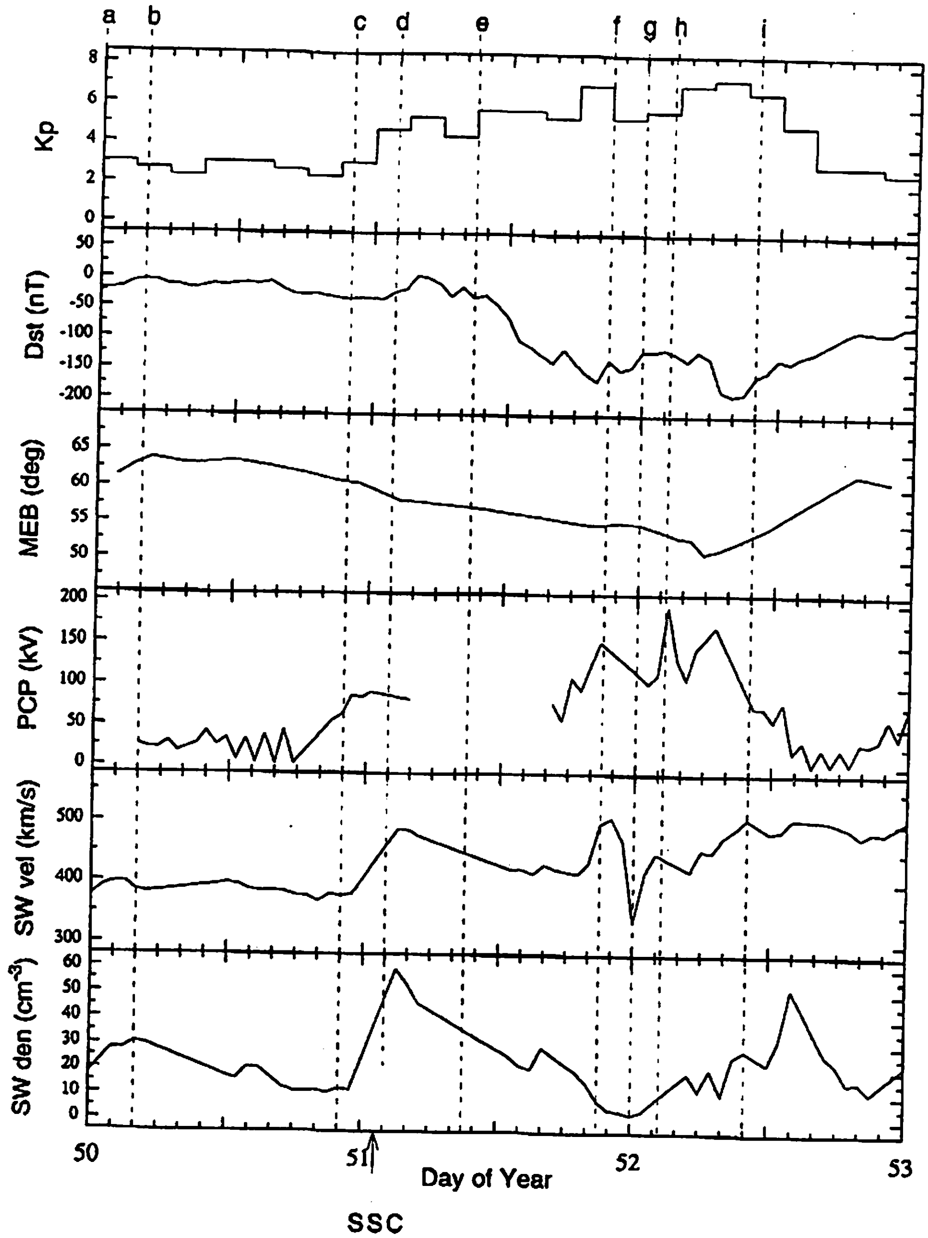
Comparison of MSFM predictions with electron fluxes observed by the Los Alamos MPA detector, for August 26, 1990. Data courtesy of D. McComas.

Comparison with CRRES Observations of ~ 14 keV Electrons



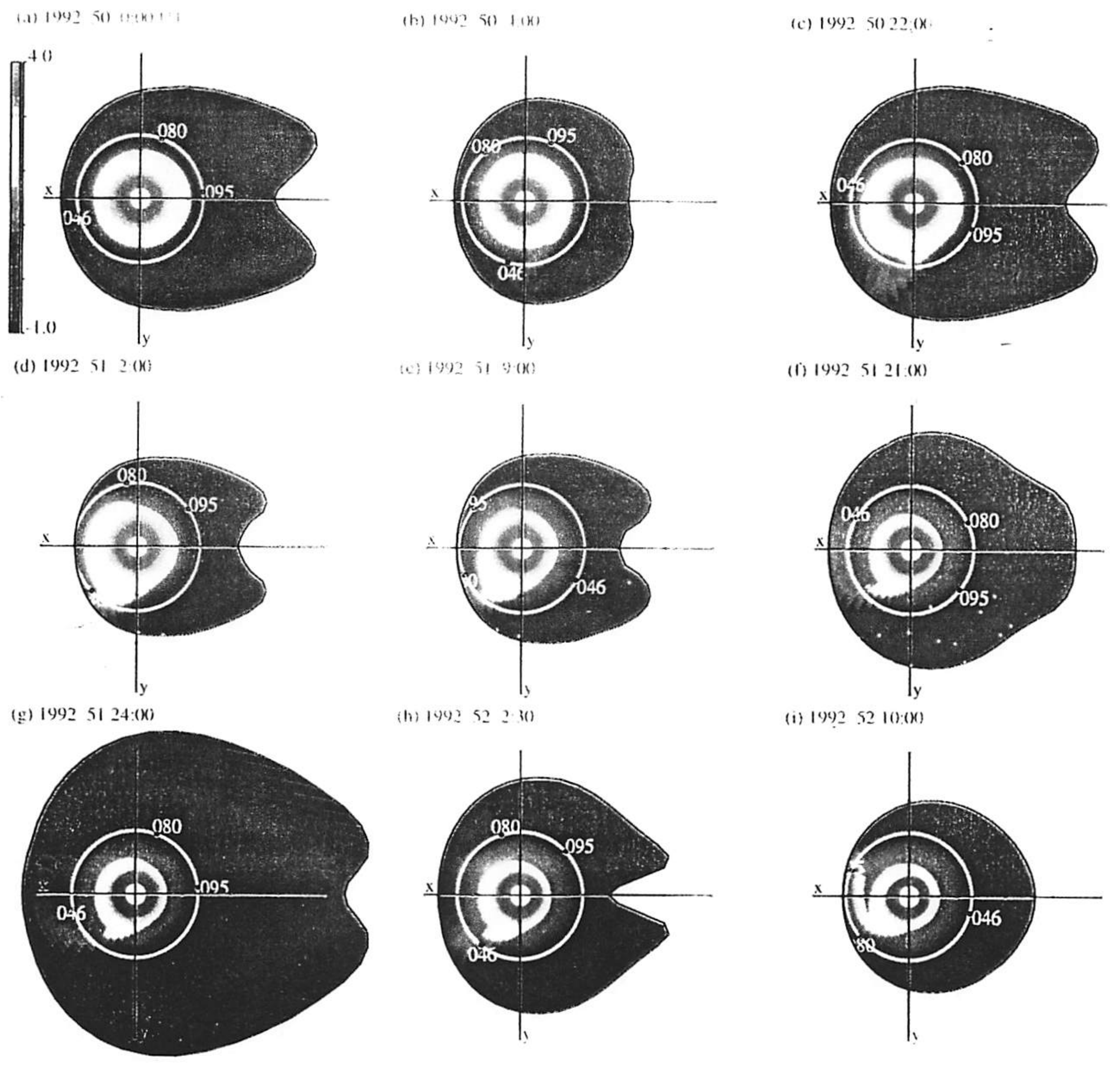
Comparison of MSFM predictions with electron fluxes observed by the CRRES LEPA detector in the August 1990 storm. Data courtesy of D. Hardy.

Plasmasphere Simulation – Input Data



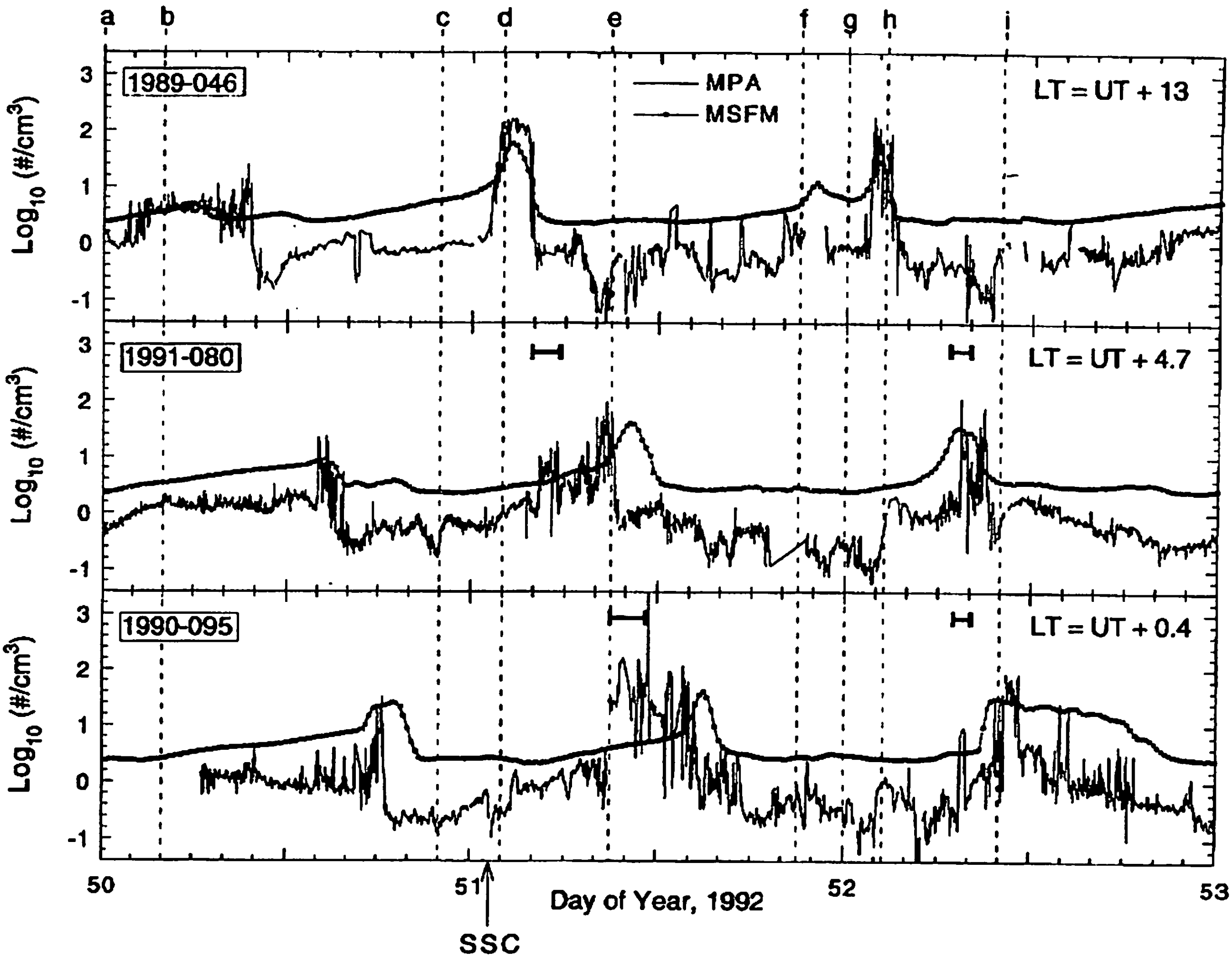
MSFM Input Data for February 19-21, 1992. From L. A. Weiss, R. L. Lambour, R. C. Elphic, and M. F. Thomsen, "Study of Plasmaspheric Evolution Using Geosynchronous Observations and Global Modeling, Submitted to *JGR*, 1996.

Plasmasphere Simulation – Equatorial Plots of MSFM Electron Density



From L. A. Weiss, R. L. Lambour, R. C. Elphic, and M. F. Thomsen, "Study of Plasmaspheric Evolution Using Geosynchronous Observations and Global Modeling, Submitted to *JGR*, 1996.

Comparison of MSFM with Observed Densities



From L. A. Weiss, R. L. Lambour, R. C. Elphic, and M. F. Thomsen, "Study of Plasmaspheric Evolution Using Geosynchronous Observations and Global Modeling, Submitted to *JGR*, 1996.

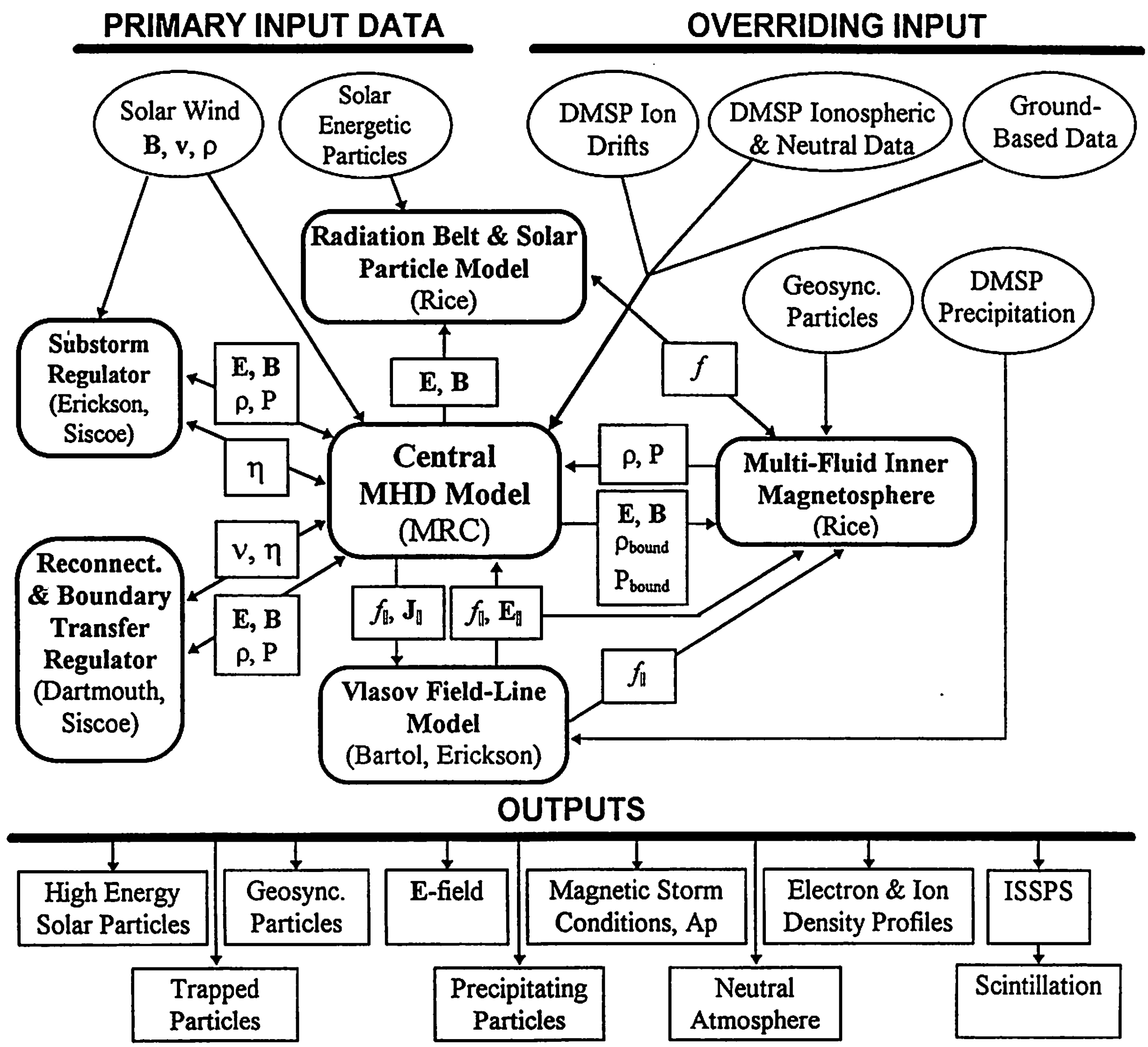
Future Possibilities

- The index approach:
  - Use more indices and more statistical studies to represent more physical parameters
- The comprehensive-model approach:
  - Use different computational approaches in different regions:
    - To make models more comprehensive, need to use different algorithms in different regions.
      - Examples: Embed the RCM inside the Lyon-Fedder global-MHD code, merge RCM with Birn-Hesse tail-MHD code.
      - Integrated Space Model. Sponsored by Defense Nuclear Agency
  - Hybrid codes, full particle codes.

Integrated Space Model (ISM) – Team

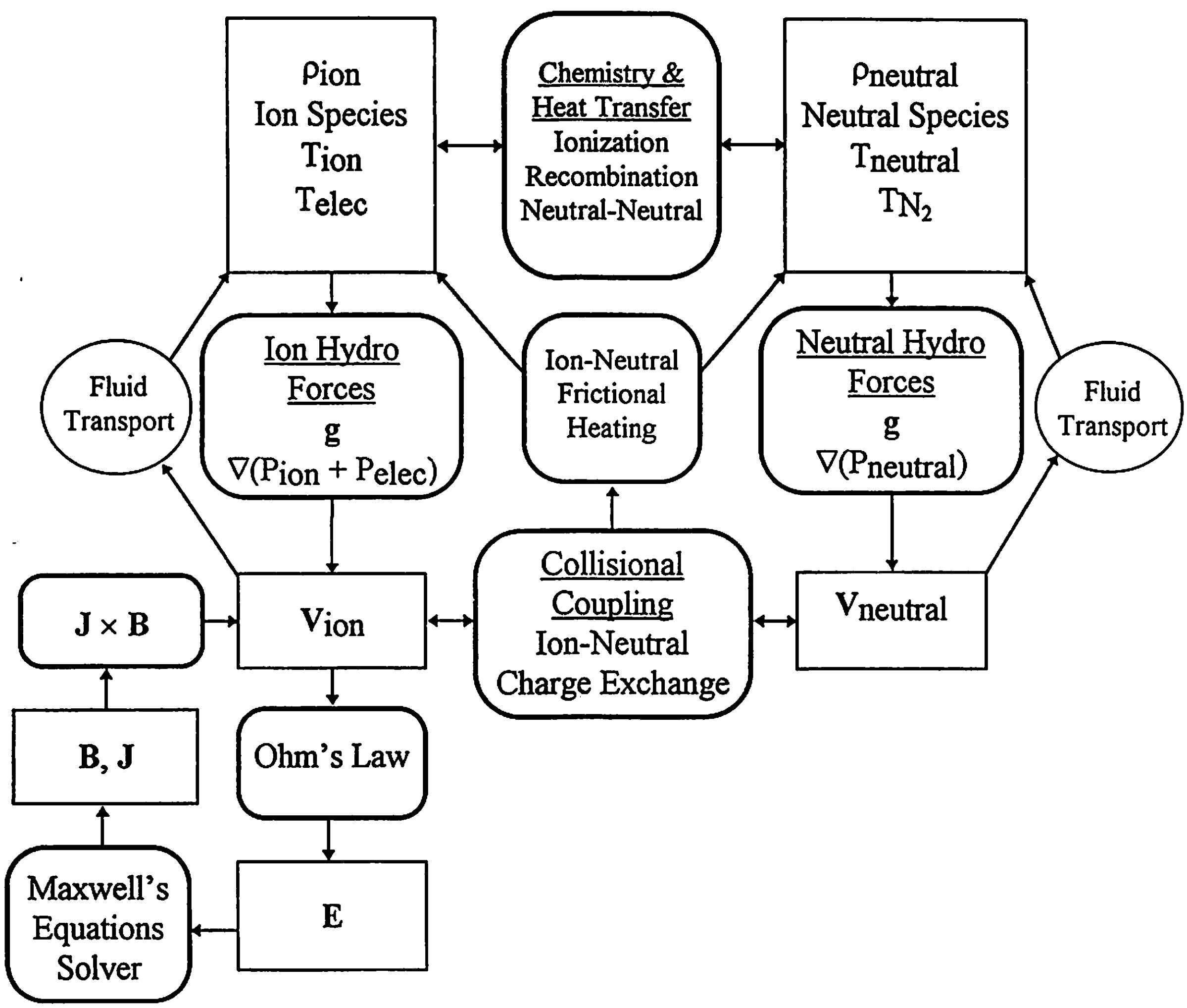
- Defense Nuclear Agency (Sponsor)
  - K. Schwartz / RAEM
  - R. Cox / SPWE
- Mission Research Corporation (Prime Contractor)
  - M. Frolli
  - G. Fry
  - A. Gregersen
  - N. Maynard
  - K. Siebert
  - W. White (Principal Investigator)
- Dartmouth College
  - B. Sonnerup
- Rice University
  - C. Ding
  - J. Freeman
  - S. Orloff
  - R. Spiro
  - R. Wolf
- Bartol Research Institute (Univ. of Delaware)
  - D. Pontius
- Consultants
  - G. Erickson (Boston Univ.)
  - G. Siscoe (Boston Univ.)

Integrated Space Model – Overall Flow Diagram



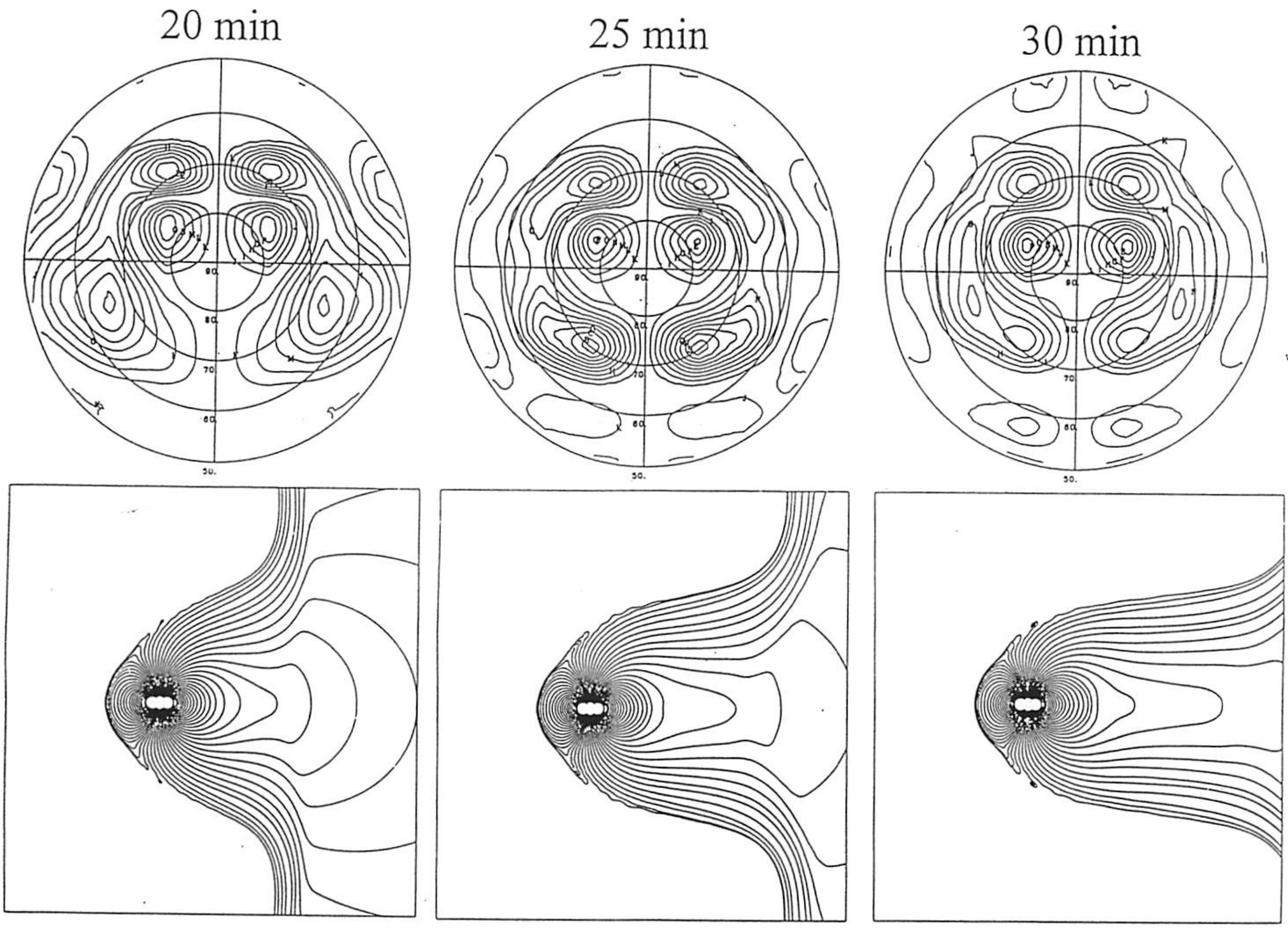
Logic diagram of ISM.

Integrated Space Model – Central Two-Fluid MHD Model



Integrated Space Model – Sample Results

Evolution of Inner Region Parallel Currents and Field Line Topology



Results of test of ISM with composite grids, one beyond 3.5 R_E and one from 100 km to 3.5 R_E.

Concluding Comments

- MSM is in operational use at the 50th Weather Squadron.
- MSFM will be transitioned starting in a few months.
- These models are partly data-driven, part theoretical calculation..
- Cover region from inner magnetosphere out through inner plasma sheet.
- They do a reasonable job of providing
  - Magnetospheric particle fluxes up to ~ 100 keV
  - Global **E** and **B** models

  but they are not highly accurate.
- MSFM provides reasonable high-latitude ionospheric electric fields and precipitation patterns
  - Other models may do a better job of specifying and/or forecasting ionospheric inputs at high latitudes:
    - AIMIE, IZMEM, Weimer
    - Toffoletto-Hill, 3D Global MHD
  - We really need a comprehensive, organized test
- MSFM also provides a reasonable estimate of the prompt-penetration E-field at low latitudes
  - Wind-driven fields need to be added
  - More research is badly needed
- More advanced and comprehensive models are coming...