Division III Reporter Review: Global Dynamics

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Task and Scope

- Provide a review of the literature related to modeling the interaction of the magnetosphere-ionosphere system with the solar wind on a global scale
- Scope
  - Only included peer reviewed publications in major journals, e.g. JGR, GRL, SW, AG, JASTP, from 7/09 to 6/11
  - Reporting content of papers not providing any scientific assessment
  - Papers must have a global modeling as a significant component
  - Only 40 minutes so the coverage is not comprehensive
    - Apologies to papers I may have had to skip for time

Broad Topic Areas I

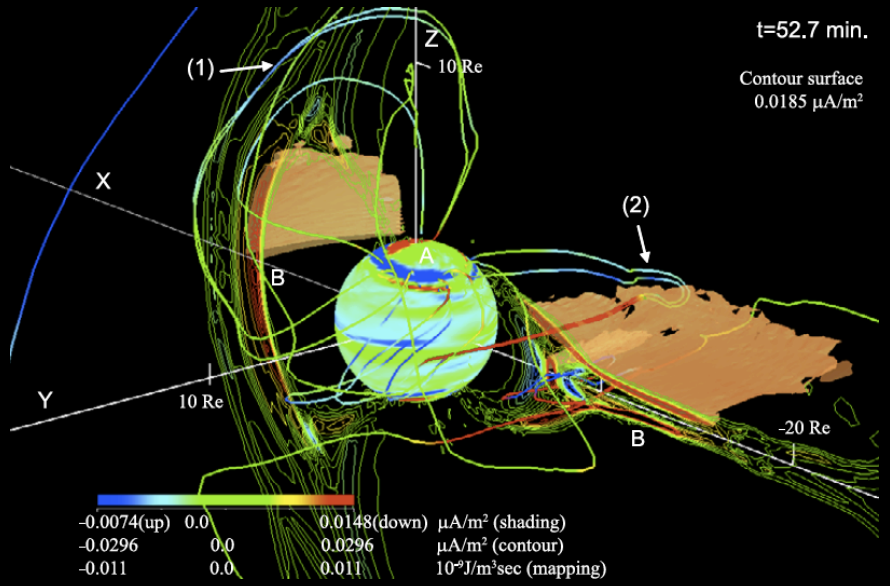
- Substorms
  - Efforts to model the onset and evolution of substorms
- Ionospheric Outflow modeling
  - Developments related to modeling with more than one fluid including ionospheric outflow
- Other IMF Directions
  - Using models to look at system for IMF directions besides B_Z
- Polar Cap Potential Saturation
  - Modeling efforts to understand the nonlinear saturation of the polar cap potential
- Interlude
  - A brief break of global simulations

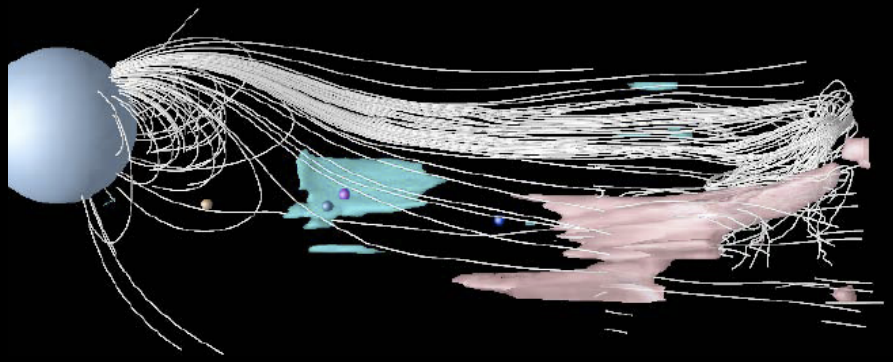
Broad Topic Areas II

- Dayside Reconnection
  - Structure and dynamics of the magnetic reconnection process on the dayside especially FTEs
- Waves
  - Using global models to study the structure and distribution of waves in the magnetosphere
- Validation and Verification
  - Studies assessing the accuracy of global models
- Miscellaneous
  - Papers that didn't fit, but had neat ideas

Substorms

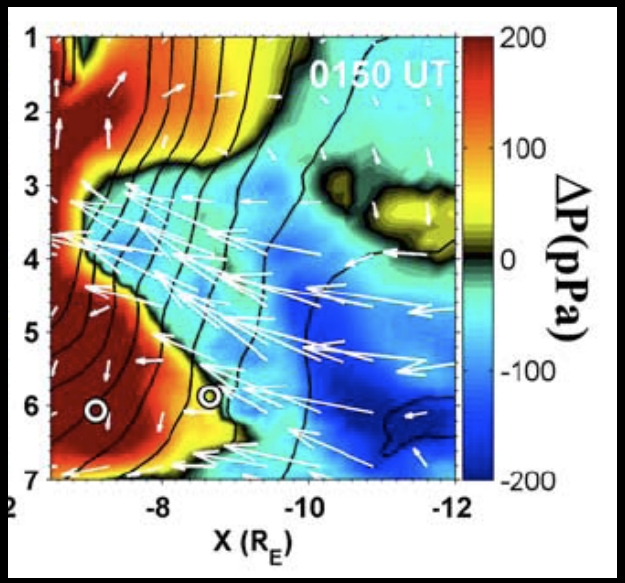
- Tanaka et al., JGR, 2010
  - Used his global MHD model
  - Examined the structure and evolution of the current systems for an idealized event
    - Substorm current wedge formed at onset
    - Shows complicated interaction of current systems





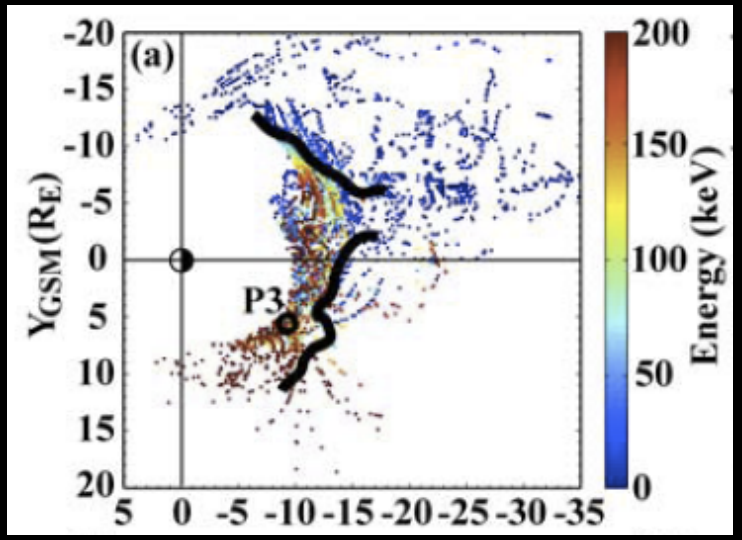
- Harnett et al., JGR, 2008
  - Used the Winglee Multifluild model
  - Examined initiation of substorm on 26 Feb 2008
    - State that arrival of heavy ions in magnetotail leads to substorm onset
    - Fast flows link reconnection and aurora
    - Onset in simulation precedes THEMIS observations

Substorms II

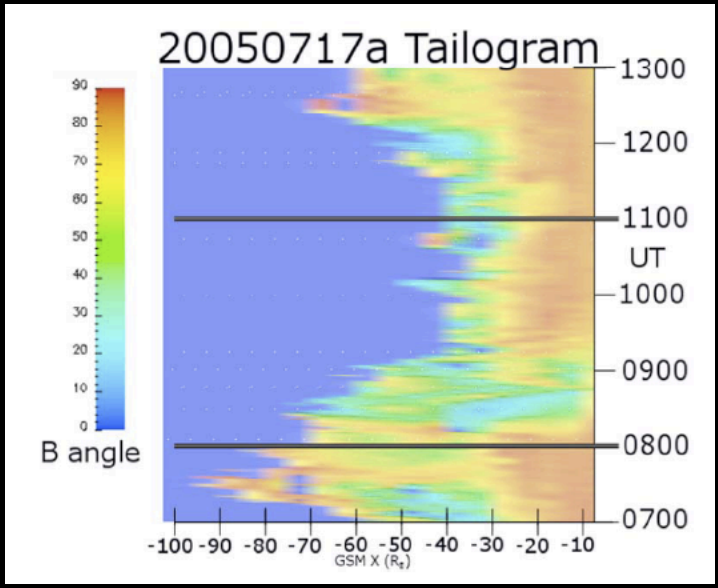


- Ashour-Abdalla et al., JGR, 2009
  - Used the UCLA Model + LSK
  - Examined particle motions in MHD fields for substorm on 1 Mar 2008
  - Acceleration mostly occurred in regions with large electric fields and nonadiabatic motion
  - Prior to onset contribution to cross tail current from ionospheric sources

- El Alaoui et al., JGR, 2009
  - Used the UCLA Model
  - Compared results to THEMIS observations for substorm on 1 Mar 2008
  - Complex dynamics in magnetotail
    - Reconnection prior to onset on closed field lines
    - Vorticies near P3 and P4
    - Multiple NL merging to for single NL

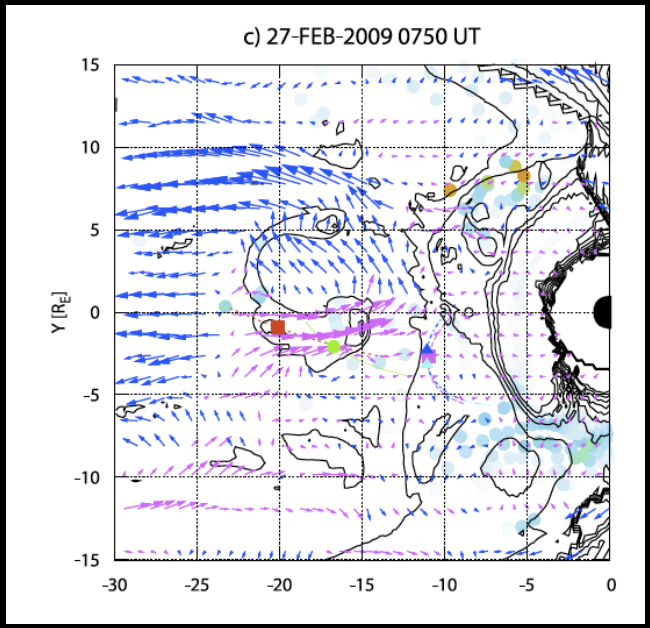


Substorms III

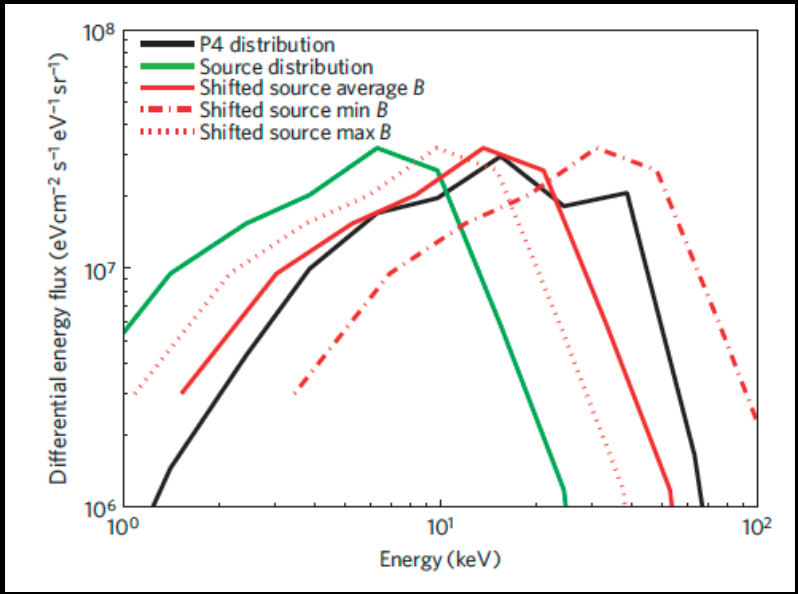


- Farr et al., JGR, 2010
  - Used the LFM model
  - Focused on the recovery phase of the substorm by simulating 7 different substorm intervals
  - Saw evidence in simulation for retreat of tail reconnection line to conditions in the solar wind

- Ge et al., JGR, 2011
  - Used the OpenGGCM Model
  - Event study of 27 Feb 2009 substorm onset
  - Auroral breakup caused by vortices at edge of BBFs
  - Examines relationship between DF structures and multiple X lines in simulation



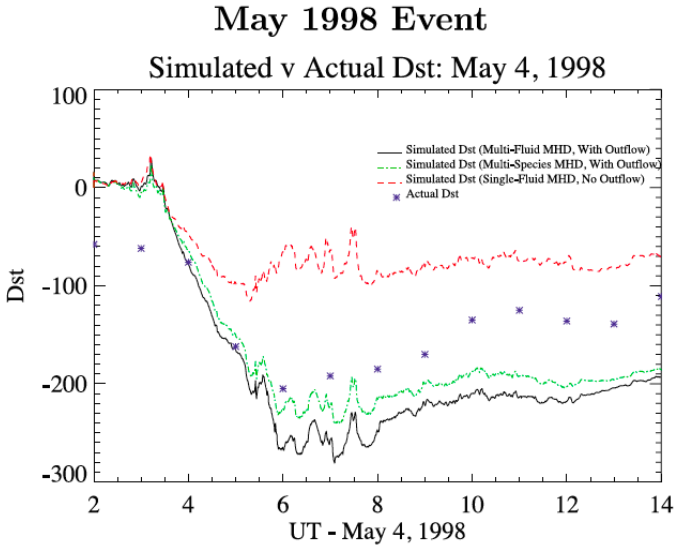
Substorm IV

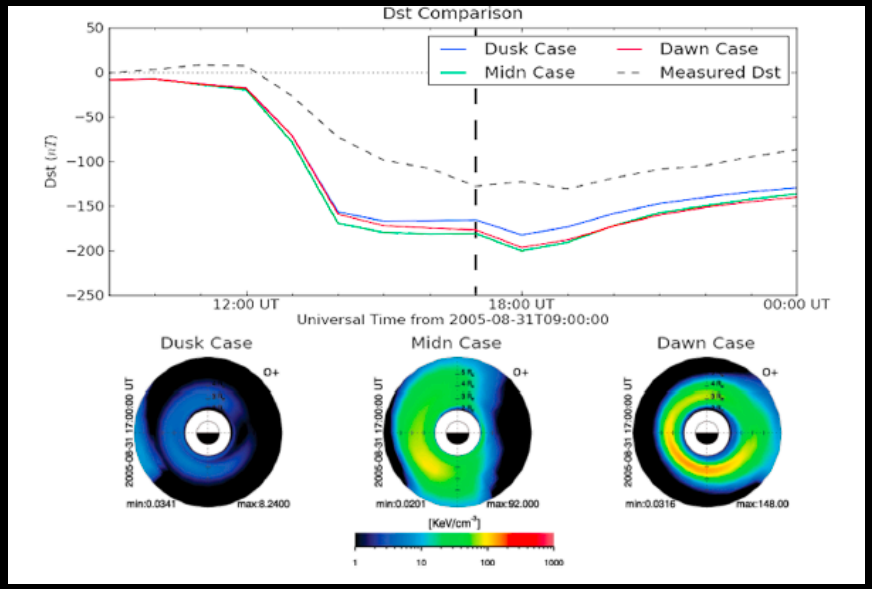


- Ashour-Abdalla et al., Nature Physics, 2011
  - Used the UCLA Model + LSK
  - Examined particle motions in MHD fields for substorm on 15 Feb 2008
  - Particle energization is associated with both magnetic reconnection and with betatron acceleration

Ionospheric Outflow Modeling

- Glocer et al., JGR, 2009
  - Used the SWMF
    - Adds a Polar Wind Outflow Model (PWOM)
  - Event studies for two geomagnetic storms
  - Multispecies MHD is used track the evolution and impact of O+
    - Reduces RMS error of GOES magnetic field comparison by 50%

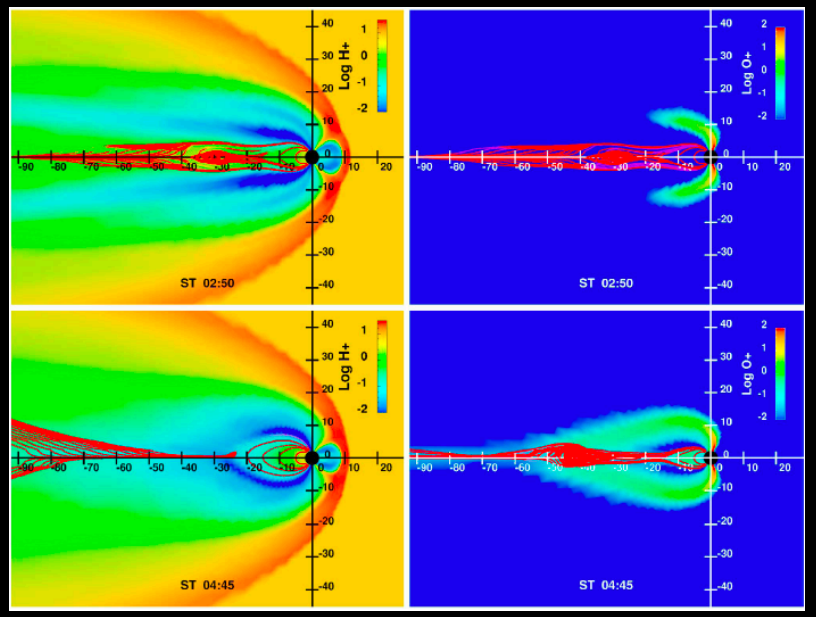


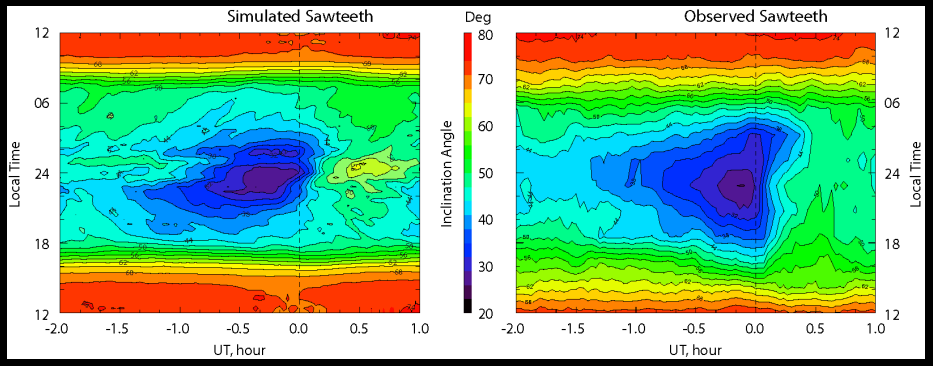


- Welling et al., JGR, 2009
  - Used the SWMF and PWOM
    - Adds RCM-SCB Ring current model
  - Examined how outflow effects ring current
    - Reductions in convection electric field
    - Non trivial local time dependencies

Ionospheric Outflow Modeling II

- Wiltberger et al., JGR, 2010
  - Used the MFLFM MHD model
  - Specified O+ outflow from cusp after southward turning of IMF
    - Without Outflow only one substorm
    - Outflow can cause second substorm
    - Depends on speed and intensity of outflow parameters

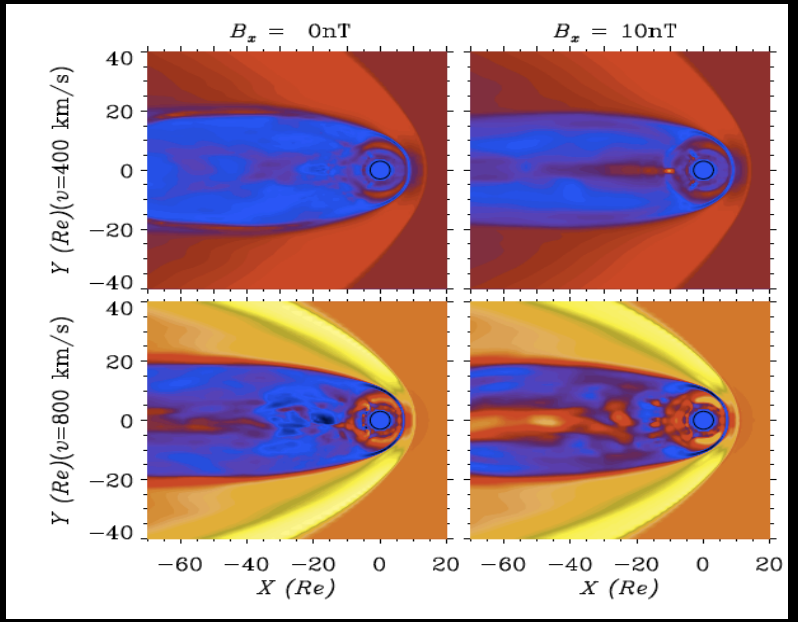


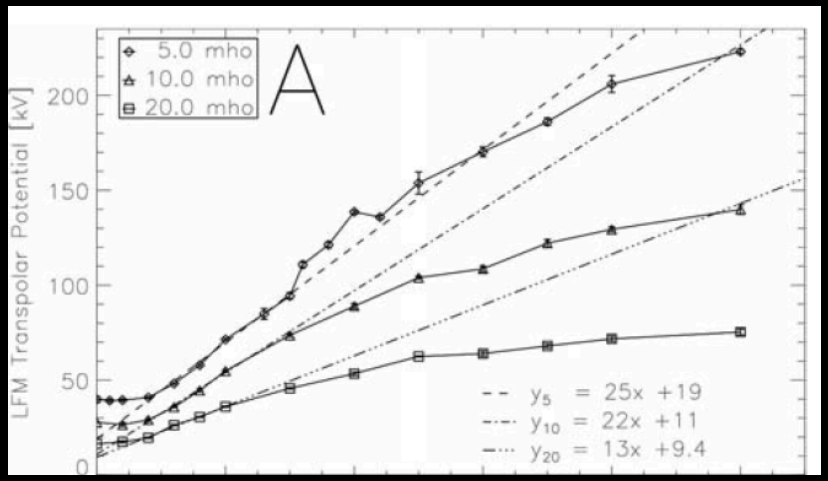


- Brambles et al., Science, 2011
  - Used the MFLFM model
  - Outflow parameterized using Strangeway Relationships
  - Simulation produces sawtooth events for steady driving conditions
    - Makes prediction for relationship between peroid and outflow flux

Other IMF Directions I

- Peng et al., JGR, 2010
  - Used Chinese PPMLR-MHD Model
  - Looked at affects of IMF Bx
    - Shifts MP location direction depends on sign
    - Shifts merging line location when combined with southward IMF
    - MP reconnection rate decreases with increasing IMF Bx

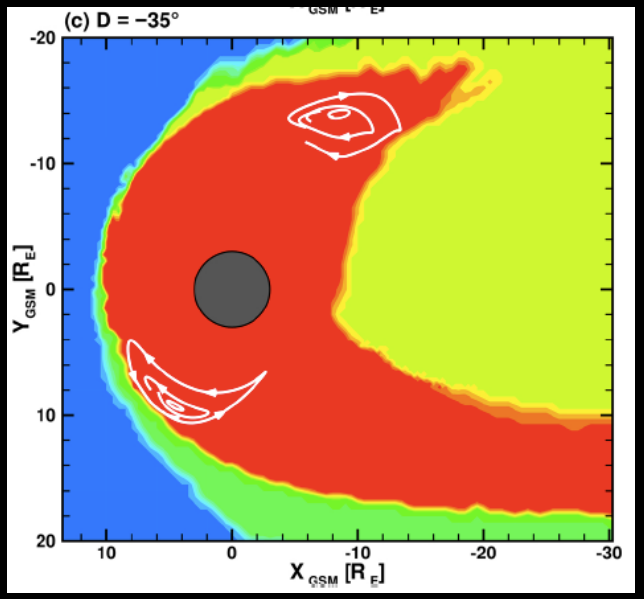


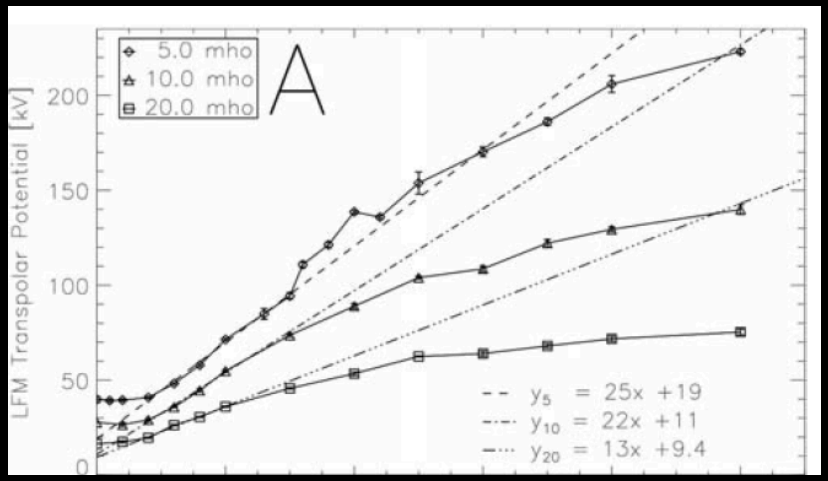


- Mitchell et al., JGR, 2010
  - Used the LFM model
  - Examined polar cap potential saturation during conditions with IMF By
    - Saturation is seen at smaller values of potential, but similar magnitude of IMF
  - Presents supporting data from DMSP observations

Other IMF Directions II

- Watanabe et al., JGR, 2010
  - Used BATSRUS Global MHD Model
  - Looked at combination of IMF B_Y and dipole tilt effects
    - Viscous cell centers rotate eastward in NH as tilt increases
    - Round/crescent cell pattern in ionosphere with large distortion of Dungey-type merging cell is also seen





- Mitchell et al., JGR, 2010
  - Used the LFM model
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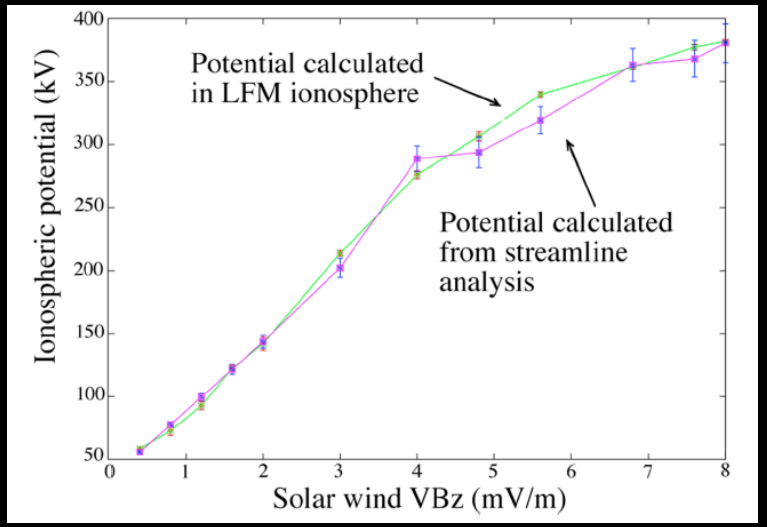
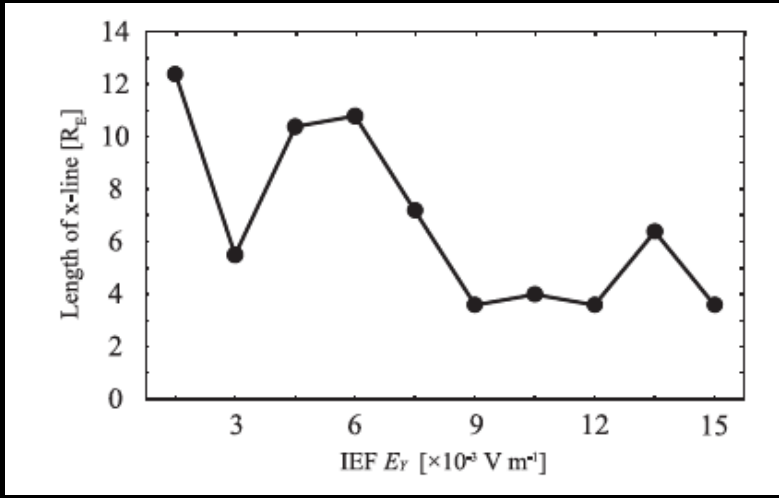
    - Saturation is seen at smaller values of potential, but similar magnitude of IMF
  - Presents supporting data from DMSP observations

Polar Cap Potential Saturation

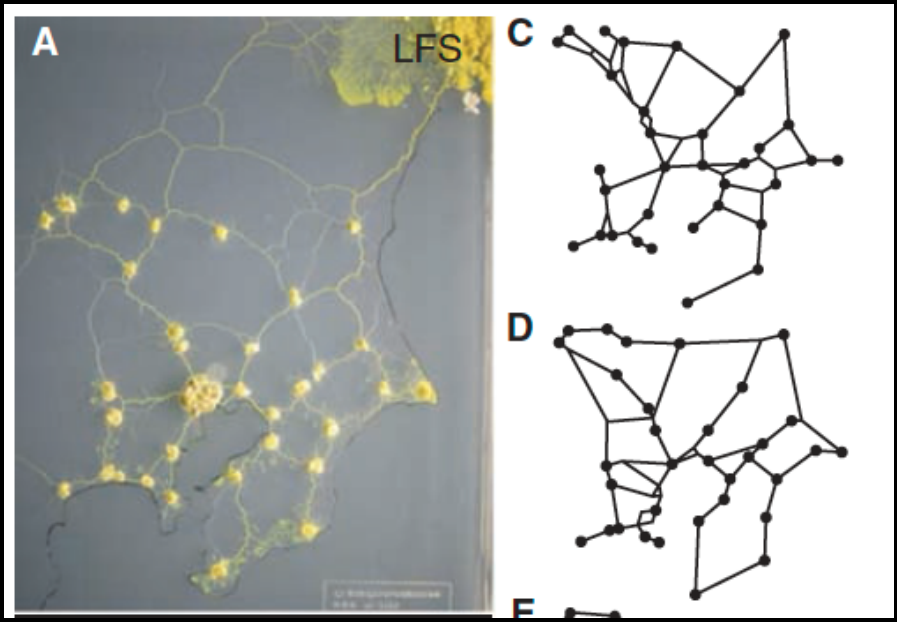
- Lopez et al., JGR, 2010
  - Used the LFM model
  - Argues that saturation of potential is due to change in geoeffective length of merging region
    - At low |B| flow controlled by ∇P
    - At high |B| flow controlled by $\vec{j} \times \vec{B}$

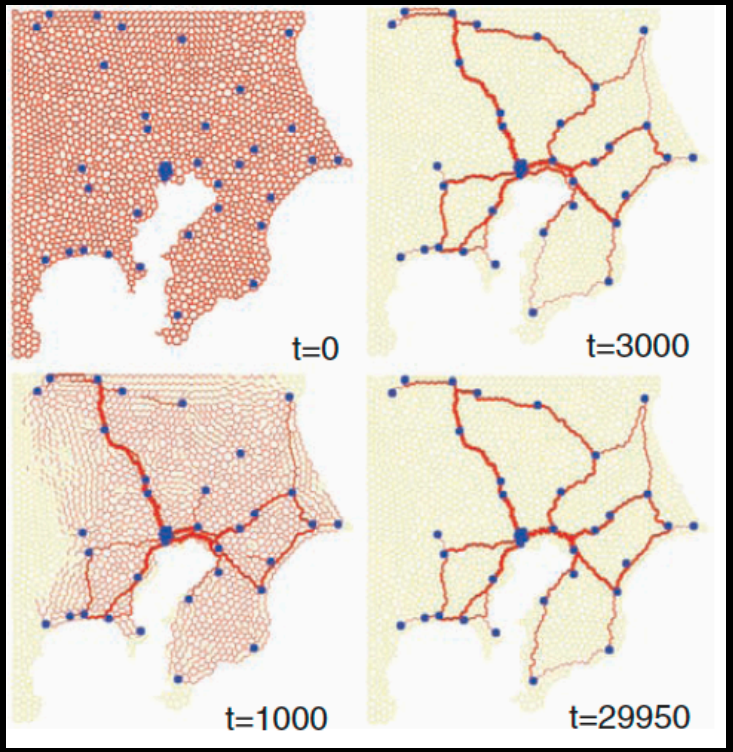




- Fukazawa et al., JASTP, 2010
  - Used the Ogino MHD model
    - Replaced ionosphere coupling with empirical model
  - Notes a change in flow characteristics around subsolar point for high IMF
    - Notes a difference between increases in speed and |B| when looking at E_Y

Ignoble Award Break

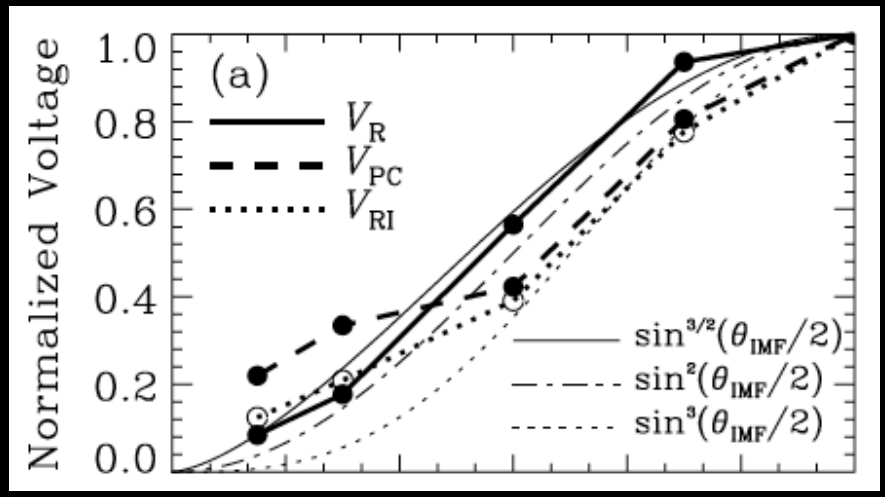


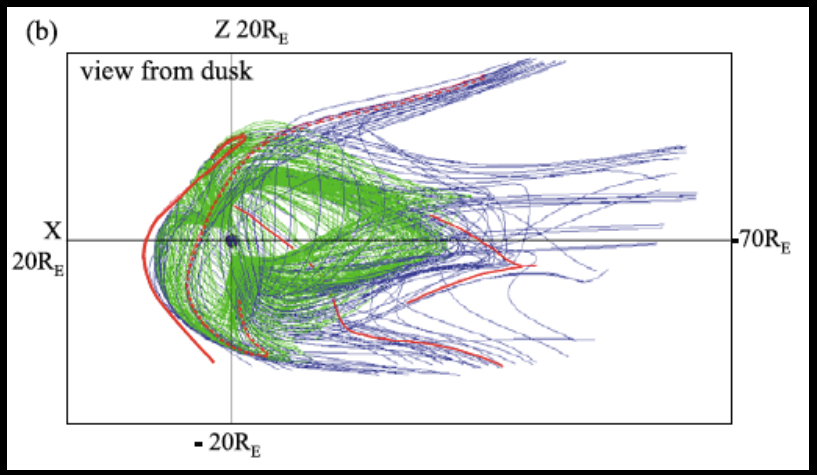


- Global simulation efforts have been accused of pushing the envelope for applying techniques to simulation the system
- Tero et al. 2010 built a simulation of Tokyo rail system built on modeling slime mold for which they recived an Ignoble Award

Dayside Reconnection

- Hu et al., JGR, 2009
  - Used Chinese PPMLR-MHD Model
  - Developed technique for defining merging region in 3D
    - Combine min B, last closed and selected closed field lines
    - Calc E field along this region
  - Reconnection voltage and ionospheric voltage are not the same

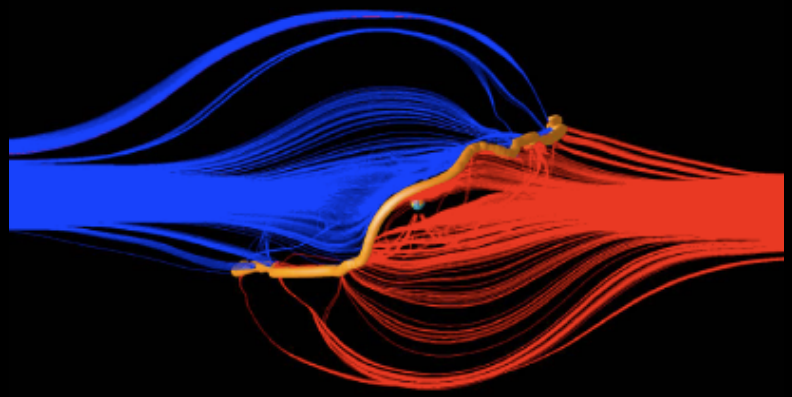


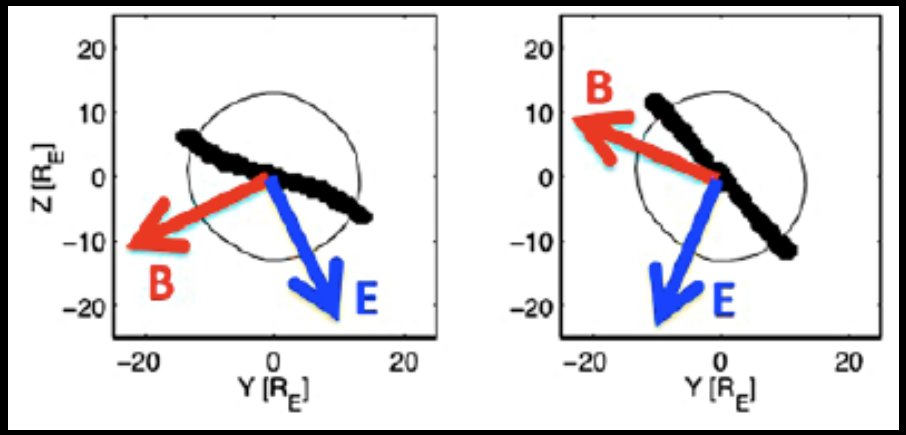


- Park et al., GRL, 2009
  - Used Ogino's Global MHD Model
  - Examined dayside reconnection for northward and duskward IMF with positive dipole tilt
    - Electric fields peak in region of anti-parallel magnetic field
    - In contrast to previous results see stronger currents in winter hemisphere

Dayside Reconnection II

- Ouellette et al., JGR, 2010
  - Used the LFM Model
  - Examined IMF from 0° to 180° in 45° steps
  - Found antiparallel reconnection
    - 45° and 90° near cusps
    - 135° and 180° belt across subsolar region
  - Also found guide field reconnection for 45° and 90°

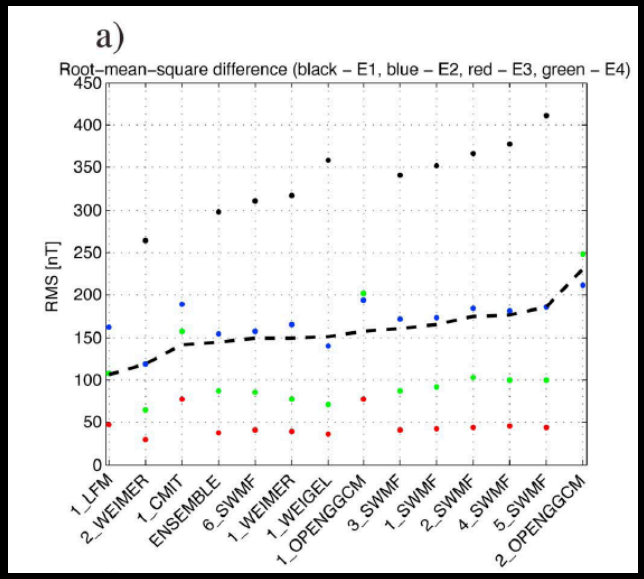


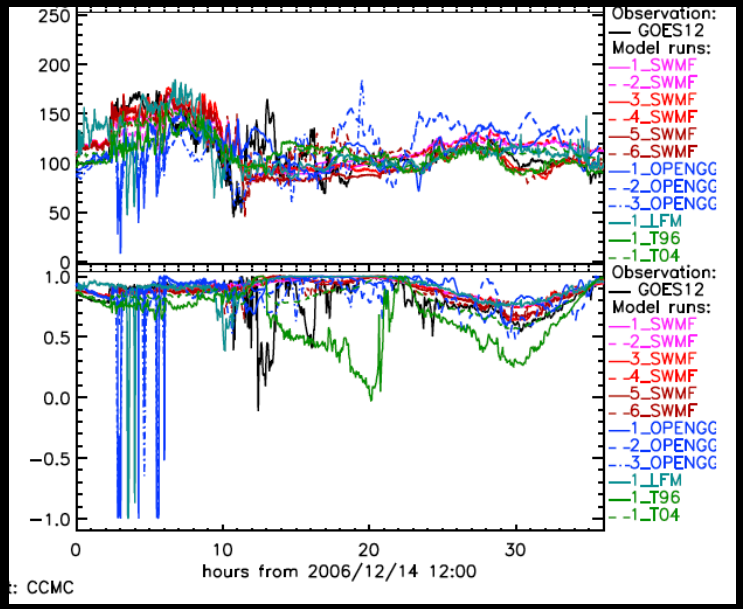


- Pulkkinen et al., JGR, 2010
  - Used the GUMICS MHD model
  - Examined a slowly varying IMF direction
  - Found energy input and response scale with electric field along reconnection line – E_{PAR}
    - Response/EPAR is independent of clock angle
    - Illustrate the importance of localized reconnection line on controlling energy input into coupled MI system

Verification and Validation

- Pulkkinen et al., SW, 2011
  - CCMC Comparisons of SWMF, OpenGGCM, and LFM/CMIT
  - Used a variety of metrics to quantitatively asses model performance during 4 different intervals
  - Focused on ground magnetic field perturbations
    - No model uniformly best on all metrics
    - Intra-model variability larger than inter-model variability for some measures

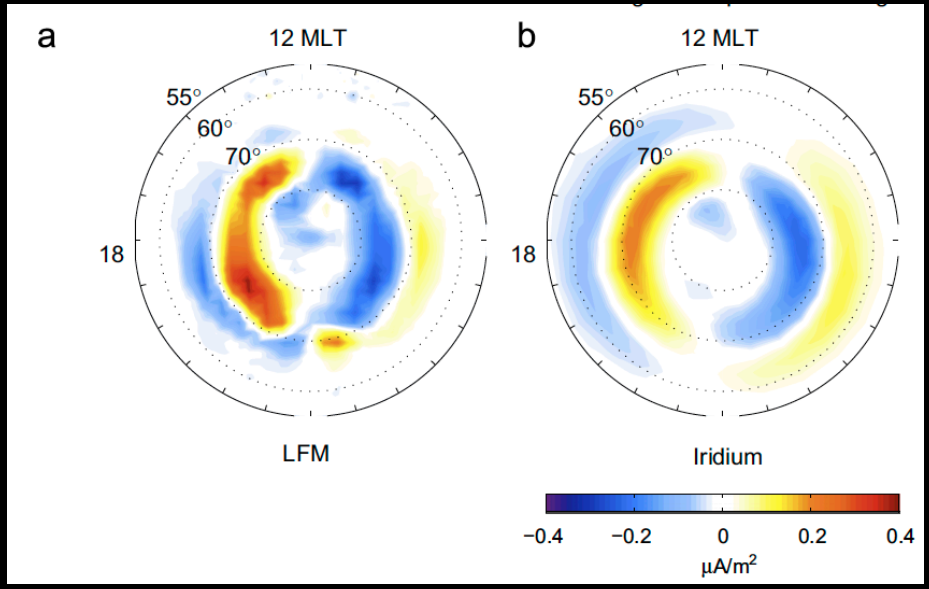


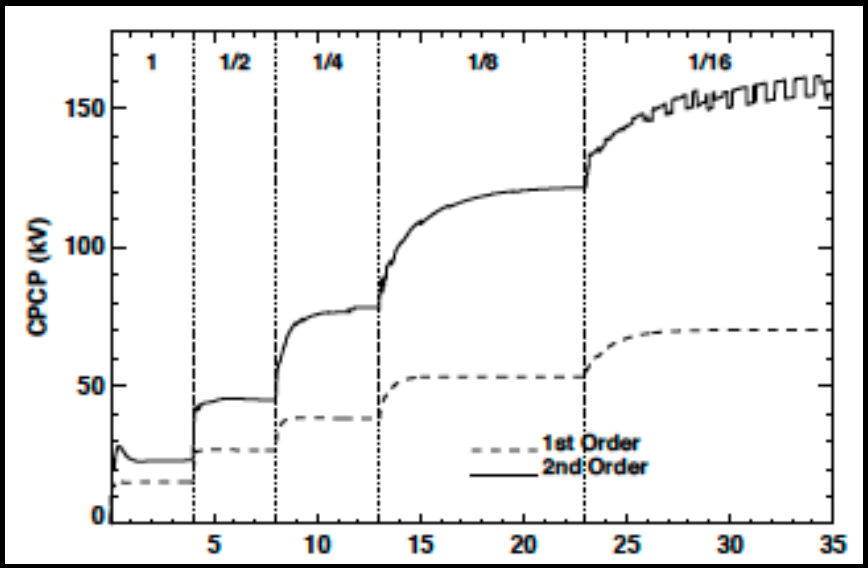


- Rastatter et al., SW, 2011
  - CCMC Comparisons of SWMF, OpenGGCM, and LFM/CMIT
  - Focused on Geosynchronous Magnetic Fields
  - Compared |B|, elevation angle, and spectral power
    - Once again no model best on all metrics
    - Inclusion of inner magnetosphere model improves results

Validation and Verification II

- Zhang et al., JASTP, 2011
  - Used the LFM Model
  - Used LFM "Long Run" Intervals
    - Two months – 2/23/96-04/26/96
  - Binned data by IMF direction and compared with Weimer 05 and Iridium
    - Good CPCP pattern, but magnitude high
    - Good agreement with Iridium

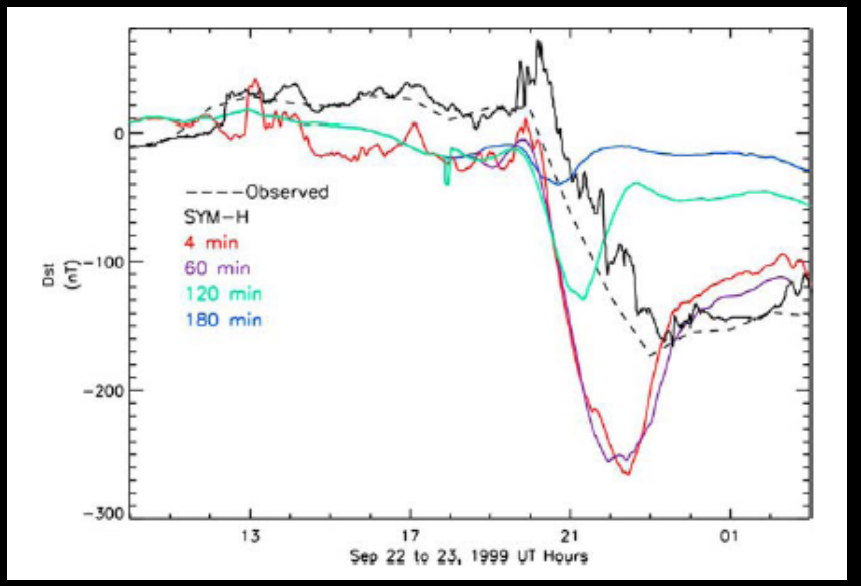


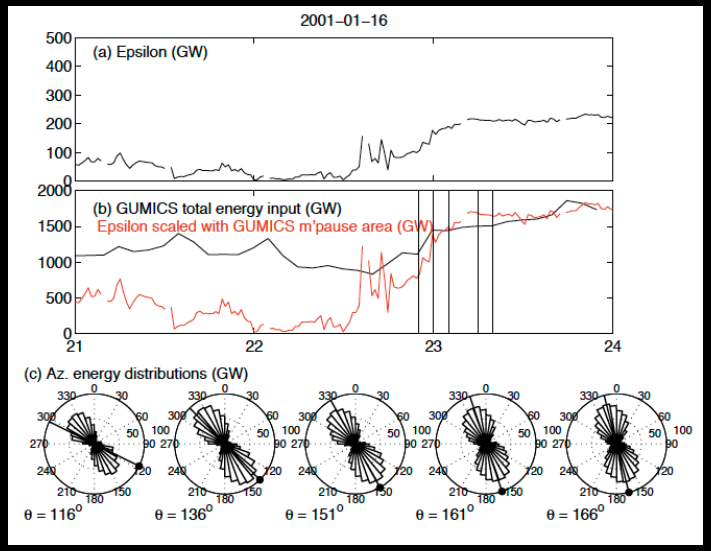


Ridley et al., AG, 2010
- Used the BATSRUS
- Under idealzied solar wind conditions examined the effect of numerical scheme, resolution, limter, etc
  - Solutions not grid converged with best solver and highest resolution
  - Boris 'Speed of Light' correction helps
  - Nonlinear interaction between numerical effects

Validation and Verification III

- Ilie et al., JGR, 2010
  - Used the SWMF
  - Averaged SW inputs over 4,60,120, and 180 minutes to examine affects on response of model
    - All parameters affect results by dependence on Bz strongest
    - Greater than 60 minute avg reduces plasma sheet density and pressure
    - Nonlinear dependence with threshold condition

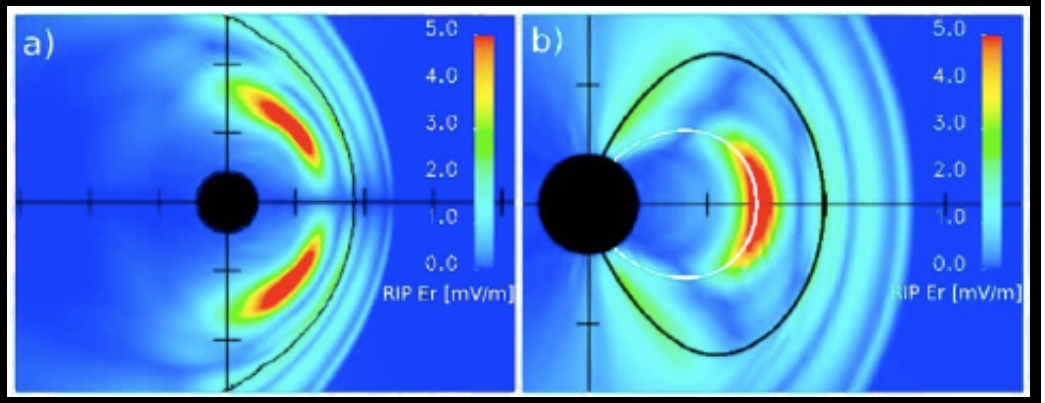


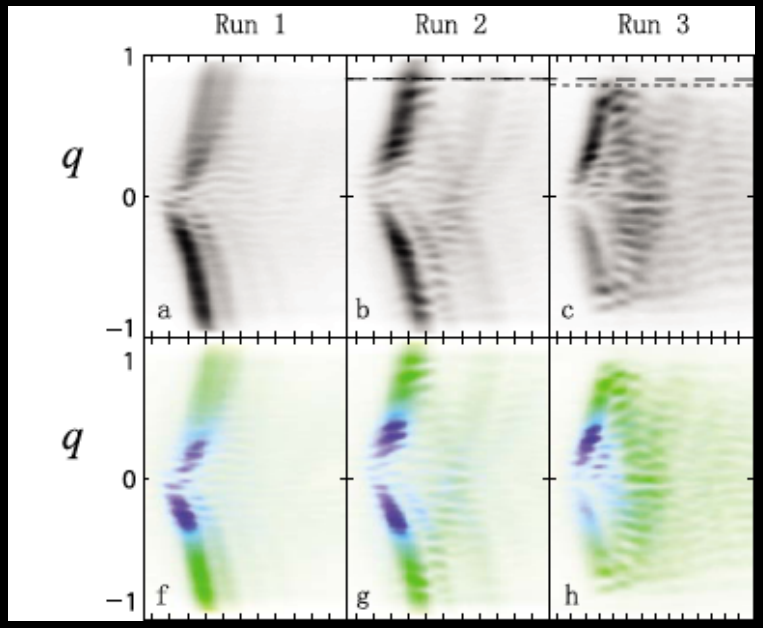


- Palmroth et al., AG, 2011
  - Used the GUMICS model
  - Comparison Cluster observations during magnetopause crossings for two events
    - Good spatial agreement, but GUMICS is 30% weaker
  - Scaling ε with MP area indicates that it may significantly underestimate energy input

Waves I

- Claudepierre et al., JGR, 2010
  - Used the LFM Model
  - Placed ULF dynamic pressure fluctuations in SW driver
  - Monochoromatic SW fluctuations drive toroidal mode FLRs where eigenfreq matches driving
  - Continuum driving drives spectrum of FLRs

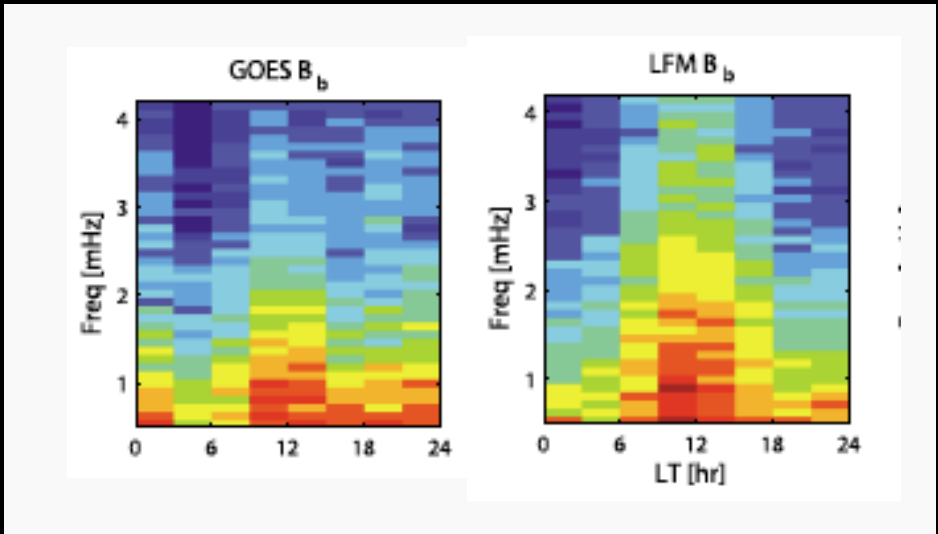




- Hu et al., JGR, 2010
  - Hybrid simulation EMIC waves in a multi-ion plasma in a dipole
    - Start in MHD equilibrium
    - Generate waves at the equator
  - Waves become polarized as they propagate to higher latitudes
  - Importance of wave particle interactions depend heavily on density

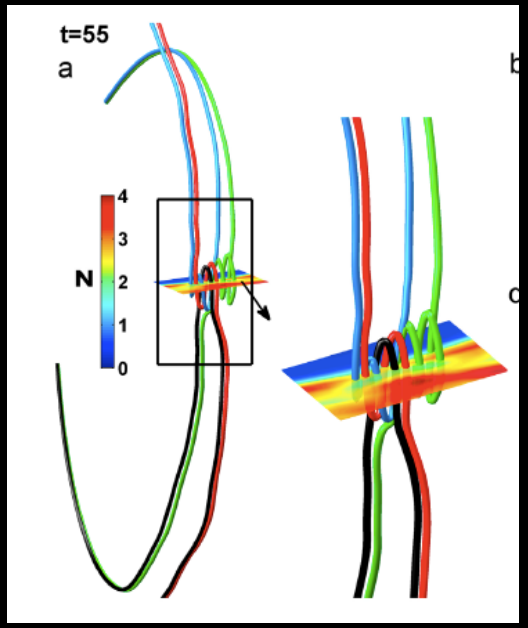
Waves II

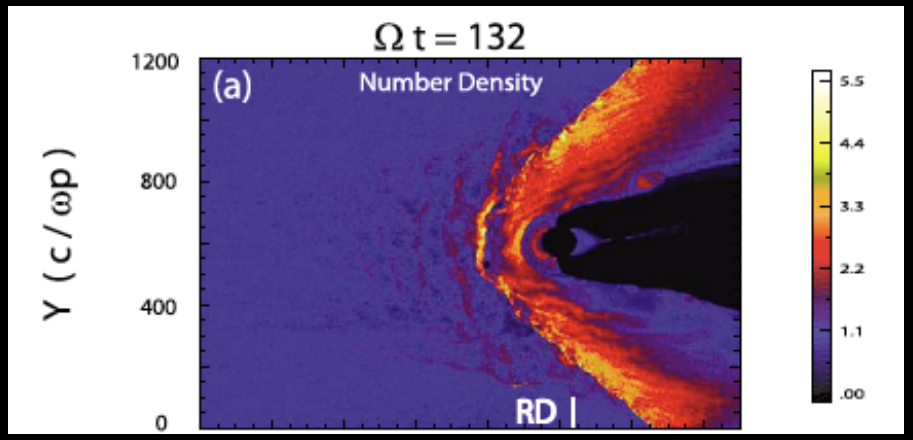
- Huang et al., JGR, 2010a,b
  - Used the LFM Model
  - Compared results from 27 days simualtion with statistical results from 9 years of GOES obs
    - LFM does a good job producing statistcal chararistics of wave power
    - Provides wave field data needed to model radiation electrons



Misc - Hybrid Simulations

- Peng et al., JGR, 2011 and Tan et al. JGR 2010
  - Newly developed 3D Global Hybrid Model
  - Examined dayside reconnection during southward IMF
    - Multiple X lines form with FTEs consistent with satellite observations
  - Examined passage of TD in solar wind
    - Thin TD lead to flux ropes in magnetosheath
    - SN TD could contribute to boundary layer

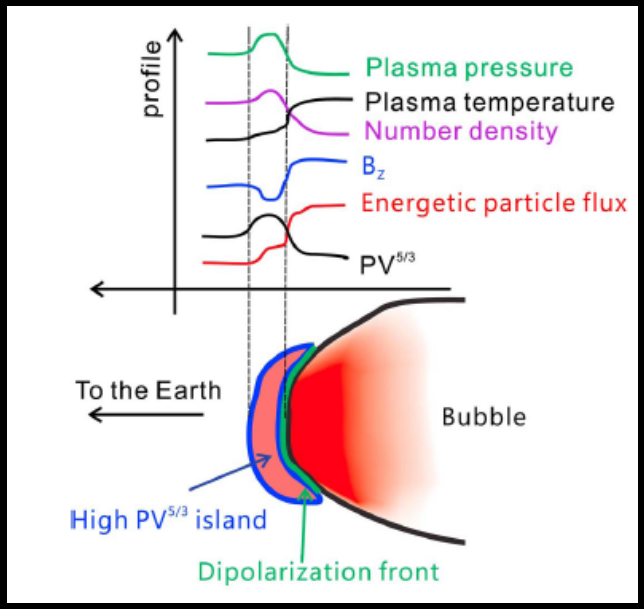


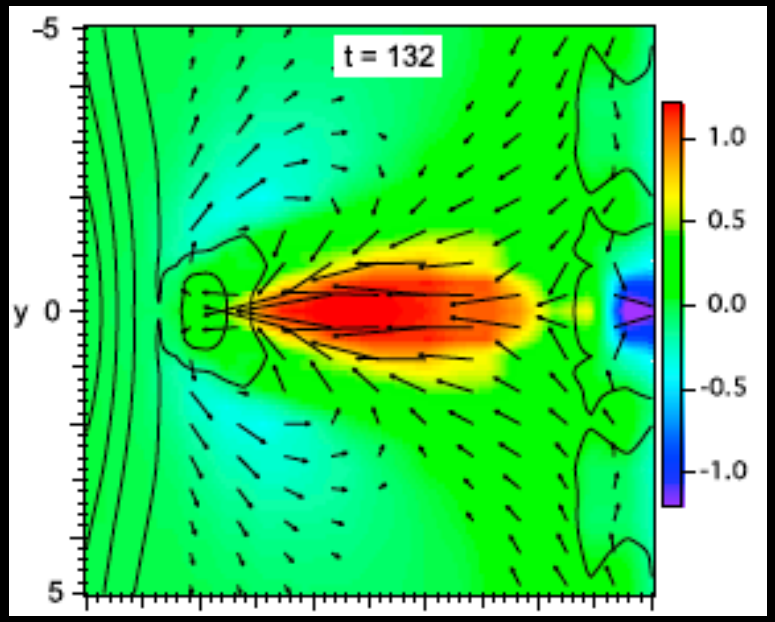


- Omidi et al., JGR, 2011
  - Used 2.5D Hybrid Simulation
  - Observed the formation of a new feature called 'Foreshock bubbles' during passage of SW discontinuities
    - Leading edge has fast shock
    - Core contains hotter less dense plasma with lower |B|
    - Impacts affect plasma injection into cusp

Miscellaneous - BBFs and DFs

- Yang et al., JGR, 2011
  - Used the RCM-E
  - Examined the structure of BBF for an idealized substorm with localized bubble
    - Injection boundary coincident with Earthward edge of bubble
    - Suggest that bubble are core part of particle injections

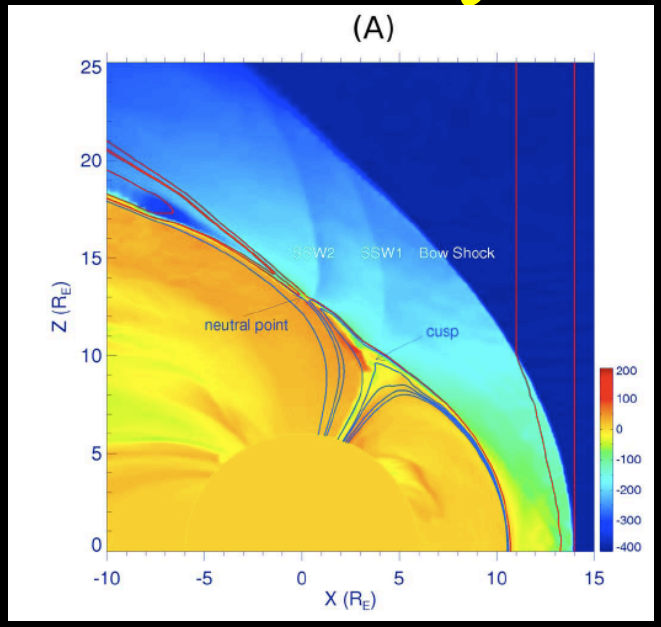


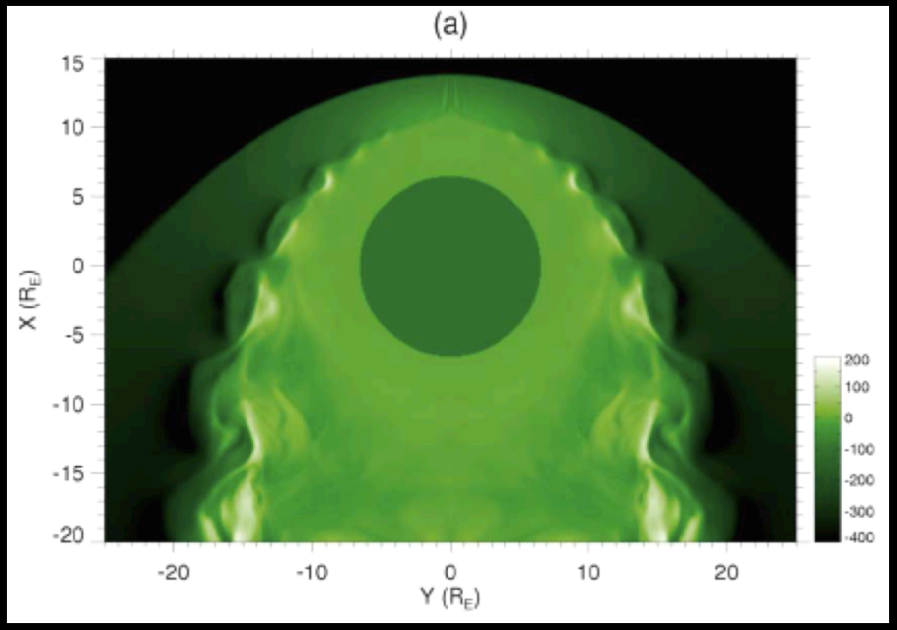


- Birn et al., JGR, 2011
  - Used 3D MHD Magnetotail Simulation
  - Examined flow of bubble created by magnetic reconnection in tail
  - General characteristics in agreement with THEMIS
    - Initial Phase is earthward prop DF
    - When stopped expands azimuthally and tailward
    - Vortices present outside many flow

Miscellaneous - Boundary

- Guo et al., JGR, 2011
  - Used Chinese PPMLR-MHD Model
  - Found standing shock waves in the magnetosheath
    - Occur at mid- and high latitude
    - Can lead to distortions in shape of BS
    - SSW are excited by indentations on magnetopause



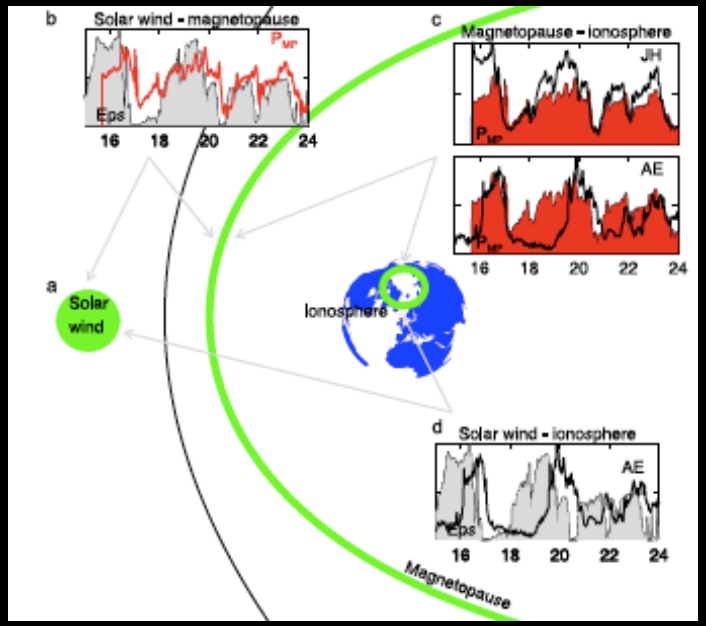


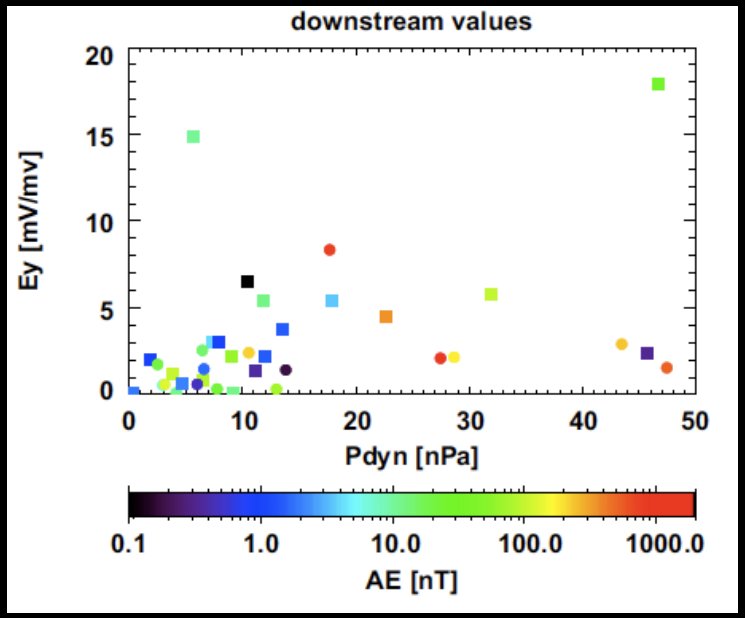
Guo et al., JGR, 2010

- Used Chinese PPMLR-MHD Model
- Examined fomation of KH at MP during northward IMF
- KH vortices generate on dayside are transported to far distant magnetotail
  - Generates at 28° off Sun-Earth line
  - Wavelengths vary 1 to 8 R_E
  - Confined to 30° of equatorial plane

Miscellaneous - Propagation

- Pulkkinen et al., JGR, 2010
  - Used GUMICS MHD model
  - Clear, repeatable delay between changes in SW and energy input through MP
    - JH responds promptly energy input
    - AE response delayed for increase
    - AE response prompt for decrease

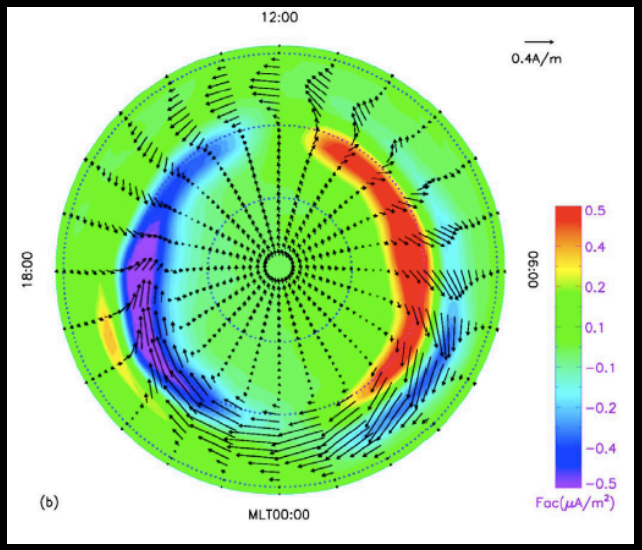


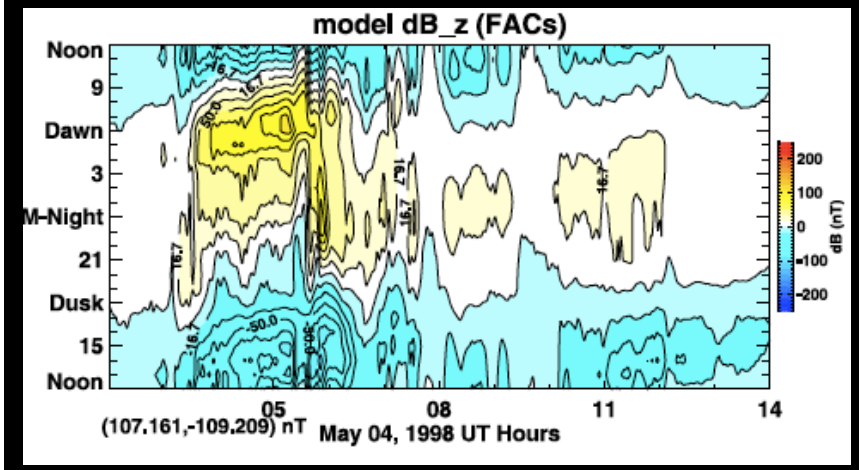


- Andreeova et al., JGR, 2010
  - Used the GUMICS MHD Model
  - Examined coupling efficiency in response to dynamic pressure changes
    - Higher speed has higher ionospheric activity
    - Efficiency is highest for small values of E_Y
    - Driving independent of reconnection E

Miscellaneous – MI Coupling

- Tang et al., JGR, 2011
  - Used Chinese PPMLR-MHD Model
  - Examine the effects of ionospheric conductance on westward electrojet
    - For low conductance two cell pattern
    - For $\Sigma_H/\Sigma_P > 2$ intense electrojet
    - Electrojet is cowling current driven by the southward E due to current closure in plasma sheet





- Yu et al., JGR, 2010
  - Used the SWMF
  - Extended physics for calculating ground magnetic field perturbations to include FAC in gap region
    - Most important for Northward perturbations
    - Largest effect during storm main phase

Conclusions

- Global scale simulations have been used to examine a wide range of scientific questions
  - Efforts continue to verify and validate the results coming from these simulations
  - Providing insight on the behavior of the system under a vast array of conditions
  - Continuing success in modeling substorms
  - A useful tool in the study of 3D reconnection
- CCMC is broadening the utilization of global models
  - Conducting essential inter-model comparisons
  - Not a model developer, so continued support to the development community is needed

References

- Alaoui El M, Ashour-Abdalla M, Walker RJ, Peroomian V, Richard RL, et al. (2009) Substorm evolution as revealed by THEMIS satellites and a global MHD simulation. Journal of Geophysical Research Space Physics 114: A08221. doi: 10.1029/2009JA014133
- Ashour-Abdalla M, Bosqued JM, Alaoui El M, Peroomian V, Zhou M, et al. (2009) A simulation study of particle energization observed by THEMIS spacecraft during a substorm. Journal of Geophysical Research Space Physics 114: A09204. doi: 10.1029/2009JA014126
- Ashour-Abdalla M, Alaoui El M, Goldstein M~, Zhou M, Schriver D, et al. (2011) Observations and simulations of non-local acceleration of electrons in magnetotail magnetic reconnection events. Nature Physics 7: 360–365. doi:10.1038/nphys1903
- Brambles OJ, Lotko W, Zhang B, Wiltberger M, Lyon J, et al. (2011) Magnetosphere Sawtooth Oscillations Induced by Ionospheric Outflow. Science 332: 1183–1186. doi: 10.1126/science.1202869
- Birn J, Nakamura R, Panov E~, Hesse M (2011) Bursty bulk flows and dipolarization in MHD simulations of magnetotail reconnection. Journal of Geophysical Research Space Physics 116: A01210. doi:10.1029/2010JA016083
- Claudepierre SG, Hudson MK, Lotko W, Lyon JG, Denton R~ (2010) Solar wind driving of magnetospheric ULF waves: Field line resonances driven by dynamic pressure fluctuations. arXiv 115: A11202. doi:10.1029/2010JA015399

References

- Farr NL, Baker DN, Wiltberger M (2010) Using a global magnetohydrodynamic model to study the start of the substorm recovery phase. J. Geophys. Res 115: 12237. doi: 10.1029/2010JA015802
- Fukazawa K, Aoyama T, Ogino T, Yumoto K (2010) Response of the reconnection electric field and polar cap potential to the IMF and velocity of solar wind. Journal of Atmospheric and Solar-Terrestrial Physics 72: 1019–1023. doi:10.1016/j.jastp. 2010.06.002
- Ge Y~, Raeder J, Angelopoulos V, Gilson M~, Runov A (2011) Interaction of dipolarization fronts within multiple bursty bulk flows in global MHD simulations of a substorm on 27 February 2009. Journal of Geophysical Research Space Physics 116: A00I23. doi:10.1029/2010JA015758
- Glocer A, Tóth G, Ma Y, Gombosi T, Zhang J, et al. (2009) Multifluid Block-Adaptive-Tree Solar wind Roe-type Upwind Scheme: Magnetospheric composition and dynamics during geomagnetic storms—Initial results. J. Geophys. Res 114: 12203. doi: 10.1029/2009JA014418
- Guo XC, Wang C, Hu YQ (2010) Global MHD simulation of the Kelvin-Helmholtz instability at the magnetopause for northward interplanetary magnetic field. Journal of Geophysical Research Space Physics 115: A10218. doi:10.1029/2009JA015193

- Guo XC, Wang C, Hu YQ (2010) Global MHD simulation of the Kelvin-Helmholtz instability at the magnetopause for northward interplanetary magnetic field. Journal of Geophysical Research Space Physics 115: A10218. doi:10.1029/2009JA015193

References

- Harnett EM, Winglee RM, Lerud T (2010) Multiscale-multifluid simulations of the 26 February 2008 substorm: Evidence for internal triggering of a substorm. Journal of Geophysical Research Space Physics 115: A12238. doi:10.1029/2010JA015672
- Hu Y, Denton R~, Johnson JR (2010) Two-dimensional hybrid code simulation of electromagnetic ion cyclotron waves of multi-ion plasmas in a dipole magnetic field. Journal of Geophysical Research Space Physics 115: A09218. doi: 10.1029/2009JA015158
- Hu YQ, Peng Z, Wang C, Kan JR (2009) Magnetic merging line and reconnection voltage versus IMF clock angle: Results from global MHD simulations. Journal of Geophysical Research Space Physics 114: A08220. doi:10.1029/2009JA014118
- Huang C-L, Spence HE, Singer HJ, Hughes WJ (2010) Modeling radiation belt radial diffusion in ULF wave fields: 1. Quantifying ULF wave power at geosynchronous orbit in observations and in global MHD model. J. Geophys. Res 115: 06215. doi: 10.1029/2009JA014917
- Huang C-L, Spence HE, Hudson MK, Elkington SR (2010) Modeling radiation belt radial diffusion in ULF wave fields: 2. Estimating rates of radial diffusion using combined MHD and particle codes. J. Geophys. Res 115: 06216. doi: 10.1029/2009JA014918
- Ilie R, Liemohn MW, Ridley A (2010) The effect of smoothed solar wind inputs on global modeling results. J. Geophys. Res 115: 01213. doi:10.1029/2009JA014443

References

- Lopez RE, Bruntz R, Mitchell EJ, Wiltberger M, Lyon JG, et al. (2010) Role of magnetosheath force balance in regulating the dayside reconnection potential. J. Geophys. Res 115: 12216. doi:10.1029/2009JA014597
- Mitchell EJ, Lopez RE, Bruntz RJ, Wiltberger M, Lyon JG, et al. (2010) Saturation of transpolar potential for large Y component interplanetary magnetic field. J. Geophys. Res 115: 06201. doi:10.1029/2009JA015119
- Omidi N, Eastwood JP, Sibeck DG (2010) Foreshock bubbles and their global magnetospheric impacts. Journal of Geophysical Research Space Physics 115: A06204. doi:10.1029/2009JA014828
- Ouellette JE, Rogers BN, Wiltberger M, Lyon JG (2010) Magnetic reconnection at the dayside magnetopause in global Lyon-Fedder-Mobarry simulations. J. Geophys. Res 115: 08222. doi:10.1029/2009JA014886
- Park K~, Ogino T, Kim Y~ (2010) Effects of the dipole tilt and northward and duskward IMF on dayside magnetic reconnection in a global MHD simulation. Journal of Geophysical Research Space Physics 115: A02208. doi:10.1029/2009JA014212
- Pang Y, Lin Y, Deng X~, Wang XY, Tan B (2010) Three-dimensional hybrid simulation of magnetosheath reconnection under northward and southward interplanetary magnetic field. Journal of Geophysical Research Space Physics 115: A03203. doi: 10.1029/2009JA014415
- Peng Z, Wang C, Hu YQ (2010) Role of IMF B_x in the solar wind-magnetosphere-ionosphere coupling. Journal of Geophysical Research Space Physics 115: A08224. doi: 10.1029/2010JA015454

References

- Pulkkinen A, Kuznetsova M, Ridley A, Raeder J, Vapirev A, et al. (2011) Geospace Environment Modeling 2008–2009 Challenge: Ground magnetic field perturbations. Space Weather 9: S02004. doi:10.1029/2010SW000600
- Pulkkinen TI, Palmroth M, Janhunen P, Koskinen HEJ, McComas D~, et al. (2010) Timing of changes in the solar wind energy input in relation to ionospheric response. Journal of Geophysical Research Space Physics 115: A00I09. doi: 10.1029/2010JA015764
- Pulkkinen TI, Palmroth M, Koskinen HEJ, Laitinen TV, Goodrich CC, et al. (2010) Magnetospheric modes and solar wind energy coupling efficiency. J. Geophys. Res 115: 03207. doi:10.1029/2009JA014737
- Rastätter L, Kuznetsova MM, Vapirev A, Ridley A, Wiltberger M, et al. (2011) Geospace Environment Modeling 2008\ndash2009 Challenge: Geosynchronous magnetic field. Space Weather 9: S04005. doi:10.1029/2010SW000617
- Ridley AJ, Gombosi TI, Sokolov IV, Tóth G, Welling DT (2010) Numerical considerations in simulating the global magnetosphere. ANNALES GEOPHYSICAE 28: 1589–1614. doi:10.5194/angeo-28-1589-2010
- Tan B, Lin Y, Perez JD, Wang XY (2011) Global-scale hybrid simulation of dayside magnetic reconnection under southward IMF: Structure and evolution of reconnection. Journal of Geophysical Research Space Physics 116: A02206. doi: 10.1029/2010JA015580

References

- Tanaka T, Nakamizo A, Yoshikawa A, Fujita S, Shinagawa H, et al. (2010) Substorm convection and current system deduced from the global simulation. Journal of Geophysical Research Space Physics 115: A05220. doi:10.1029/2009JA014676
- Tang B~, Wang C, Hu YQ, Kan JR (2011) Intensification of the Cowling current in the global MHD simulation model. Journal of Geophysical Research Space Physics 116: A06204. doi:10.1029/2010JA016320
- Watanabe M, Kabin K, Sofko GJ, Rankin R, Gombosi TI, et al. (2010) Dipole tilt effects on the magnetosphere-ionosphere convection system during interplanetary magnetic field B_Y-dominated periods: MHD modeling. Journal of Geophysical Research Space Physics 115: A07218. doi:10.1029/2009JA014910
- Welling DT, Jordanova V~, Zaharia S~, Glocer A, Tóth G (2011) The effects of dynamic ionospheric outflow on the ring current. Journal of Geophysical Research Space Physics 116: A00J19. doi:10.1029/2010JA015642
- Wiltberger M, Lotko W, Lyon JG, Damiano P, Merkin V (2010) Influence of cusp O+ outflow on magnetotail dynamics in a multifluid MHD model of the magnetosphere. J. Geophys. Res 115. doi:10.1029/2010JA015579
- Yang J, Toffoletto FR, Wolf RA, Sazykin S (2011) RCM-E simulation of ion acceleration during an idealized plasma sheet bubble injection. Journal of Geophysical Research Space Physics 116: A05207. doi:10.1029/2010JA016346

References

- Yu Y, Ridley AJ, Welling DT, Tóth G (2010) Including gap region field-aligned currents and magnetospheric currents in the MHD calculation of ground-based magnetic field perturbations. J. Geophys. Res 115: 08207. doi:10.1029/2009JA014869
- Zhang B, Lotko W, Wiltberger MJ, Brambles OJ, Damiano PA (2011) A statistical study of magnetosphere–ionosphere coupling in the Lyon–Fedder–Mobarry global MHD model. Journal of Atmospheric and Solar-Terrestrial Physics 73: 686. doi:10.1016/j.jastp.2010.09.027