

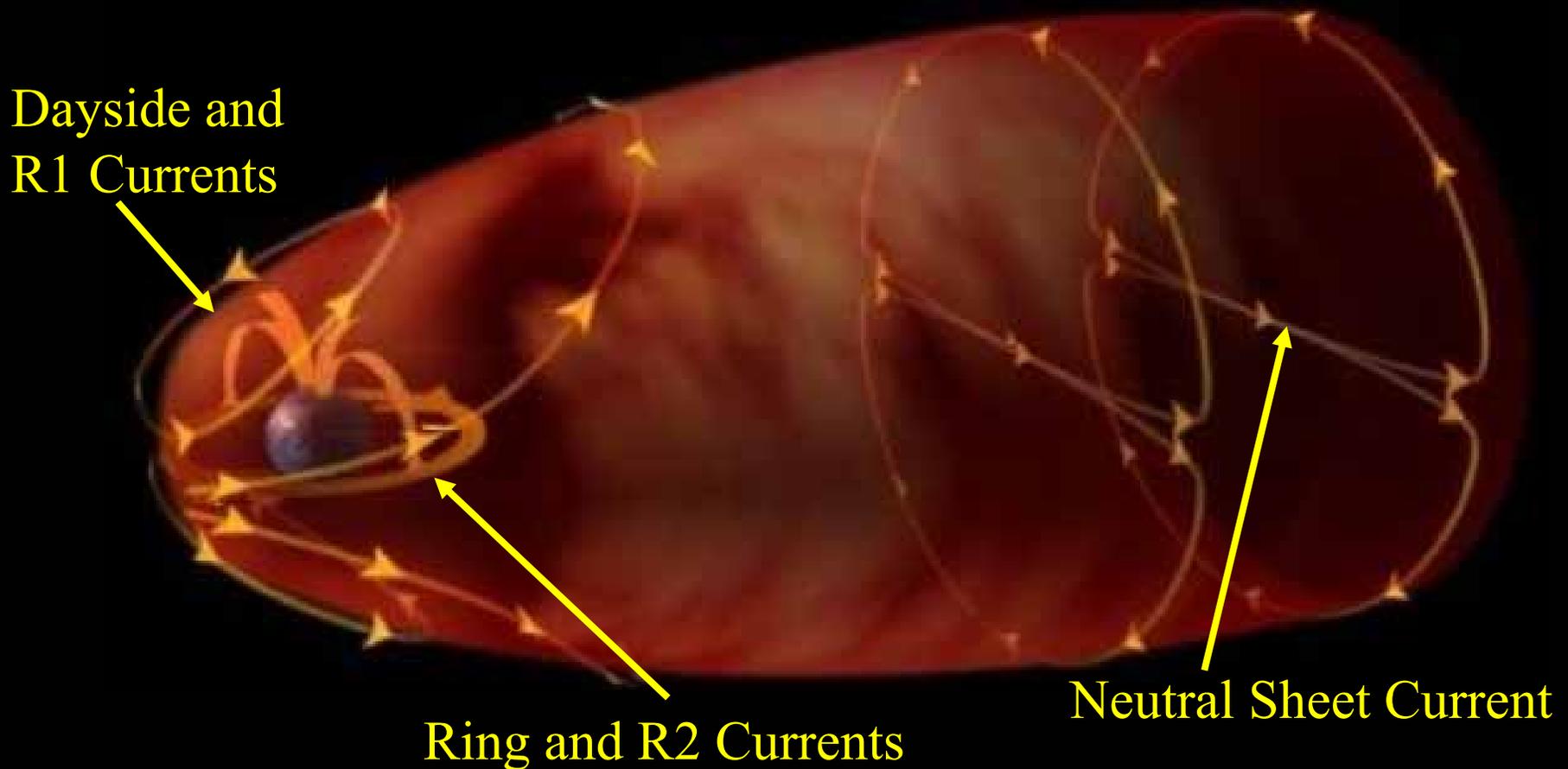
Modeling Interactions
between the
Magnetosphere, Ionosphere
&
Thermosphere

M. Wiltberger
NCAR/HAO

Outline

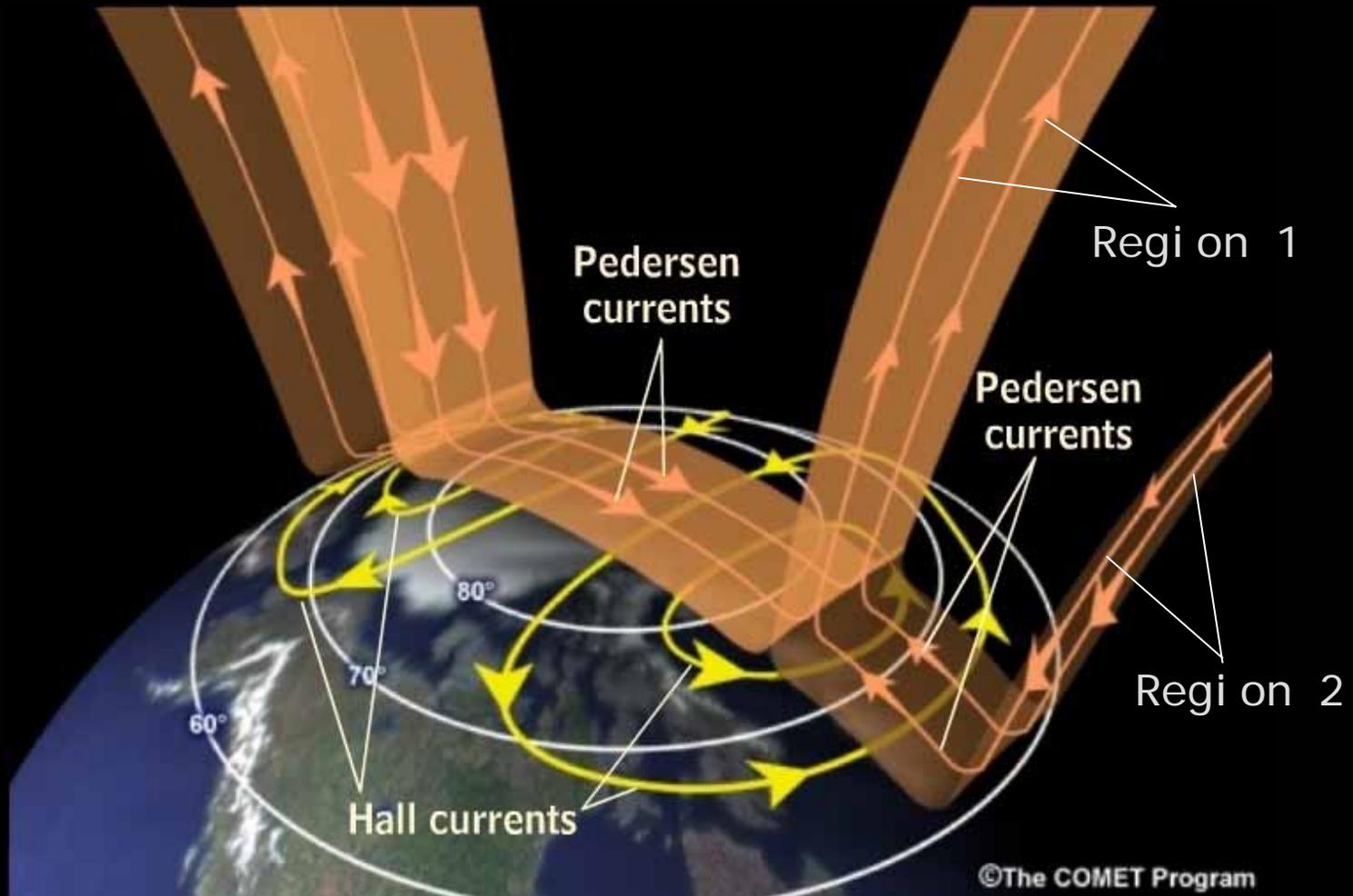
- Overview of MIT ‘circuit’
- Modeling Magnetospheric impacts on the Ionosphere
 - Energetic Particle Fluxes
- Modeling Thermospheric impacts on the Ionosphere
 - Neutral Wind Driven Currents
- Modeling Ionospheric impacts on the Magnetosphere
 - Ion Outflow
- Conclusions
- References

Magnetospheric Currents



- Magnetopause current systems are created by the force balance between the Earth's dipole and the incoming solar wind

Ionospheric Currents



- FAC from the magnetosphere close though Pedersen and Hall Currents in the ionosphere

MI Coupling Eqs

- As described in *Kelly [1989]* The fundamental equation for MI coupling is obtained by breaking the ionospheric current into parallel and perpendicular components and requiring continuity

$$\nabla \cdot \vec{J} = \nabla_{\perp} \cdot \vec{J}_{\perp} + \frac{\partial J_{\parallel}}{\partial s} = 0$$

- Assuming no current flows out the bottom of the ionosphere we get

$$J_{\parallel} = \int_{\Delta s} (\nabla_{\perp} \cdot \vec{J}_{\perp}) ds$$

- Further assuming the electric field is uniform with height we get

$$J_{\parallel} = \nabla_{\perp} \cdot (\vec{\Sigma} \cdot \vec{E}_I)$$

- And finally using an electrostatic approximation in the MI coupling region we obtain

$$J_{\parallel} = -\nabla_{\perp} \cdot (\vec{\Sigma} \cdot \nabla_{\perp} \Phi)$$

Conductances from Particle Flux

- *Spiro et al.* [1982] used Atmospheric Explorer observations to determine a set of empirical relationships between the average electron energy and the electron energy flux

$$\Sigma_P = \left(\frac{20E_0}{4 + E_0^2} \right) \phi^{0.5} \qquad \Sigma_H = E^{0.625} \Sigma_P$$

- *Robinson et al.* [1987] revised the relationships using Hilat data and careful consideration of Maxwellian used to determine the average energy

$$\Sigma_P = \left(\frac{40E_0}{16 + E_0^2} \right) \phi^{0.5} \qquad \Sigma_H = 0.45E^{0.85} \Sigma_P$$

- *Hardy et al.* [1987] reports a slightly mistaken version of the Robinson et al. revision of the Spiro's results

$$\Sigma_P = \left(\frac{40E_0}{16 + E_0^2} \right) \phi^{0.5} \qquad \Sigma_H = 0.45E^{0.625} \Sigma_P$$

Calculation of Particle Fluxes

- Empirical relationships are used to convert MHD parameters into a characteristic energy and flux of the precipitating electrons

- Initial flux and energy

$$\varepsilon_o = \alpha c_s^2 \quad \phi_o = \beta \rho \varepsilon_o^{1/2}$$

- Parallel Potential drops (*Knight* [1972], *Chiu* [1981])

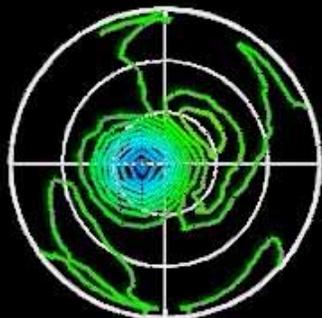
$$\varepsilon_{\parallel} = \frac{RJ_{\parallel} \varepsilon_o^{1/2}}{\rho}$$

- Effects of geomagnetic field (*Orens and Fedder* [1978])

$$\varepsilon = \varepsilon_o + \varepsilon_{\parallel} \quad \phi = \phi_o \left(8 - 7e^{\frac{-\varepsilon_{\parallel}}{7\varepsilon_o}} \right) \quad \forall \quad \varepsilon_{\parallel} > 0$$

$$\phi = \phi_o e^{\frac{\varepsilon_{\parallel}}{\varepsilon_o}} \quad \forall \quad \varepsilon_{\parallel} < 0$$

Substorm Simulation



Pot

Eng



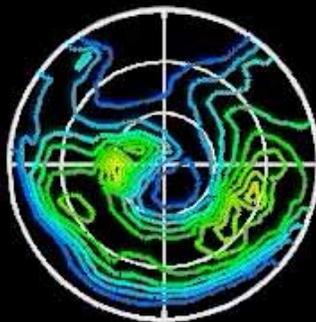
FAC
19 - 21:52:33

Flux



Ped

Hall



Brief History of Neutral Wind Effects

- *Killeen and Roble* [1984] used the TGCM to find that neutral winds can be driven to follow the ion convection pattern by ion drag forcing.
- *Forbes and Harel* [1989] modified the RCM and TGCM to include the “effective winds” and found that these winds had a relatively small effect on the system, but lacked a fully coupled ionospheric model.
- *Deng et al.* [1993] used the TIGCM to study the neutral wind “flywheel” effect and determine that it can make significant contributions to the FAC system during northward IMF conditions after a geomagnetic storm.
- More recently, *Peymirat et al.* [2002] used the MTIE-GCM to determine that the influence of neutral winds is limited to the auroral zone and the produces a $\sim 10\%$ change in potential and a 20% reduction in inner magnetospheric pressure.
 - *Ridley et al.* [2003] found similar results by coupling the TIEGCM with the BATS-R-US global MHD model of the magnetosphere.

Neutral Wind Feedback Eqs

- We can express the horizontal current in the ionosphere as

$$J_{\perp} = \sigma \cdot (\vec{E} + \vec{U} \times \vec{B})$$

where \vec{E} is the electrostatic electric field
and $\vec{U} \times \vec{B}$ is the neutral wind term

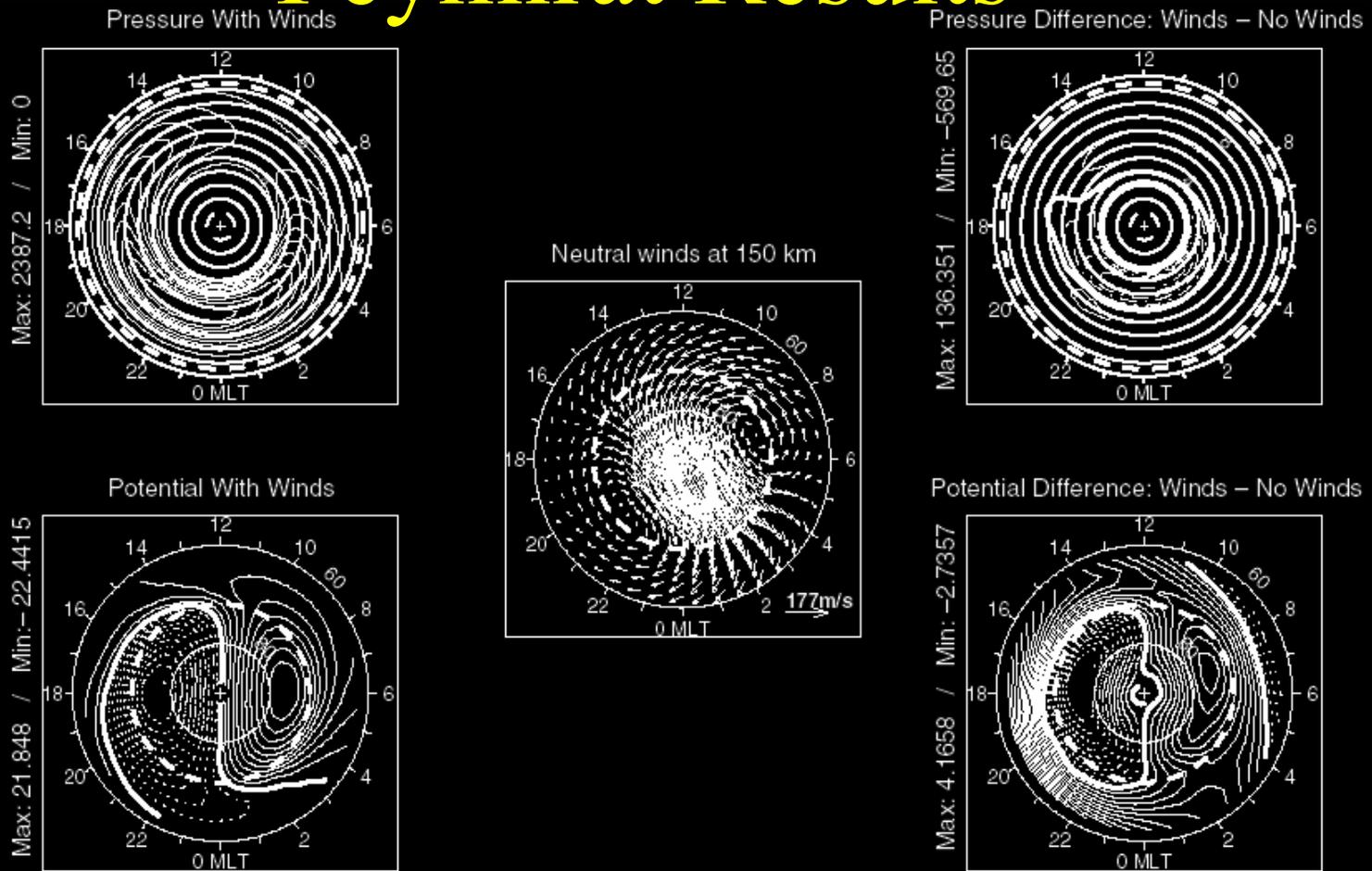
- Following a similar analysis as we did for the MI coupling equations gives us

$$J_{\parallel} = \nabla \cdot \int_{\Delta s} (\sigma \cdot \vec{E} + \sigma \cdot \vec{U} \times \vec{B}) ds$$

$$J_{\parallel} = \nabla \cdot \vec{\Sigma} \cdot \vec{E} + \nabla \cdot \int_{\Delta s} \sigma \cdot \vec{U} \times \vec{B} ds$$

$$J_{\parallel} - J_w = \nabla \cdot \vec{\Sigma} \cdot \vec{E}$$

Peymirat Results



- Neutral winds in the MTIEGCM with the SWM dynamo allow to act like a hybrid current/voltage generator increase the polar cap potential slightly and have significant changes near the auroral zones. A small increase in magnetospheric pressure is seen in the region far away from the Earth.

Ion Outflow Overview

- The magnetosphere has two main sources of plasma
 - Solar wind entry
 - *Borovsky et al. [1997]* showed that Plasma sheet density is well correlation with solar wind density especially during northward IMF
 - Ionospheric outflow
 - Numerous observations from polar orbiting satellites show fluxes of ion like O⁺ at levels that correspond to plasma sheet observations
- Two different categories of modeling ion outflow and its impacts on the magnetosphere
 - Uniform source of ions at MHD inner boundary
 - Localized outflow regions

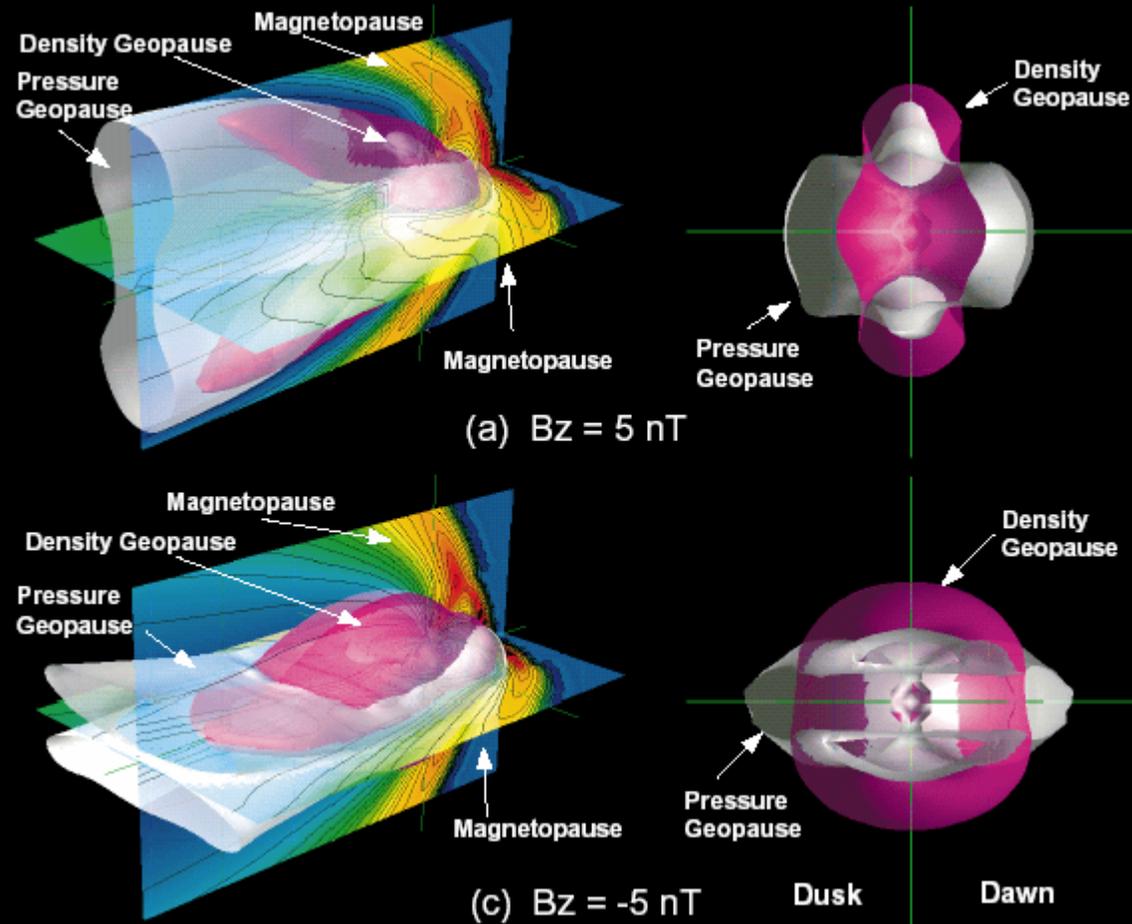
Winglee Results

- *Winglee* [2000] used a multi-fluid MHD description of the magnetosphere to study the transport of ionospheric plasma within the magnetosphere

- Uniform O^+ distribution is accelerated out of the ionosphere by two processes

- Centrifugal acceleration by the fast convection of flux tubes
- Build up of pressure gradients between ionosphere and magnetotail

- Tracked the location of the density and pressure geopauses under varying IMF conditions



Gagne Localized Outflow Model

1. Compute S_{\parallel}
 $S_{\parallel} = (\mathbf{E} \times \delta\mathbf{B} / \mu_0)_{\parallel}$

2. Dipole Map S_{\parallel}
to FAST altitude.

3. Compute Outflow Flux
 $F_i = 2.14 \times 10^7 \cdot S_{\parallel}^{1.265} \cdot f(e^- \text{ Flux})$

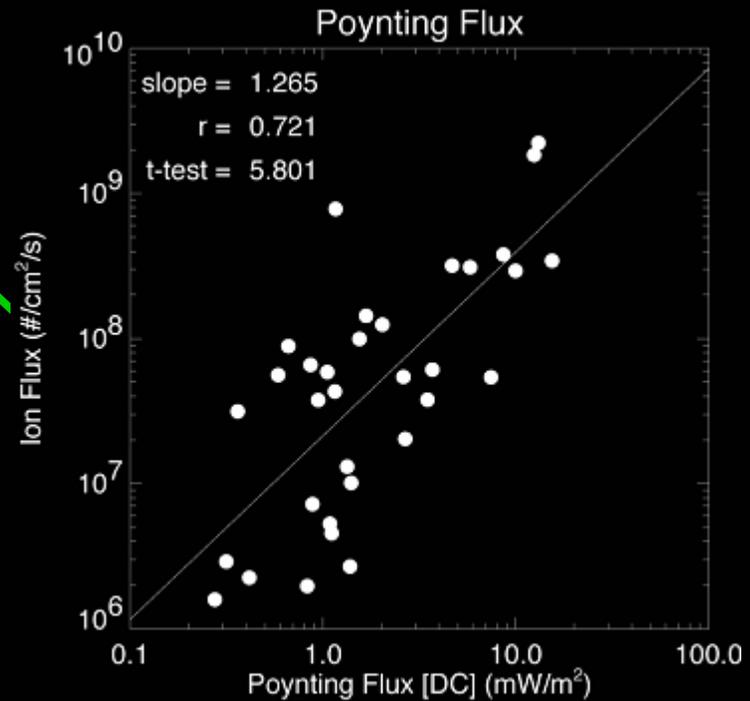
4. Map Outflow Flux back
to Inner Boundary

Rho: $\rho = f(\text{alt})$ (from Gallagher)

Vel: $v_i = F_i / \rho$

Modify v_i and ρ in LFM

Strangeway Formula:
Ion Outflow vs. Poynting Flux-CUSP

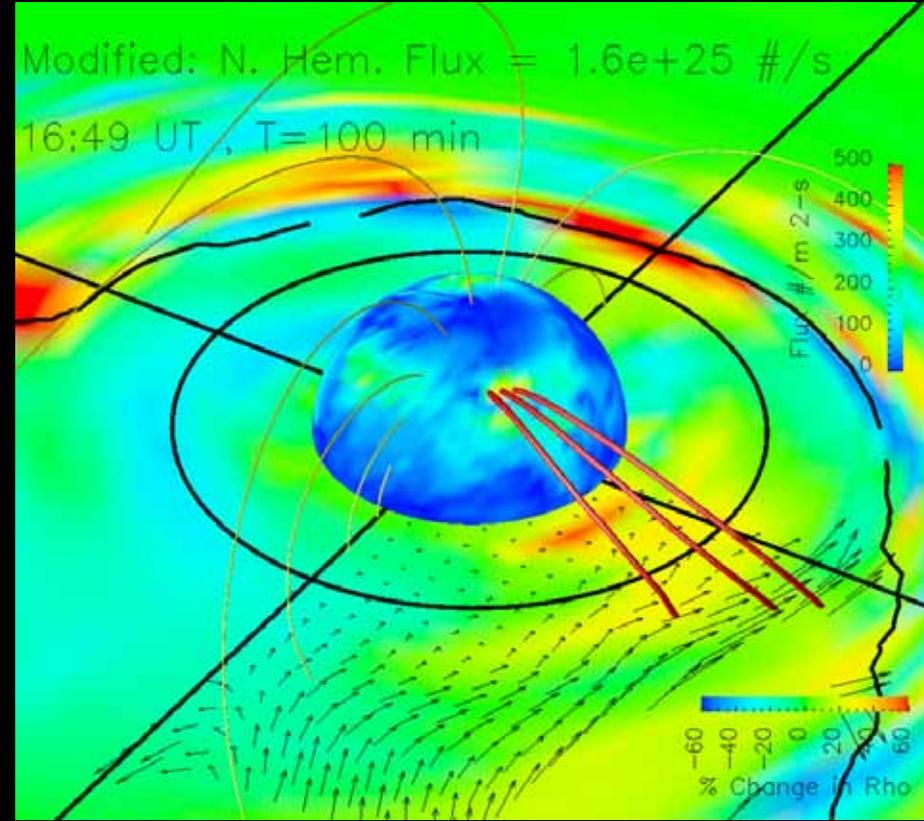
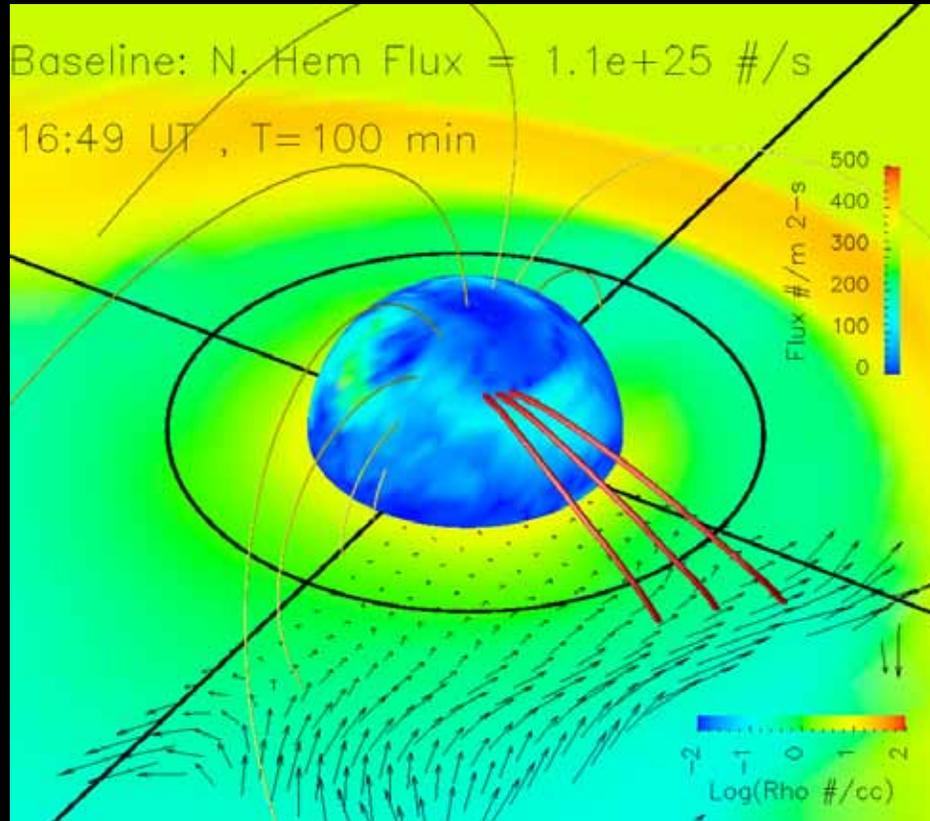


FAST Alt.
~1.6 Re

LFM: i=1
~3.5 Re

LFM: i=5
~5 Re

Gagne Results



- On the left an image from an LFM simulation 100 minutes into a period with steady southward IMF is contrasted with an image on right with the MORDOR module activated within the LFM showing localized outflow and significant changes in the plasma sheet density.

Conclusions

- Magnetosphere – Ionosphere – Thermosphere modeling is an active field with a long and interesting history of discovery.
- Using particle fluxes to determine conductivities has firm physics theory, but there is room for improvement in the methods used for getting the fluxes from MHD models.
- Thermospheric neutral wind coupling with the ionosphere and magnetosphere is an active area of research with the next generation of models which coupling existing regional models together.
 - Careful consideration needs to be given to making sure these couplings preserve the conservation of mass, energy and momentum between regions.
- Ion outflow into the magnetosphere is the newest of field and the fledging models are promising interesting results for the future.

References I

- Current system images from COMET program
- Kelly, M. C., *The Earth's Ionosphere: Plasma Physics and Electrodynamics*, Academic Press, San Diego, 1989.
- Spiro, R. W., P. H. Reiff, and L. J. Maher Jr., Precipitating Electron Energy and Auroral Zone Conductances – An Empirical Model, *J. Geophys. Res.*, 87, 8215-8227, 1982.
- Robinson, M., R. R. Vondrak, K. Miller, T. Dabbs, and D. Hardy, *J. Geophys. Res.*, 92, 2565-2569, 1987.
- Hardy, D. A., M. S. Gussenhoven, and R. Raistrick, Statistical and Functional Representations of the Pattern of Auroral Energy Flux, Number Flux, and Conductivity, *J. Geophys. Res.*, 92, 12275-12294, 1987.
- Chiu, Y. T., A. L. Newman, and J. M. Cornwall, On the structures and Mapping of Auroral Electrostatic Potentials, *J. Geophys. Res.*, 86, 10029-10037, 1981.
- Knight, S. Parallel Electric Fields, *Planet. Space Sci.*, 21, 741-750, 1972
- Orens, J. H. and J. A. Fedder, The effects of geomagnetic field aligned potential differences on precipitating magnetospheric particles, *NRL Memo. Rep.*, 3573, 1978.

References II

- Killeen, T. L. and R. G. Roble, An Analysis of the High Latitude thermospheric wind pattern calculated by a thermospheric general circulation model, *J. Geophys. Res.*, 89, 7509-7522, 1984.
- Forbes, J. M. and M. Harel, Magnetosphere-Thermosphere Coupling: An Experiment in Interactive Modeling, *J. Geophys. Res.*, 94, 2631-2644, 1989.
- Deng, W., T. L. Killeen, A. G. Burns, R. G. Roble, J. A. Slavin, L. E. Wharton, The Effects of Neutral Inertia on Ionospheric Currents in the High-Latitude Thermosphere Following a Geomagnetic Storm, *J. Geophys. Res.*, 98, 7775-7790, 1993.
- Peymirat, C., A. D. Richmond, and R. G. Roble, Neutral wind influence on the electrodynamic coupling between the ionosphere and magnetosphere, *J. Geophys. Res.*, 107, 10.1029/2001JA900106, 2002.
- Ridley, A. J., A. D. Richmond, T. I. Gombosi, D. L. De Zeeuw, and C. R. Clauer, Ionospheric Control of the Magnetospheric Configuration: Thermospheric Neutral Winds, *J. Geophys. Res.*, 108, 10.1029/2002JA009464, 2003.
- Winglee, R. M., Mapping of ionospheric outflows into the magnetosphere for varying IMF conditions, *J. Atm. Solar Terr. Phys.*, 62, 527-540, 2000.
- Gagne, J. M., Implementation of Ionospheric Outflow in the LFM Global MHD Magnetospheric Simulation, *Master's Thesis*, Dartmouth College, 2005.

