Modeling the Magnetosphere with the Multi-Fluid Lyon-Fedder-Mobarry Magnetosphere Model

M.Wiltberger
NCAR/HAO
J. G. Lyon, W. Lokto, P. Damanio
Dartmouth College
V. Merkin
Boston University

Lessons from Dennis

- Use your curiosity to find interesting questions to ask, but rely on physics to find the answers
- Simulations are only meaningful when compared to observations
- Make sure your students get the chance to present their results
- Work with good people
- Eat good food!

Outline

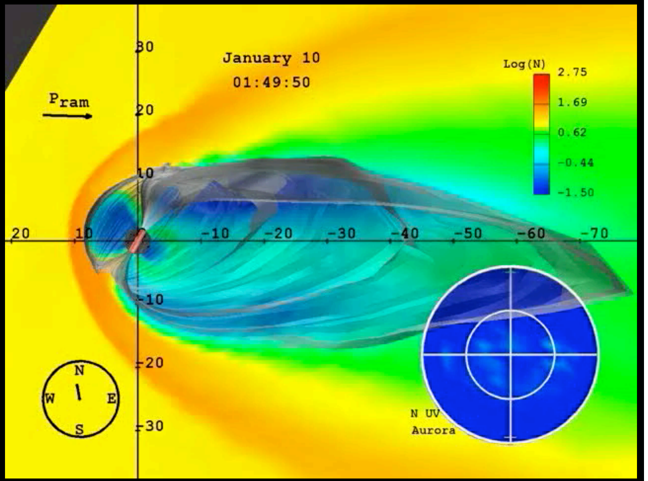
- Background and motivation
- The MultiFluid Lyon-Fedder-Mobarry Model
- Parameterized Cleft Outflow
  - Low Speed/High Flux
  - High Speed/High Flux
- Conclusions

Motivation for Including Ion Outflow

- In previous work with the LFM only electrodynamic coupling between the magnetosphere and ionosphere was considered
- Using Cluster observations *Kistler et al.* (2005) showed that O^+ can become the main component of the plasma sheet during strong magnetic storms
- *Shay and Swisdak* (2004) found that the rate of reconnection is controlled by the heavy ion species in multi-species simulations
  - They suggest this may have an impact on the size and occurance frequency of substorms
- *Winglee et al.* (2002) found a significant reduction in the CPCP with their multifluid MHD simulation
  - The LFM is known to have a high values for the CPCP
- With the advent of the multifluid version of the LFM it is now possible to consider the effect of ionospheric O^+ on magnetospheric dynamics

Multi-Fluid LFM Magnetospheric Model

- Uses the multi-fluid MHD equations to model the interaction between the solar wind, magnetosphere, and ionosphere
  - Computational domain
    - 30 $R_E < x < -300$ R_E & $\pm 100 R_E$ for YZ
    - Inner radius at 2 R_E altitude
  - Calculates
    - Solves mass, parallel and perpendicular momentum, and plasma energy for each plasma species
    - Self consistent magnetic field configuration
  - Requires
    - Solar wind MHD state vector along outer boundary
    - Empirical model for determining energy flux of precipitating electrons
    - Cross polar cap potential pattern in high latitude region which is used to determine boundary condition on flow
    - Specification of plasma outflow from inner boundary



MFLFM Equations

$$\frac{\partial \rho_\alpha}{\partial t} = -\nabla \bullet \rho_\alpha \vec{u}_\alpha$$

$$\frac{\partial \vec{p}_\alpha}{\partial t} = -\nabla \bullet \left(\vec{p}_\alpha \vec{u}_\alpha + \overleftrightarrow{I} P_\alpha \right) + \vec{F}_\alpha^d + n_\alpha q_\alpha \vec{E}_\parallel$$

$$\frac{\partial \varepsilon_\alpha}{\partial t} = -\nabla \bullet \vec{u}_\alpha \left(\varepsilon_\alpha + P_\alpha \right) + \vec{u}_\alpha \bullet \left(\vec{F}_\alpha^d + n_\alpha q_\alpha \vec{E}_\parallel \right)$$

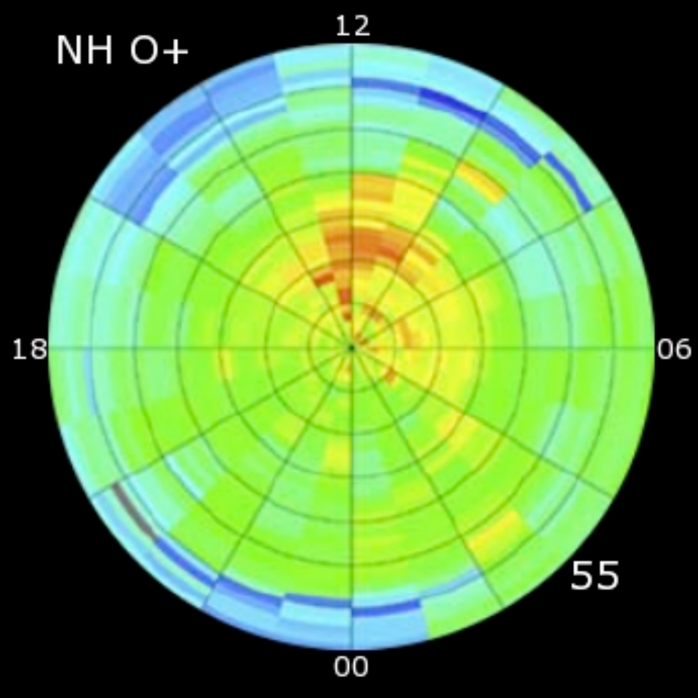
$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \left(\vec{u} \times \vec{B} \right)$$

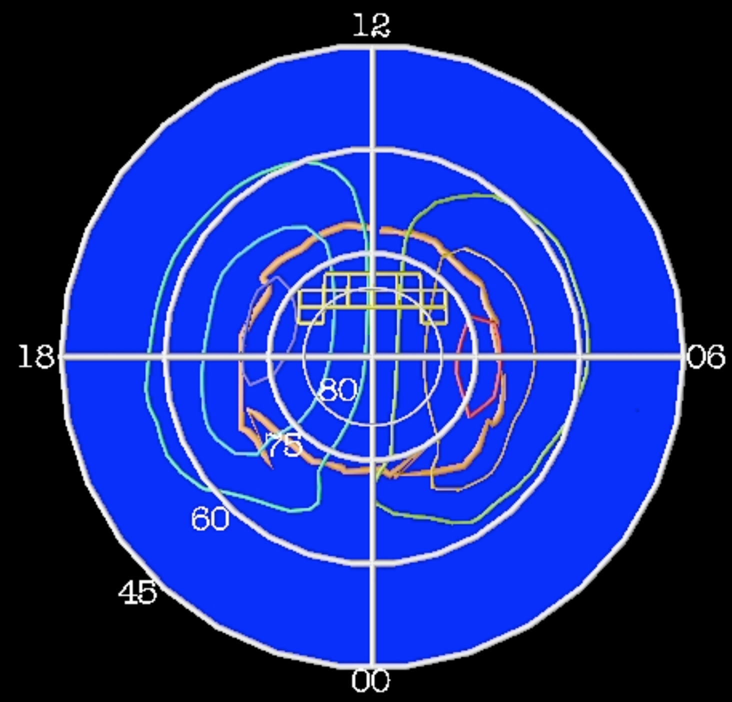
$$F_\alpha^d \equiv \hat{b} \times \left[\begin{array}{l} \vec{p}_\alpha \bullet \nabla \vec{u}_\alpha + \nabla P_\alpha + \dfrac{\rho_\alpha \left(\vec{u} - \vec{u}_\alpha \right) \bullet \hat{b}}{B} \dfrac{\partial \vec{B}}{\partial t} \\ -\dfrac{\rho_\alpha}{\rho} \left(\sum_\beta \left(\vec{p}_\beta \bullet \nabla \vec{u}_\beta + P_\beta \right) + \nabla P_e - \vec{j} \times \vec{B} \right) \end{array} \right] \times \hat{b}$$

$$\vec{E}_\parallel = -\hat{b}\hat{b} \bullet \nabla P_e / ne$$

- These equations evolve the ion density, momentum, and plasma energy
  - The electrons are assumed to be inertialess
  - E|| is the ambipolar electric field
- All ion species move with the E x B drift velocity in the perpendicular direction
  - The time rate of change of B in the drift force term transfers momentum between species when the magnetic field direction changes
- When the drift force is summed over species we recover the one fluid MHD equations less electron inertia

O^+ Outflow Region

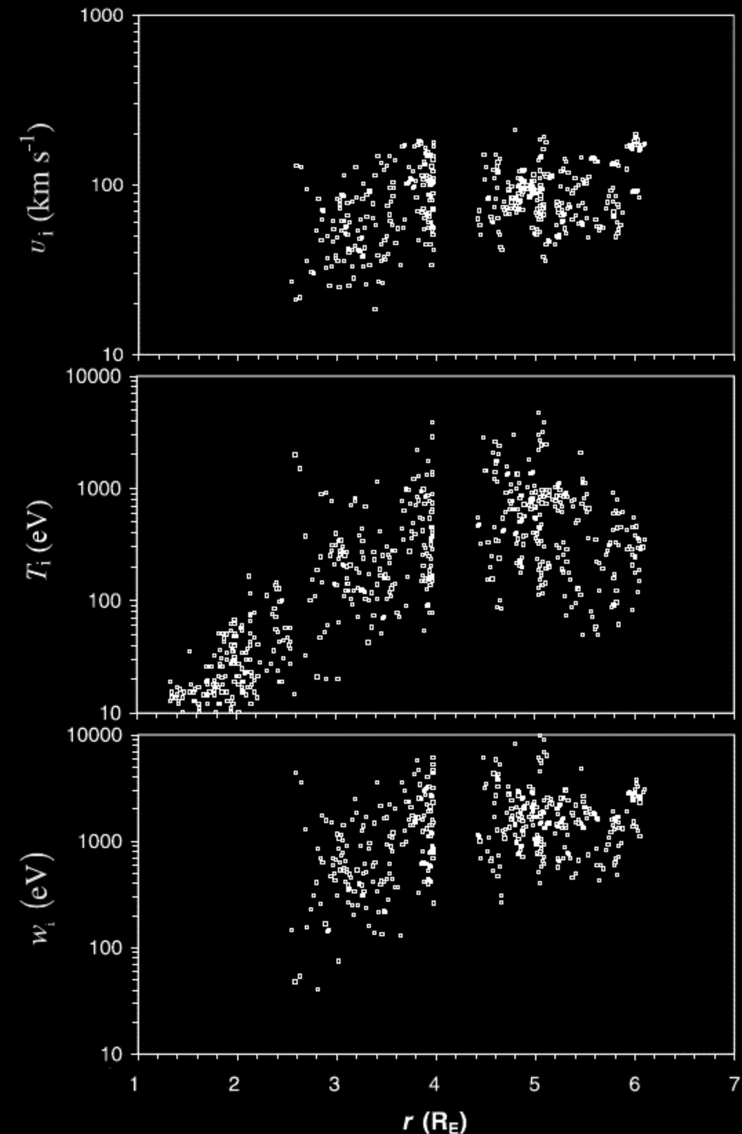




- *Lennartsson et al. 2004* and *Andersson et al. 2005* have statistically identified a cusp-like outflow region on the dayside
  - This region roughly corresponds to *Newell & Meng 1992* LLBL, cusp, and mantle electron precipitation region
- We turn on O+ in cells whose ionospheric foot points map to a similar region on the LFM ionospheric grid

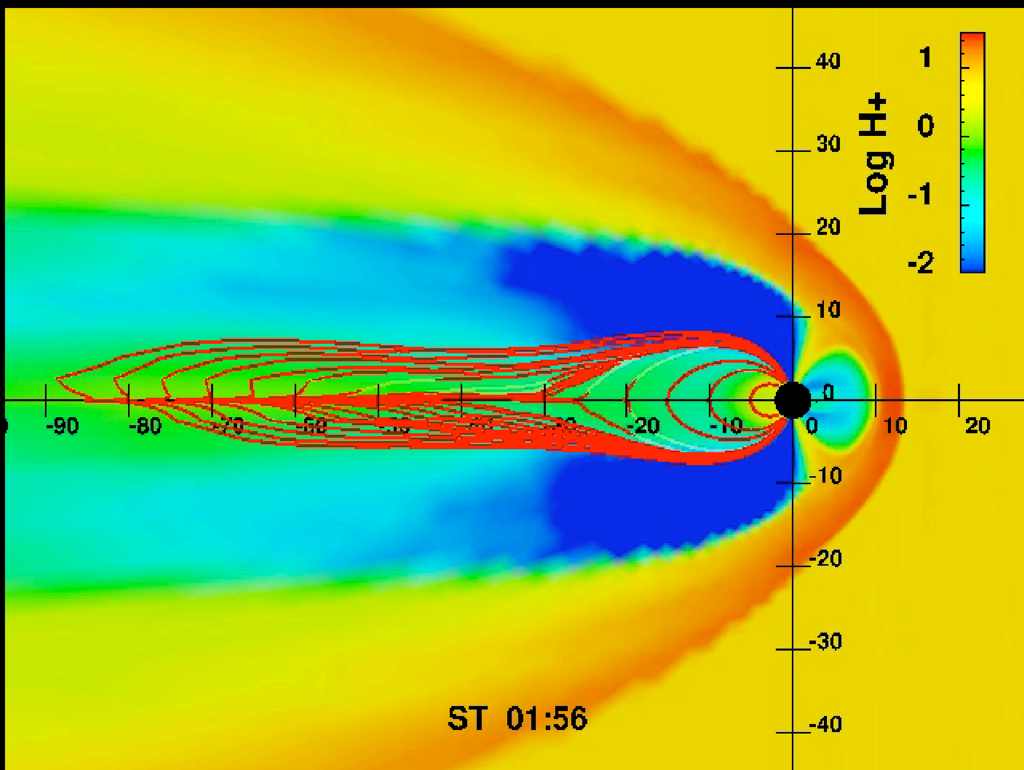
O^+ Outflow Parameters

- *Bouhram et al. 2004* used Akebono, Interball, and Cluster observations to study the altitude profile O+ ions coming out of the cleft
  - Note the broad range in measurements
    - parallel velocities 20-100 [km s^{-1}]
    - Temperature 10-100 [eV]
    - Fluxes – 10^6 [cm^{-2} s^{-1}]
  - Flux and density have a solar cycle variance, but in parallel velocity and temperature it is less
- *Strangeway et al. 2005* report cusp region fluxes at FAST altitudes ranging from 10^6 to 10^9 [cm^{-2} s^{-1}] during the Sep 24-25, 1998 geomagnetic storm
- *Nillsson et al. 2006* report fluxes ranging from 10^7 to 10^9 [cm^{-2} s^{-1}] in a statistical study of Cluster data
- Given the broad range of measurements we have chosen fix parameters for the O^+ coming from our cusp region
  - Flux - 10^9 [cm^{-2} s-1]
  - Velocity - 20 [km s^{-1}]
  - Temperature - 10 [eV]



From Bouhram et al. 2004

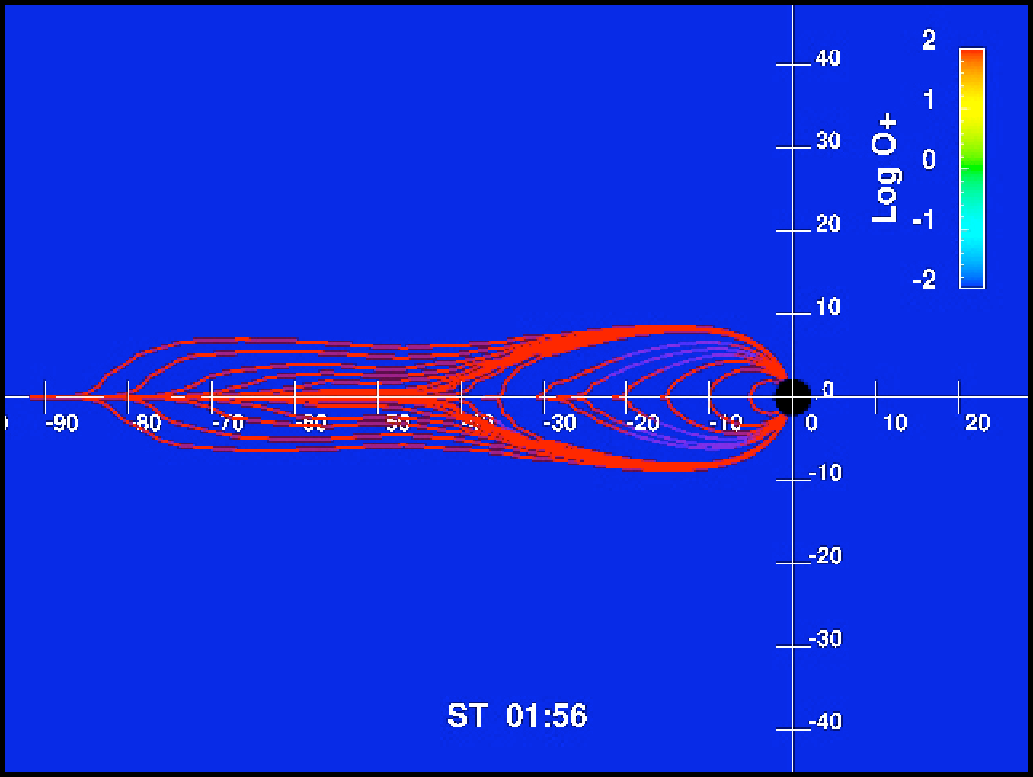
Baseline



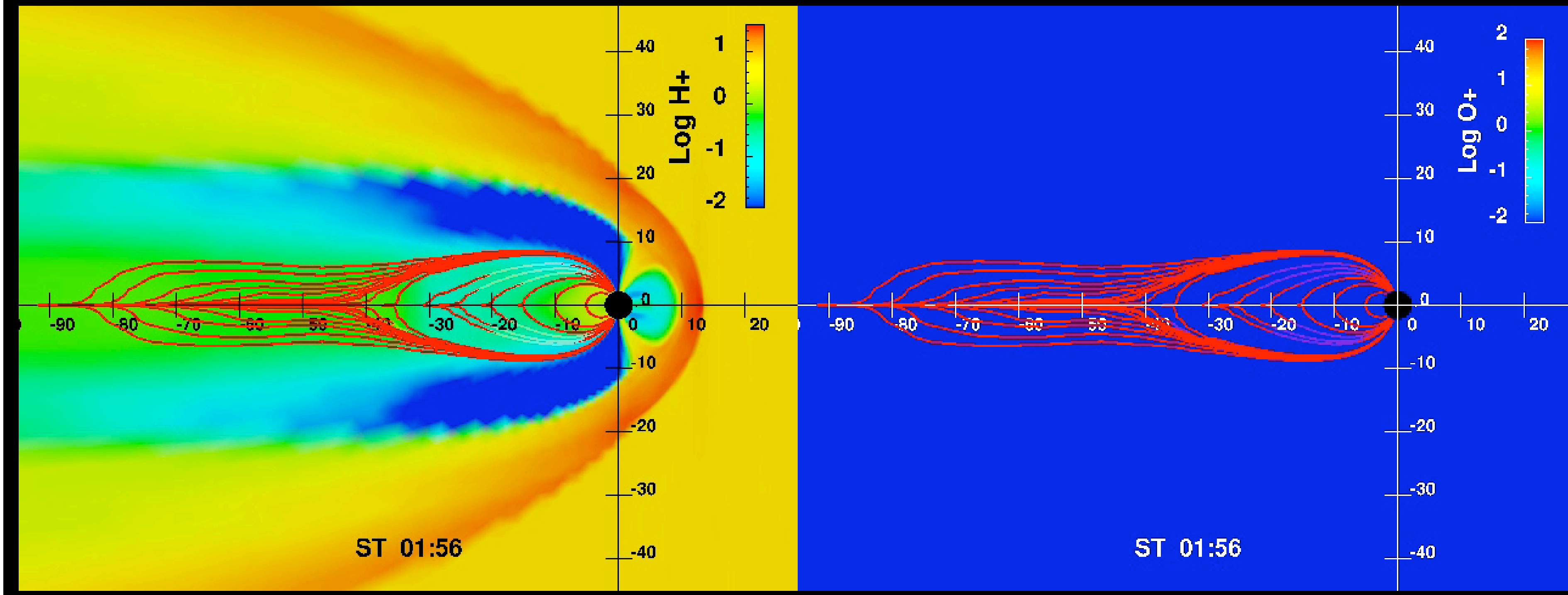
- A run of the MFLFM was completed using 99.99% H^+ in the solar wind
  - Solar wind speed is 400 km/s with a density of 5 #/cc
  - The IMF changes from +5nT at 02 ST to -5nT
- At approximately 0245 ST the simulation produces a plasmoid with reconnection site occurring at -20 R_E
- The simulation then enters a quasi-steady equilibrium with reconnection occurring near -30 R_E

Cusp-Cleft Outflow

- The initial substorm at is not dramatically affected by the outflow since it does not reach the X line
- A second substorm occurs with an onset at 0530 ST with the X line occurring earthward of -20 R_E
- Simulation then appears to enter a period of a quasi-steady reconnection with tailward of -20 R_E



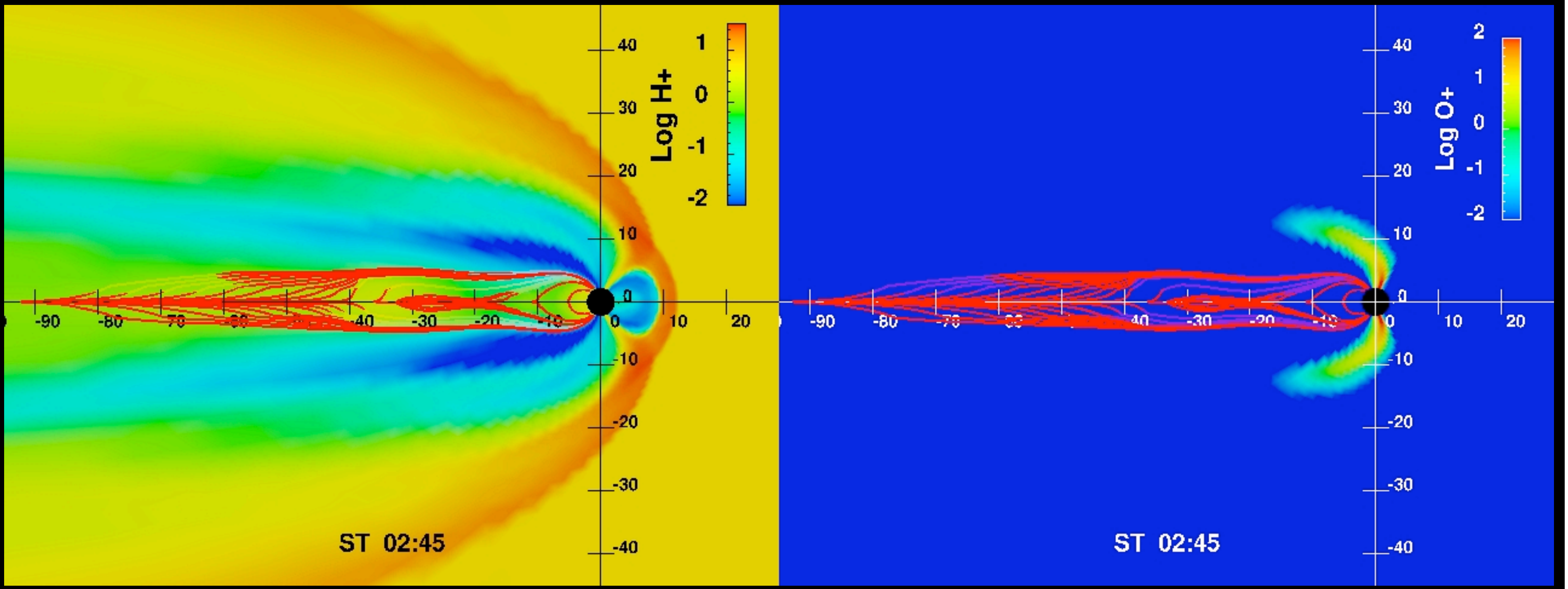
Comparison



No Outflow

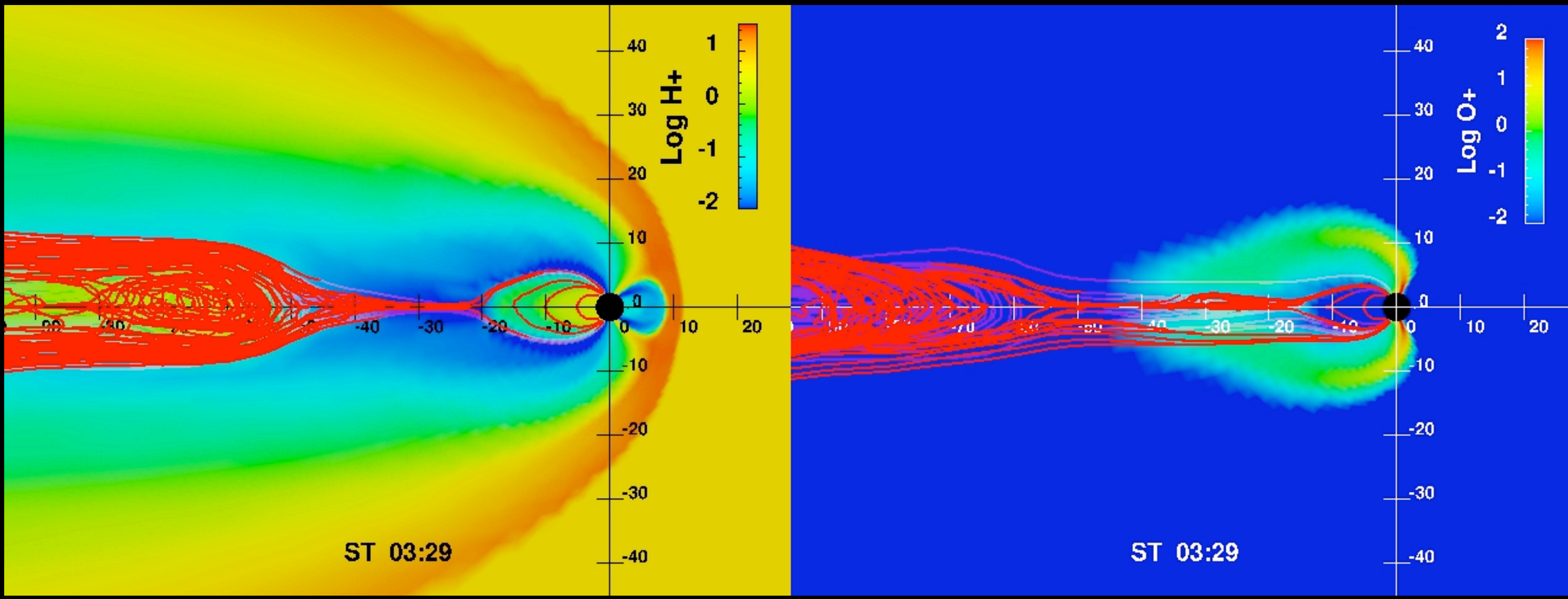
Outflow

02:45 ST



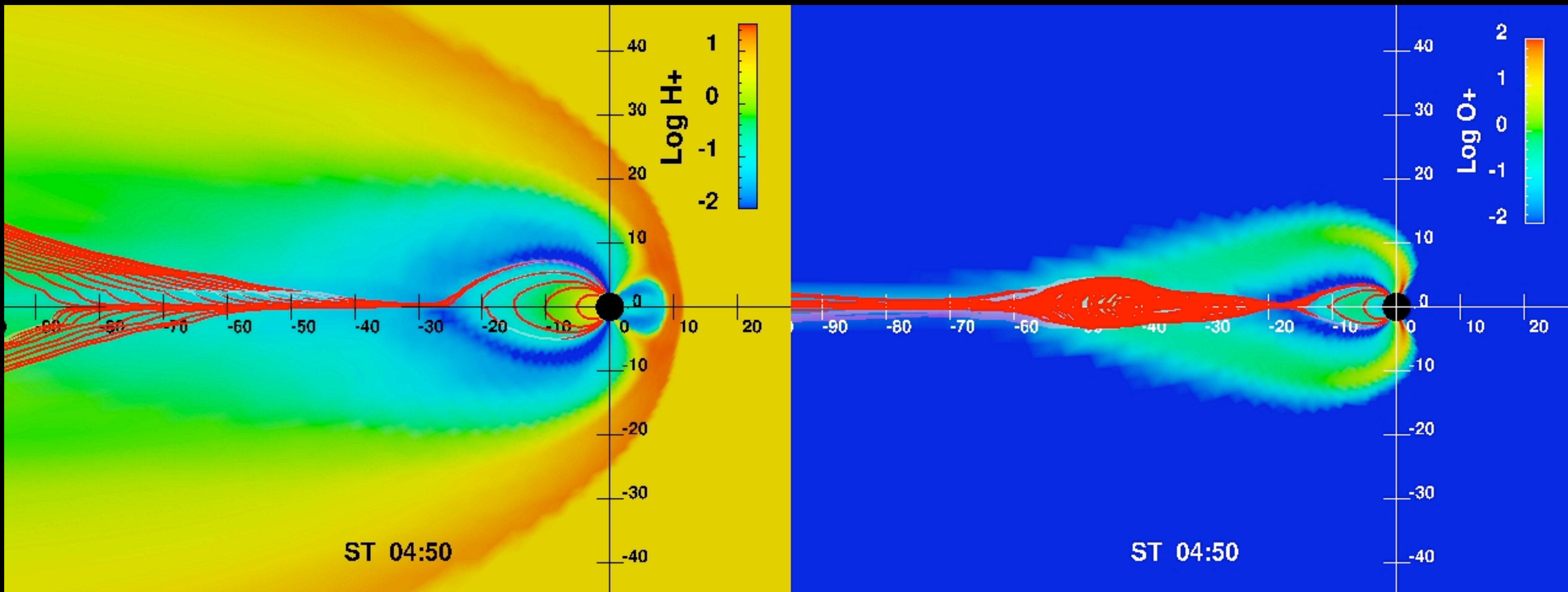
- During the initial formation of the first plasmoid the two simulations appear quite similar because the O+ flow from the ionosphere has not propagated very far into the magnetotail

03:29 ST



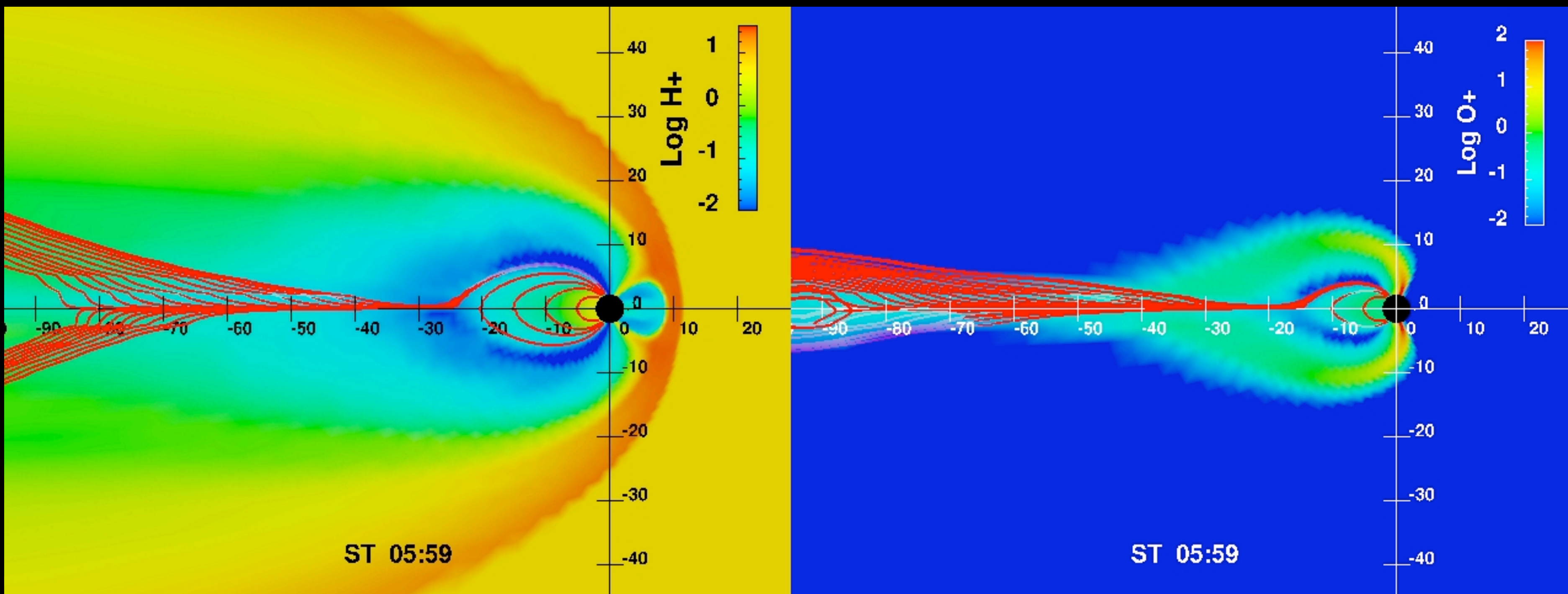
- After the release of the first plasmoid O^+ from the outflow region begins to directly enter the plasma sheet in the near Earth region
  - O^+ impact on the reconnection process has altered the shape and timing of the plasmoid

04:50 ST



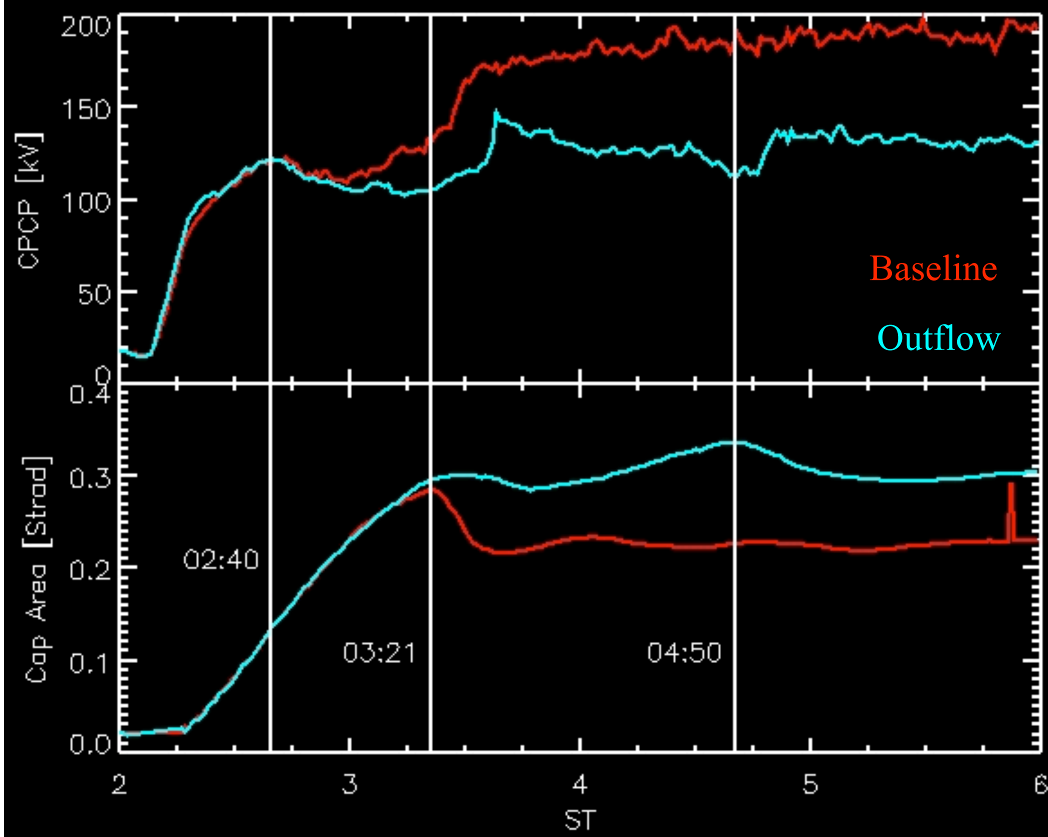
- Here we can see the release of the second plasmoid
  - Most of the O+ outflow is now landing tailward of the reconnection region
  - O+ is significant in the near Earth plasma sheet

05:59 ST



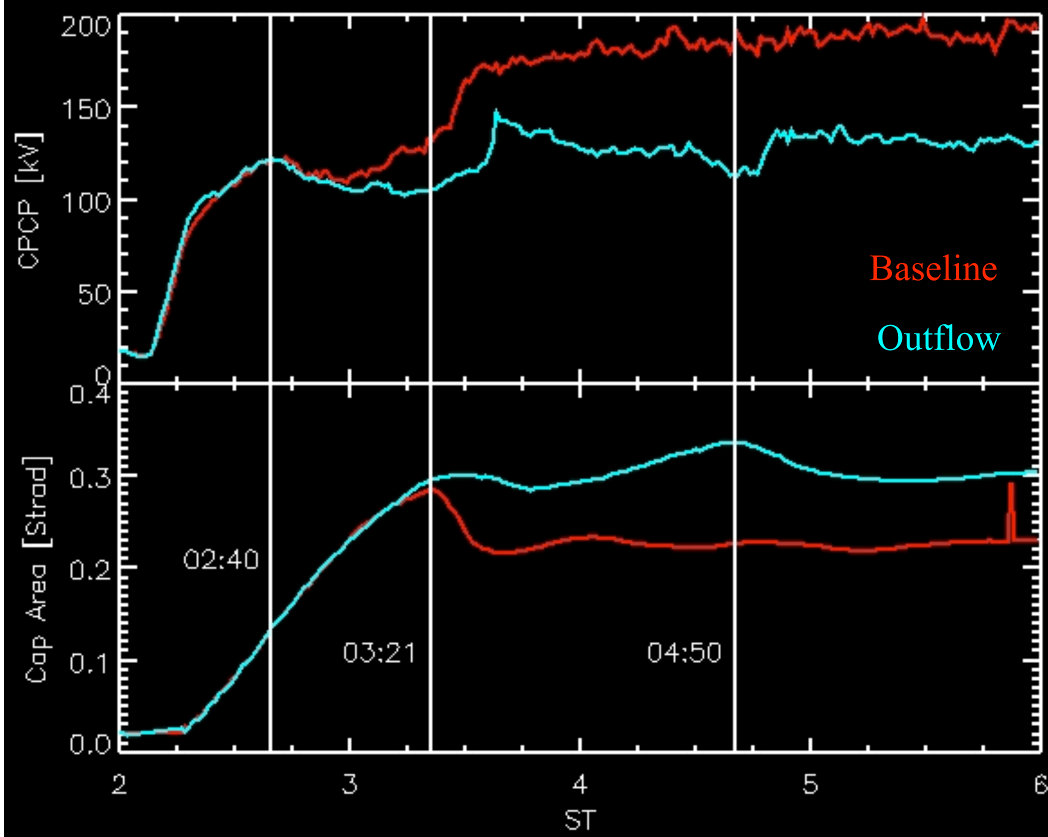
- The run with outflow has established a new quaisteady equilibrium with the reconnection line near x=-15R_E
  - Contrast that with the reconnection point in the baseline simulation of X=-20 R_E

Cross Polar Cap Potential



- Shortly after the arrival of the southward IMF both simulations show a similar response in both the polar cap potential and area
  - An initial peak is seen at 02:40 ST near the time of initial plasmoid formation
- The simulation with outflow saturates a significantly lower potential
  - A global reduction in R1 currents is also seen
    - Linked to both changes in conductance and mass loading

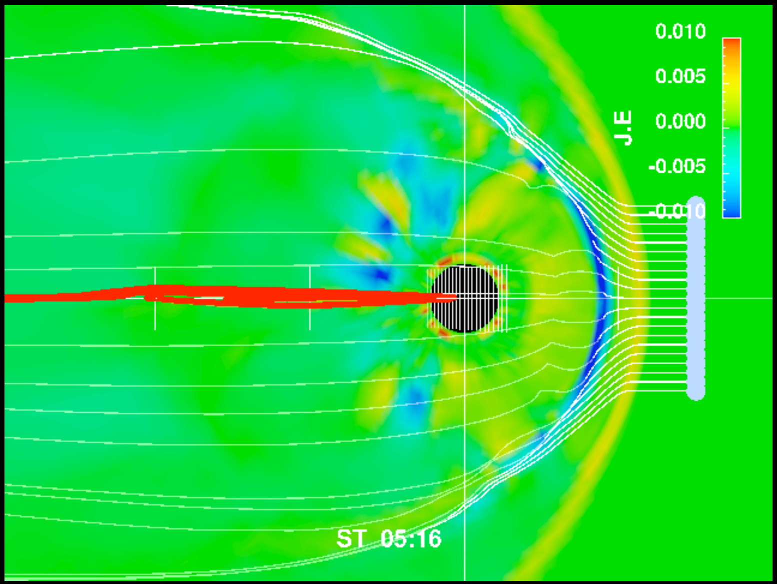
Polar Cap Area



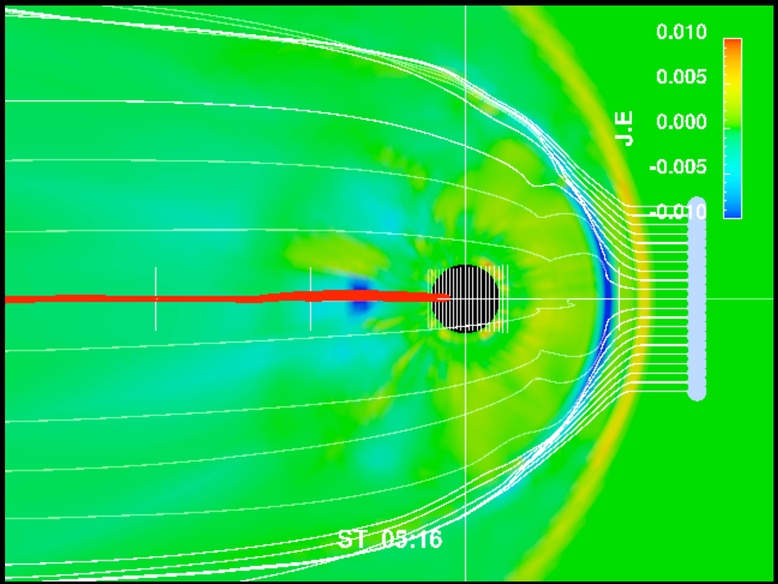
- The peak in polar cap area for the baseline run is seen at 03:21 ST, but in the outflow run it is seen 3 minutes later
  - This is a clear indication that the O+ is affecting the reconnection rate
- After the release of the first plasmoid the baseline simulation stabilizes while the polar cap area increases until a second plasmoid is released at 04:50 ST
  - A significant contributing factor is the repopulation of the plasma sheet

Hints of Nonlinearity

- Answering the question of how CPCP is lower with a lower polar cap area shows indications of nonlinear response
  - The outflow is impacting the shape of the magnetopause leading to a blunter object in the flow
  - This shape maps into a smaller region the solar wind and therefore a smaller polar cap potential



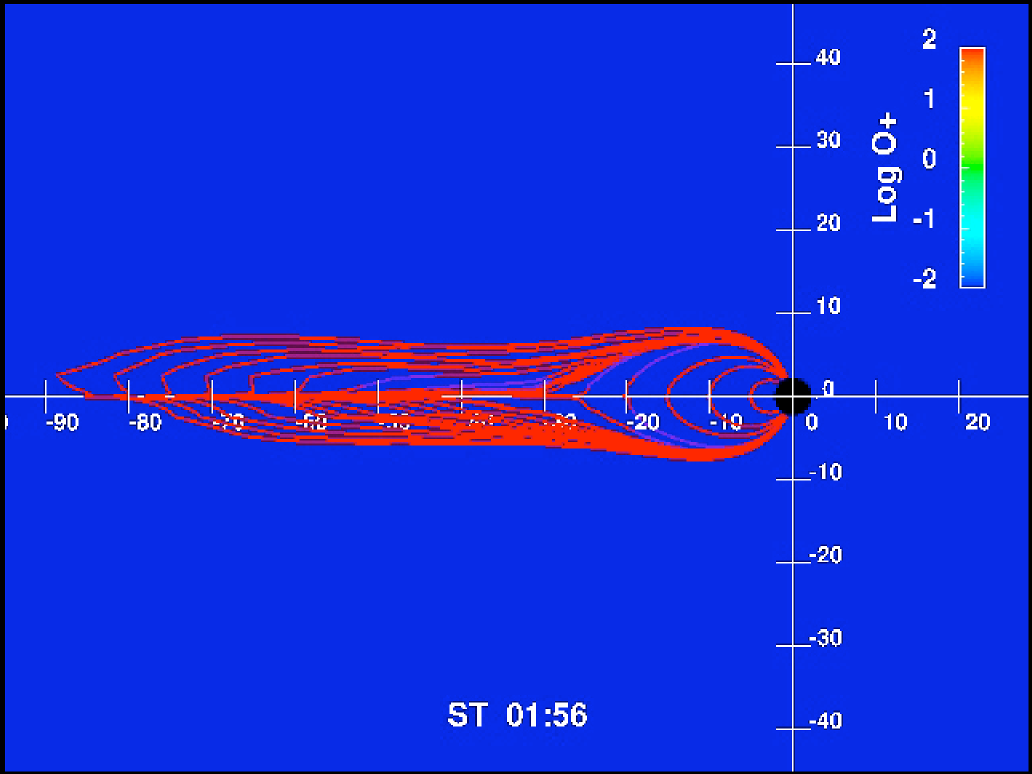
Baseline



Outflow

High Speed Cusp-Cleft Outflow

- In this case we increased the outflow velocity to 50 km/s while maintaining the same flux
- The initial substorm at is not dramatically affected by the outflow since it does not reach the X line
- Since the outflow lands tailward of the reconnection region the simulation enters the same quasi-steady state with no clear entry of O+ into the magnetotail



Ionospheric Outflow Summary

- We have clearly shown that ionospheric outflow dramatically impact the evolution of the magnetosphere
  - Cusp outflow which hits the near Earth reconnection site results in O^+ entering the plasma sheet creating conditions for a second substorm
- Initial results indicate that the impact of outflow on the evolution of the magnetosphere is sensitive to the parameters of the outflow
- Need to determine the relative importance of changes in magnetospheric shape and conductance are playing in the reduction of the cross polar cap potential
- More accurate and causally driven models of ionospheric outflow are needed

[redacted]

References

- Current system images from COMET program
- Cattell, C. J. Dombeck, C. Carlson, and J. McFadden, FAST observations of the solar illumination dependence of downgoing auroral electron beams: Relationship to electron energy flux, *J. Geophys. Res.,* 111, A02201, doi:10.1029/2005JA011337.
- Fedder, J. A. and J. G. Lyon, The solar wind – magnetosphere – ionosphere current voltage relationship, *Geophys. Res. Lett.,* 96, 2723, 1987.
- Friedman, M and J Lemaire, Relationship between auroral electron fluxes and field aligned electric potential difference, *J. Geophys. Res,*85(A2) 664, doi:10.1029/JA085iA02p00664, 1986.
- Knight, S. Parallel electric fields, *Planet. Space. Sci., 21, 741, 1972.*
- Liou,
- Morooka, M. and T. Mukai, Density as a controlling factor for seasonal and altitudinal variations of the auroral particle acceleration region, *J. Geophys. Res,*108(A7) 1306, doi:10.1029/2002JA0097886, 2003.
- Newell, P. T., C-I Meng, and K. M. Lyons, Suppresion of discrete aurorae by sunlight, *Nature, 766, 381, 1996.*
- Newell, P. T., T. Sotirelis, J. P. Skura, C-I Meng, W. Lyatsky, Ultraviolet insolation drives seasonal and diurnal space weather variations, *J. Geophys. Res.,* 107(A10), 1305, doi:10.1029/2001JA000296, 2002.
- Papitashvilli, V. O., F. Christiansen, and T. Neubert, A new model of field aligned currents derived from high-precision satellite magnetic field data, *Geophys. Res. Lett.,* 29, 1683, doi:10.1029/2001GL014207, 2002.
- Russel, C. T., and R. L. McPherron, Semiannual Variation of Geomagnetic Activity, *J. Geophys. Res.,*78, 92, 1973.

References II

- Andersson, L. W. K. Peterson, and K. M. McBryd, Estimates of the superthermal O+ outflow characteristic energy and relative location in the auroral oval, *Geophys. Res. Lett., 32,* L09104, doi:10.1029/2004GL021434, 2005.
- Bouhram, M., B Klecker, W. Miyake, H. Reme, J. A. Sauvaud, M. Malingre, L. Kistler, A. Blagau, On the altitude dependence of transversely heated O+ distributions of the cusp/cleft, *Ann. Geophys. 22,* 1787-1798, 2004.
- Kistler, L. M., C. Mouikis, E. Mobius, B. Klecker, J. A. Sauvaud, H. Reme, A. Korth, M. F. Marcucci, R. Lundin, G. K. Parks and A. Balogh, Contribution of nonadiabatic ions to the cross-tail current in an O+ dominated thin current sheet, *J. Geophys. Res, 110*, A06213, doi:10.1029/JA010653.
- Lennartsson, O. W., H. L. Collin and W. K. Peterson, Solar wind control of the Earth's H+ and O+ outflow rates in the 15-eV to 33-keV energy range, *J. Geophys. Res., 109,* A12212, doi:10.1029/2004JA010690, 2004.
- Newell, P. T. and C. I. Meng, Mapping the dayside ionosphere to the magnetosphere according to particle precipitation characteristics, *Geophys. Res. Lett., 19(6),* 609-612.
- Shay, M. A. and M. Swisdak, Three-species Collisionless Reconnection: Effect of O+ on Magnetotail Reconnection, *Phys. Rev. Lett., 93(17),* 175001, doi:10.1103/PhysRevLett.93.175001, 2004.
- Strangeway, R. J., R. E. Ergun, Y. J. Su, C. W. Carlson, and R. C. Elphic, Factors controlling ionospheric outflows as observed at intermediate altitudes, *J. Geophys. Res., 110,* A03221, doi:10.1029/2004JA010829, 2004.
- Winglee, R. M., D. Chua, M. Brittnacher, G. K. Parks, and G. Lu, Global impact of ionospheric outflows on the dynamics of the magnetosphere and cross-polar cap potential, *J. Geophys. Res, 107,* doi:10.1029/2001JA000214, 2002.