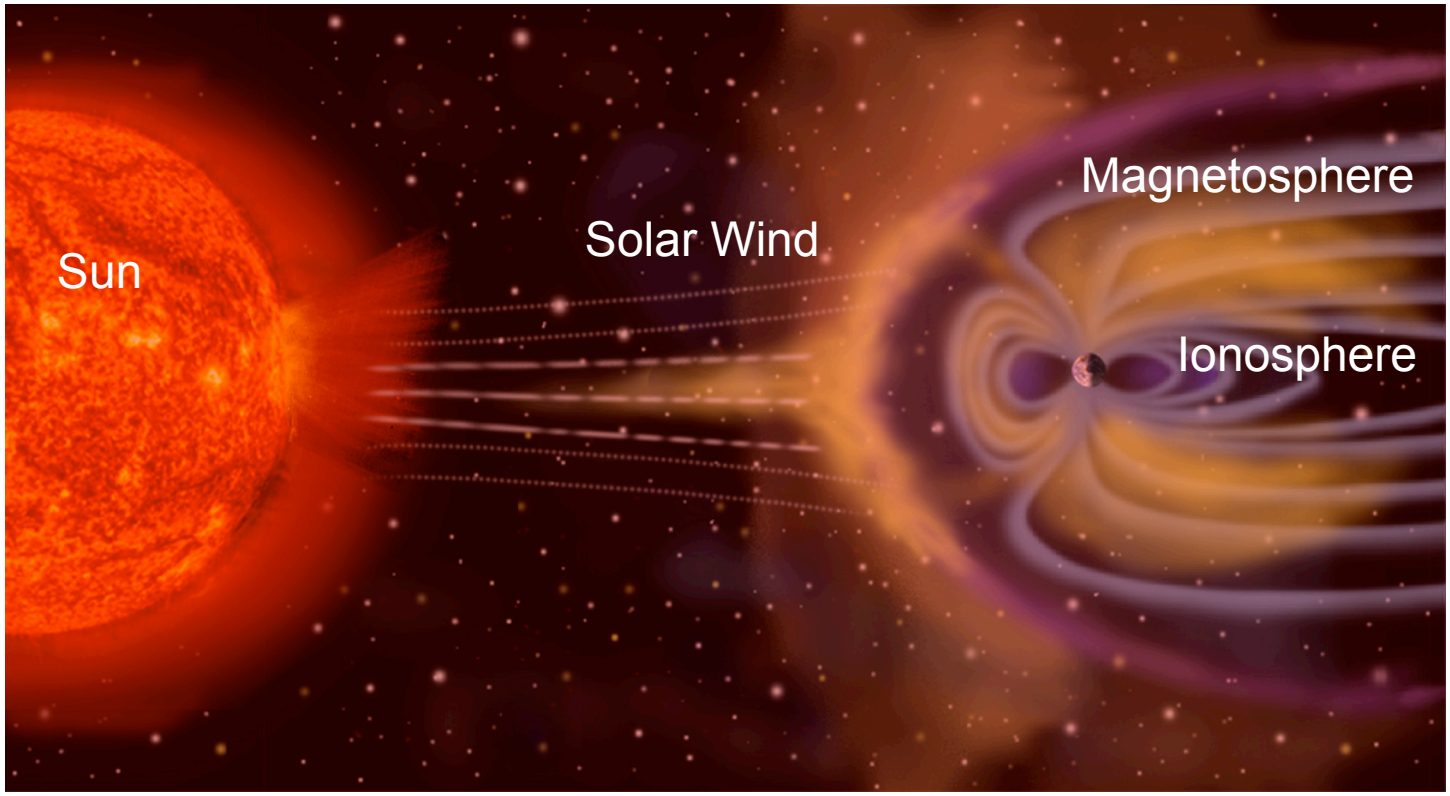
Space Physics at PPPL

Presented by
Jay R. Johnson

October 10-11, 2005
PPPL Theory Department
Five-Year Plan Review

Goal of Space Physics Research

- Coupling between the Sun, Solar Wind, Magnetosphere and Ionosphere
- Transport of Energy, Mass, Momentum
- Dynamical Evolution---Flares, Coronal Mass Ejections, Substorms
- Astrophysical Plasmas



Resources and Applications

Solar Physics
Variational Equilibrium Code
3D MHD, Hall MHD, and Three Fluid Codes
Choe, Cheng‡, Ren

- Pre-eruption configurations
- Flares and Coronal Mass Ejections
- Applications to MRX

Magnetosphere/Ionosphere Physics
MAG3D Nonvariational Equilibrium Code
Kinetic-MHD Theoretical Calculations
Wave Propagation Code
Particle Simulations
Johnson, Cheng‡, Okuda, Zaharia

- Equilibrium Studies
- Substorm Phenomena
- M-I Coupling and Transport
- Magnetopause Transport
- Auroral Acceleration/Instabilities

Astrophsyical Plasmas
Landau Fluid Extension of ZEUS
GS2 Gyrokinetics
Hammett, Sharma

- Magnetorotational Instability in Accretion Disks
- Turbulent Transport

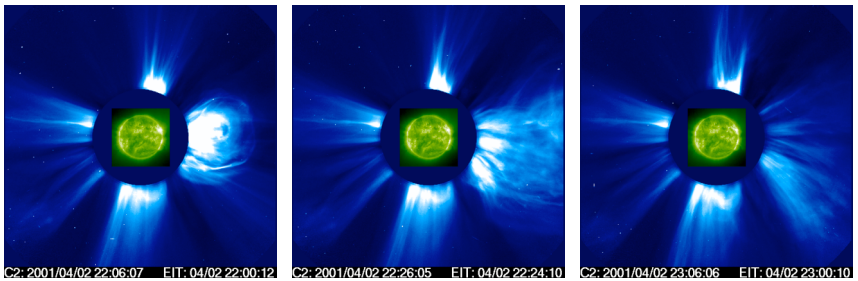
Information-Theoretical Modeling
Understanding Nonlinear Dependencies
Predictive Modeling
Johnson, Choe

- Characterizing Space Dynamics
- Understanding Solar Flare Statistics
- Applications to Disruptions

Research Supported by NASA and NSF

Energy Paradox of Magnetic Field Opening Resolved by Equilibrium Studies

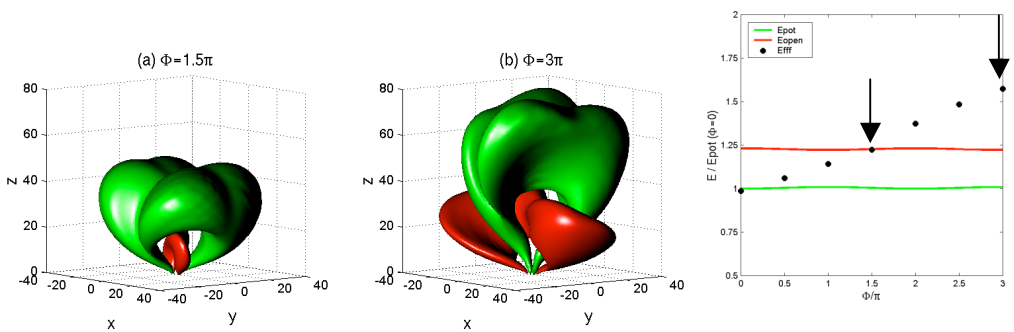
Progress of CME and Field Opening



$$E_{\text{closed}} > E_{\text{open}} \ ?$$

Denied by Aly-Sturrock Theorem

Sequence of Numerically Constructed Force-Free Fields in Multiple Flux Systems



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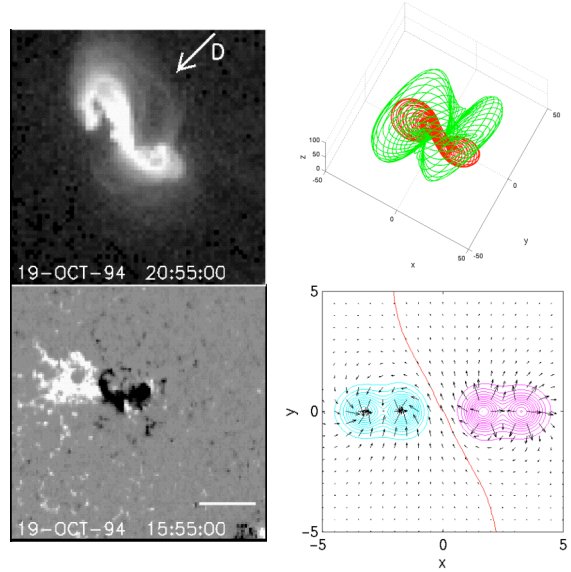
Comparison with Observation



Comparison with the observation by Moore et al. (2001) indicates that

$$2\pi \le \Phi_C \le 2.5\pi$$

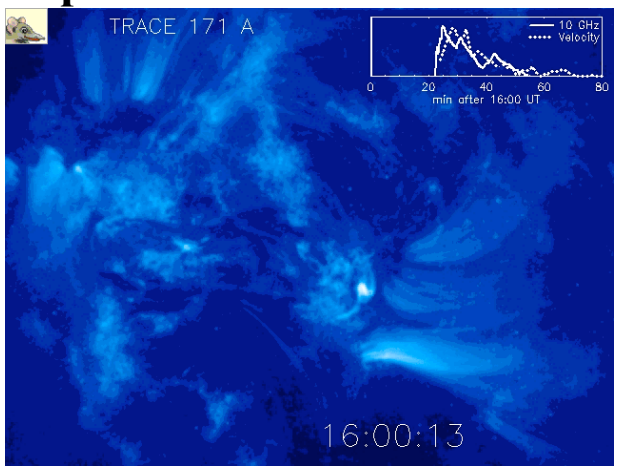
Planned Study Topics

- Construction of pre-eruption fields based on observed magnetograms
- Dynamical evolution leading to eruption and field opening

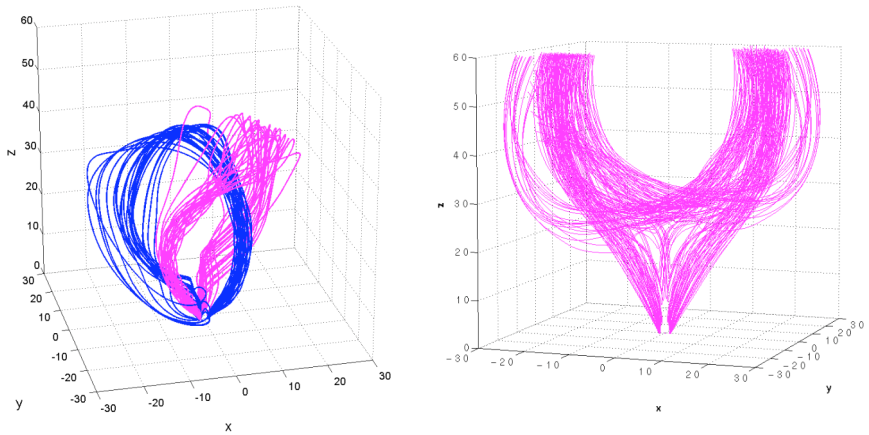
PPPL PRINCETON PLASMA PHYSICS LABORATORY

Large Scale Erupting Flux Ropes are Generated by Stepwise Reconnection of Smaller Scale Flux Tubes

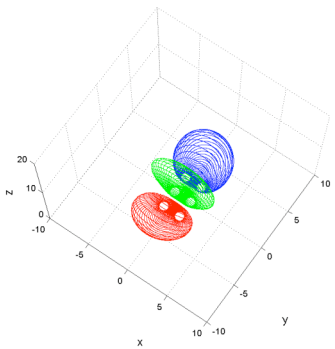
Loop Brightening before a Major Eruption– Trace 171Å Observation



Stepwise Formation of Larger Flux Ropes



System Composed of 3 Flux Tubes



Inititial potential field
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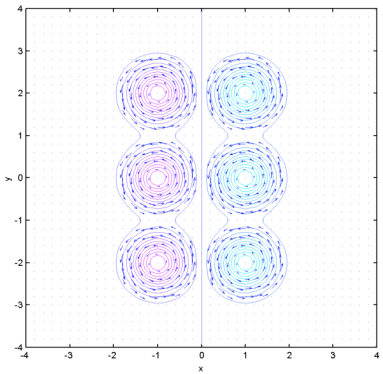


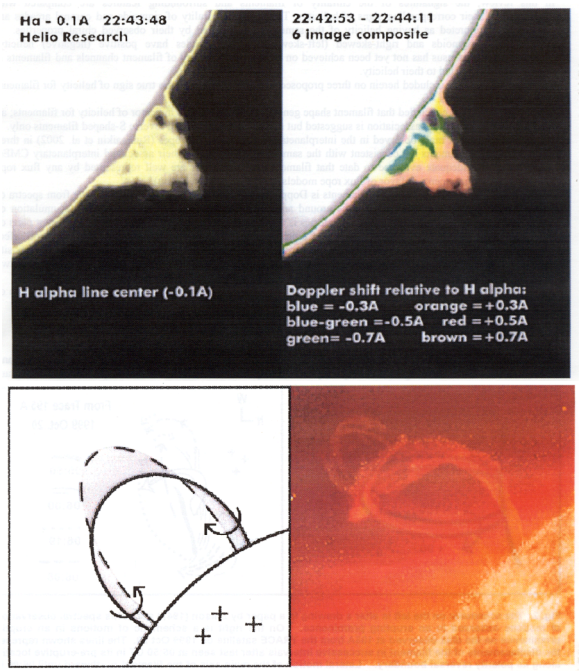
B_n contour and v_t

Planned Study Topics

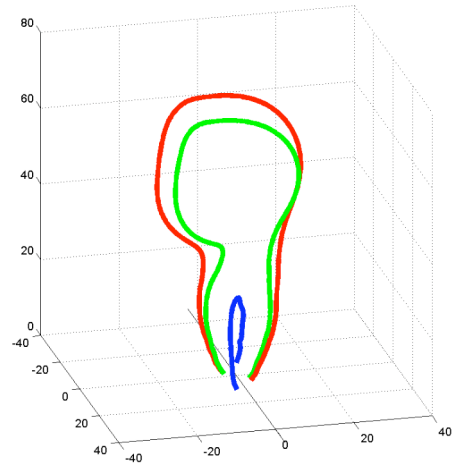
- Simulations based on real magnetograms and velocity patterns
- Helicity redistribution and conversion between self- and mutual helicities by magnetic reconnection

Roll Effect in Solar Prominence Eruptions Understood Using MHD Simulations with Anisotropic Conductivity

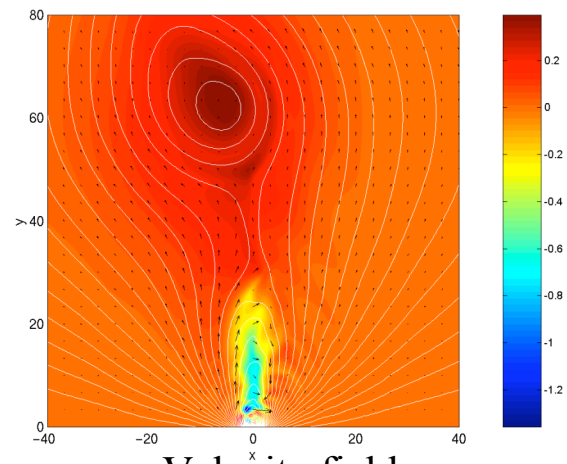
Observation of Roll Effect



Rolling of Reconnected Field Lines by Hall Effect (compare MRX)



3D view of field lines



Velocity field

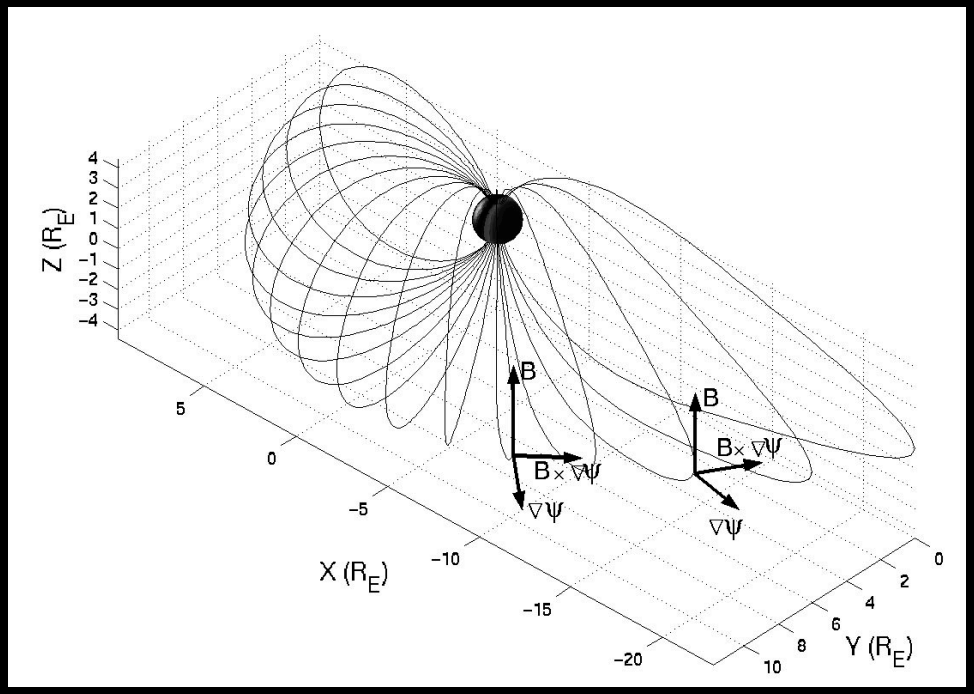
$$\mathbf{J} = \sigma_{\parallel}\mathbf{E}'_{\parallel} + \sigma_{\mathrm{P}}\mathbf{E}'_{\perp} - \sigma_{\mathrm{H}}(\mathbf{E}' \times \mathbf{B})/B$$

where $\mathbf{E}' = \mathbf{E} + \mathbf{v} \times \mathbf{B}$

Planned Study Topics

- Simulation with a three fluid (neutral-ion-electron) code that is being developed
- Simulation with a kinetic MHD code treating the hot plasma component as particles

Three-dimensional Magnetospheric Equilibrium



MAG3D Equilibrium Code

Cheng, Zaharia (student)

Planned Applications:

Field-Line Mapping

Magnetospheric Response

Stability Analysis

- Field Line Resonance
- Ballooning Instability

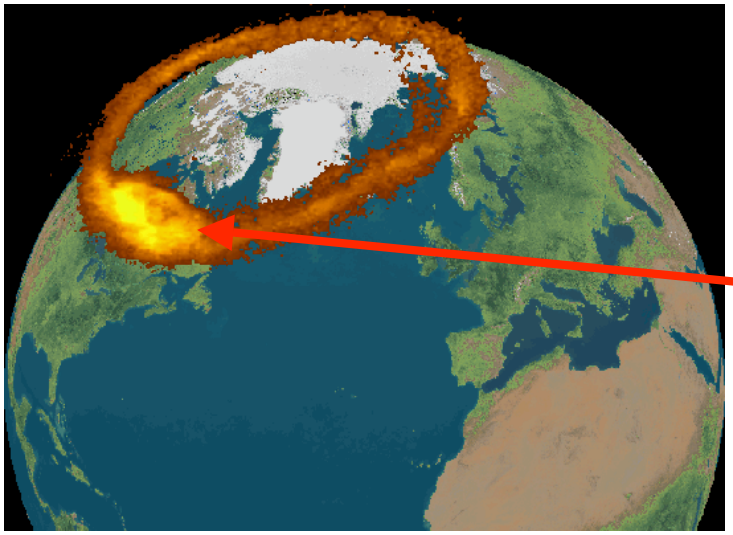
Wave Propagation

Initialize Simulation Codes

Couple to Convection Models

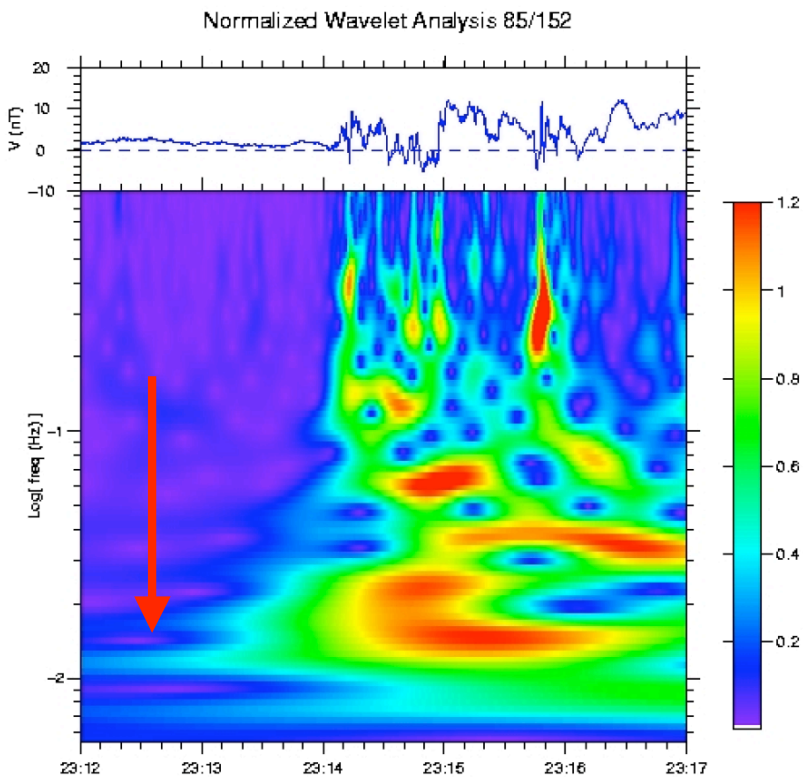
Only Magnetospheric Equilibrium Code that Allows Access to MHD Unstable but Kinetic Stable States

Example---Substorm Onset



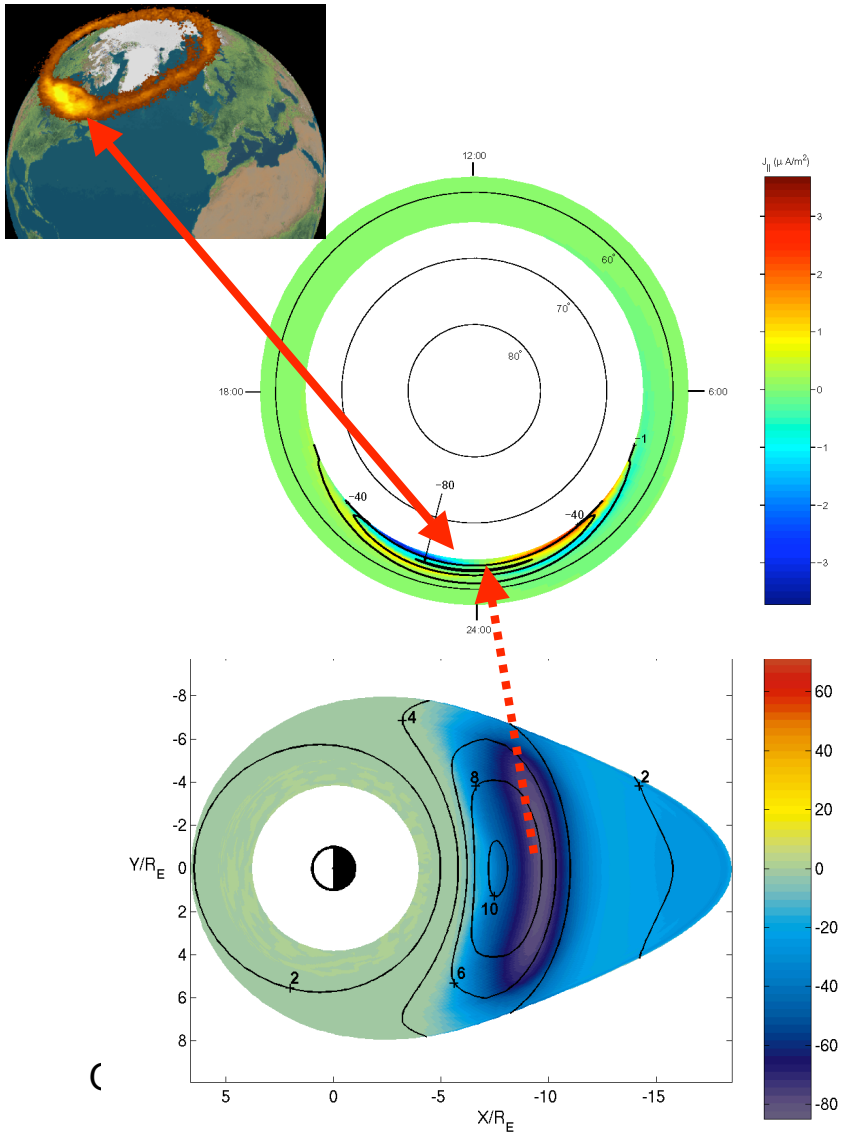
- Substorms are dynamic events that reconfigure the earth's magnetosphere
- They begin in a highly localized region near an auroral arc

Example---Substorm Onset



- Substorms are dynamic events that reconfigure the earth's magnetosphere
- They begin in a highly localized region near an auroral arc at low frequency.

…Similar to Observations of Substorm Onset



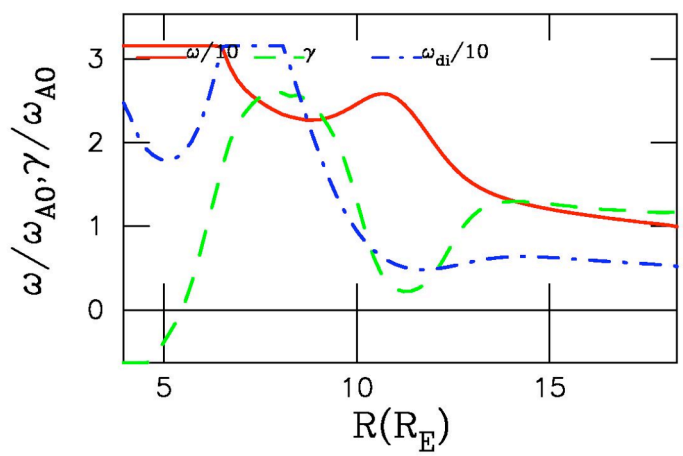
- Substorms are dynamic events that reconfigure the earth's magnetosphere
- They begin in a highly localized region near the auroral arc.
- The magnetosphere is unstable to a kinetic-ballooning mode (requires 3D equilibrium with high beta plasma sheet)
- Unstable region is localized and maps between current systems where auroral arc is observed

Johnson

Kinetic Effects on the Ballooning Instability Explain High Plasma Beta

- Kinetic Ballooning Stability Analysis
  - Trapped electrons
  - Ion gyroradius

Application to Magnetosphere

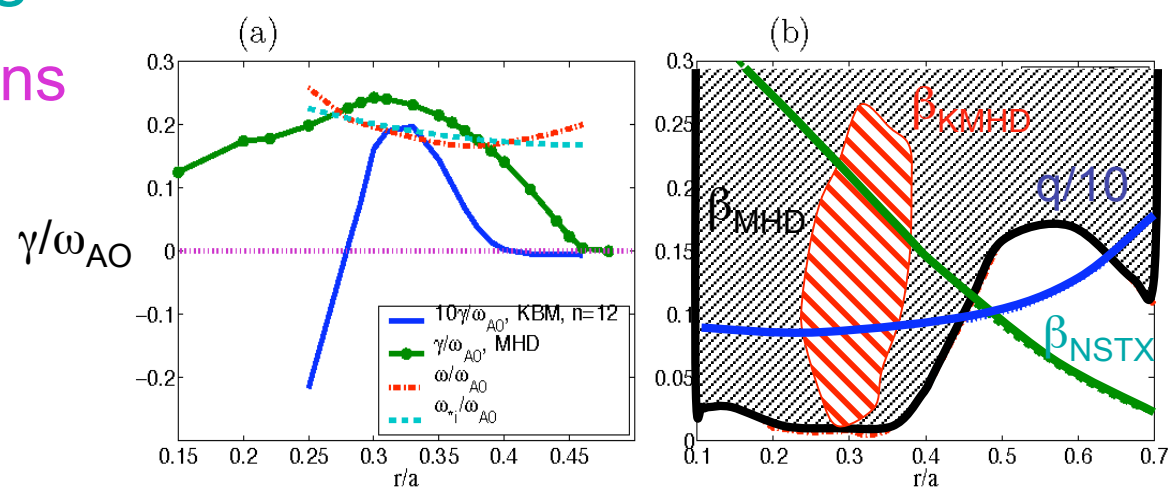


[Cheng and Lui, 1999]
[Cheng, Gorelenkov, Zaharia, 2005]

Synergism with Fusion Research

- Kinetic Ballooning Stability Analysis
  - Trapped electrons
  - Ion gyroradius

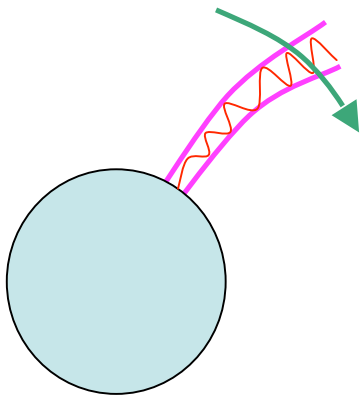
Application to NSTX

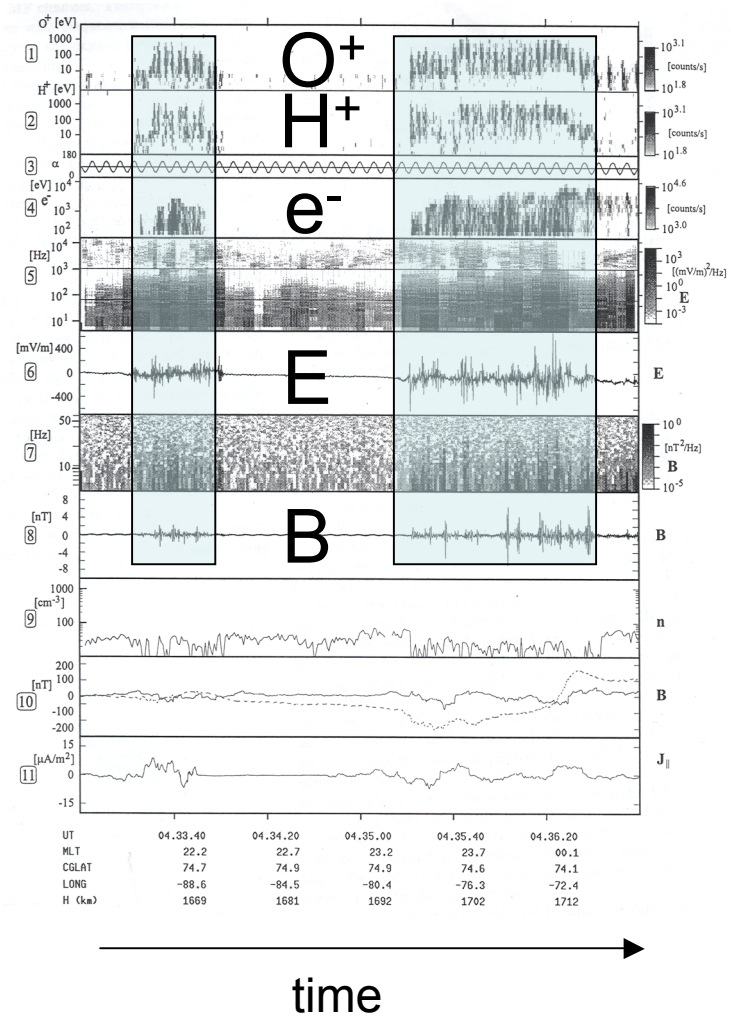


Cheng, Gorelenkov, Kramer, and Fredrickson, 2004

Ion Outflows Associated with Electromagnetic Ion Cyclotron Waves

- Ion Outflows Are Commonly Observed in Association with Electromagnetic Ion Cyclotron Waves

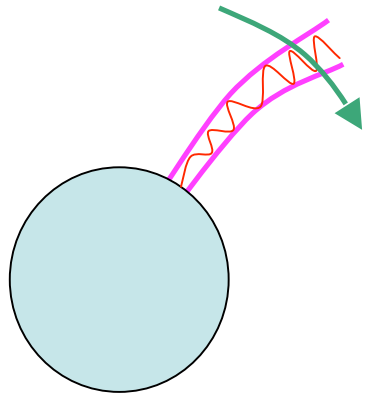


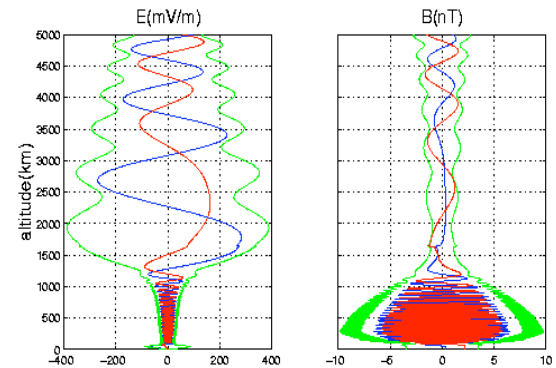


Andre et al., 1998

Self-Consistent Modeling of Ion Outflows

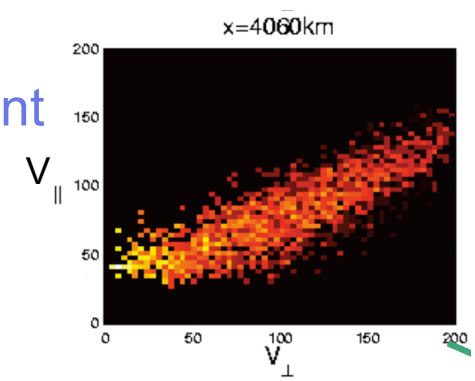
- Ion Outflows Commonly Observed in Association with Electromagnetic Ion Cyclotron Waves
- EMIC Wave Propagation Code Coupled with Monte Carlo Code ⇒ Steady State

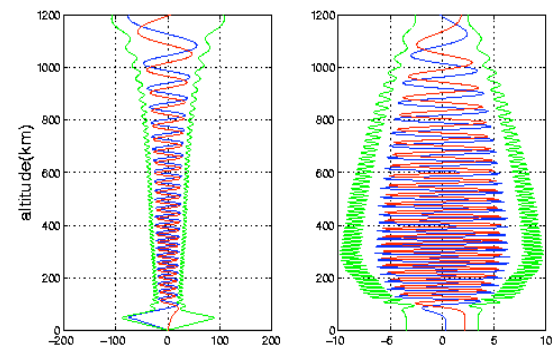




Planned Activities

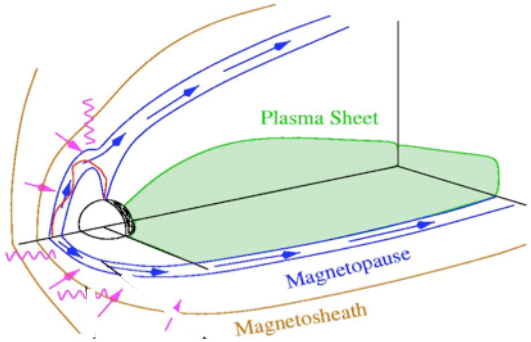
- Model Temporal Development of Plasma Profiles
- Include Parallel Potential Drops
- Model Feedback on Wave Source

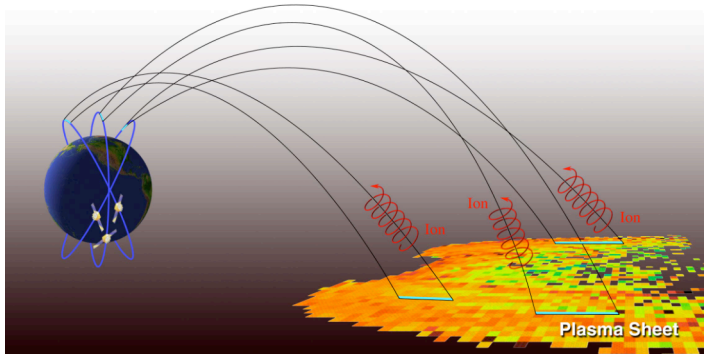




Solar Wind Conditions Control Plasma Sheet Populations

- Particle Entry at Magnetopause Populates Plasma Sheet

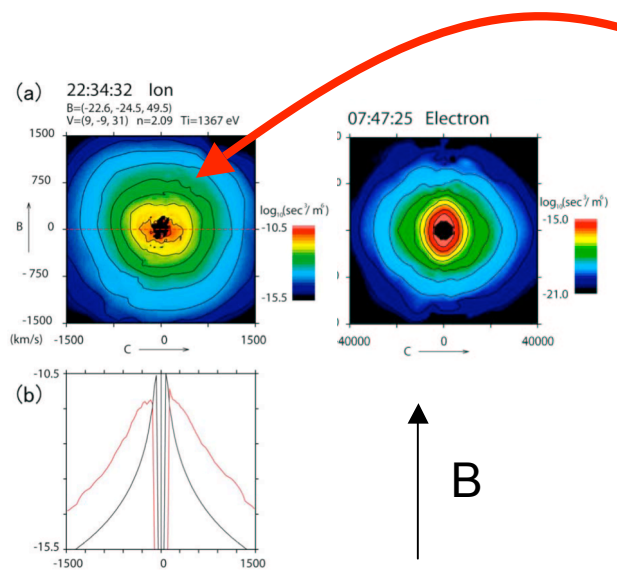


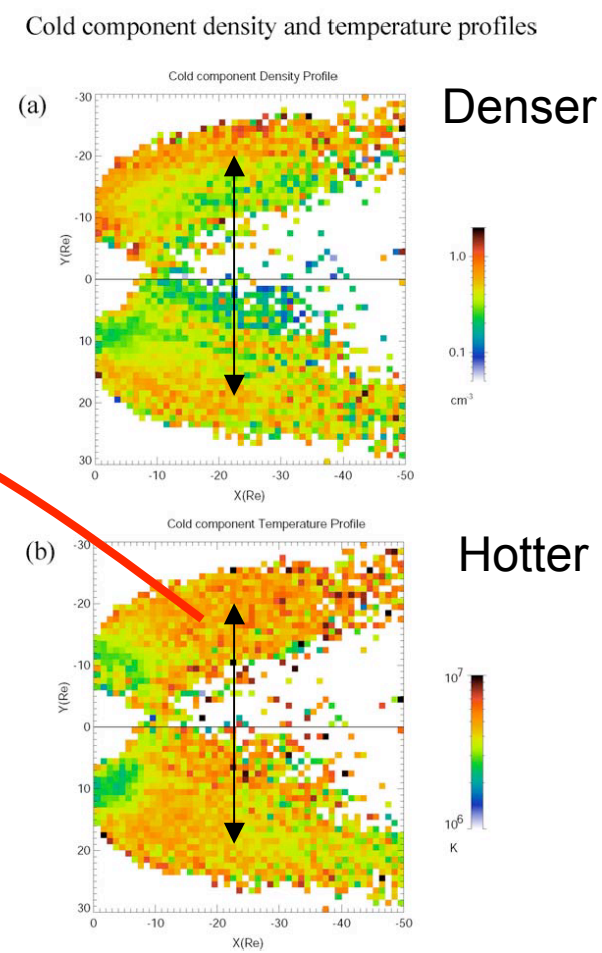


Asymmetries Constrain Particle Entry

- Particle Entry At Magnetopause Populates Plasma Sheet
- Asymmetries Provide Observational Constraints on the Entry Process

[Hasegawa et al., 2004]

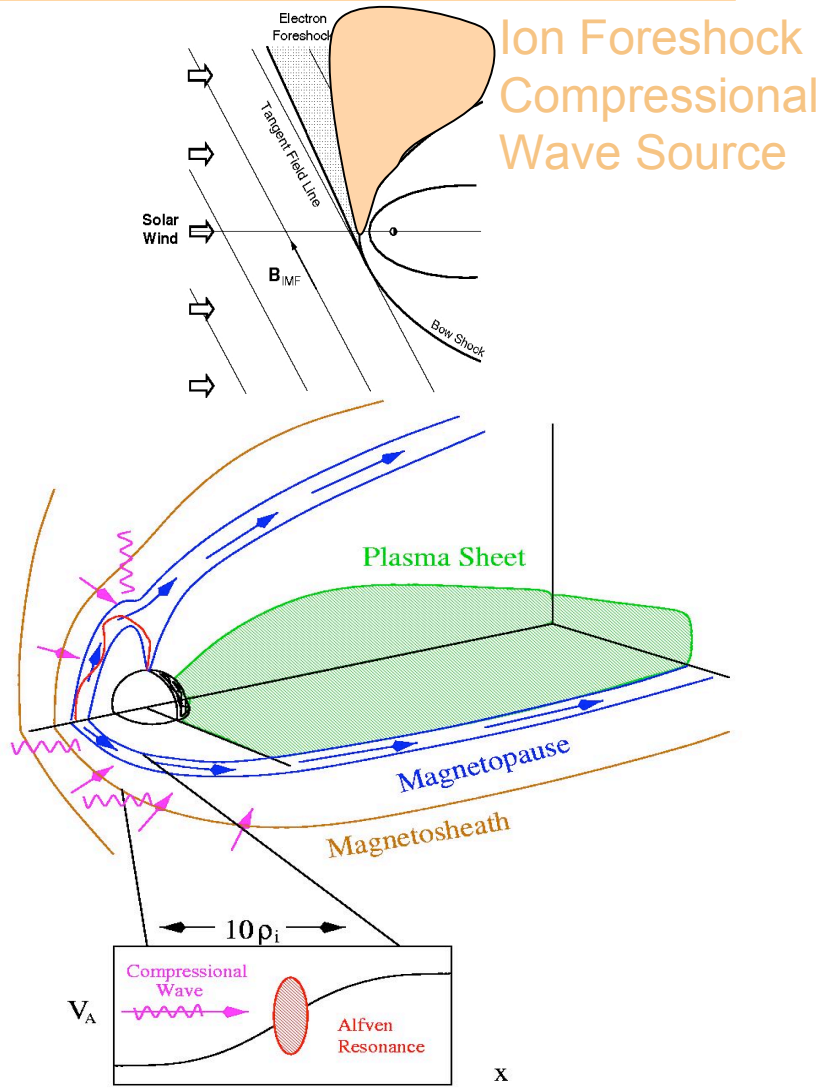




[Wing, Johnson, Newell, and Ming 2005]

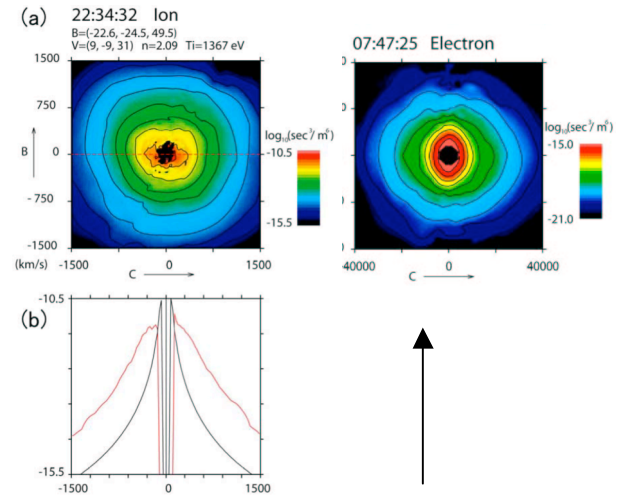
Kinetic Alfven Waves Lead to Particle Entry

- Particle Entry At Magnetopause Populates Plasma Sheet
- Asymmetries Provide Observational Constraints on the Entry Process
- Mode Conversion of Compressional Foreshock Waves to Kinetic Alfven Waves
  - Provides Asymmetric Source for Wave Induced Transport and Heating

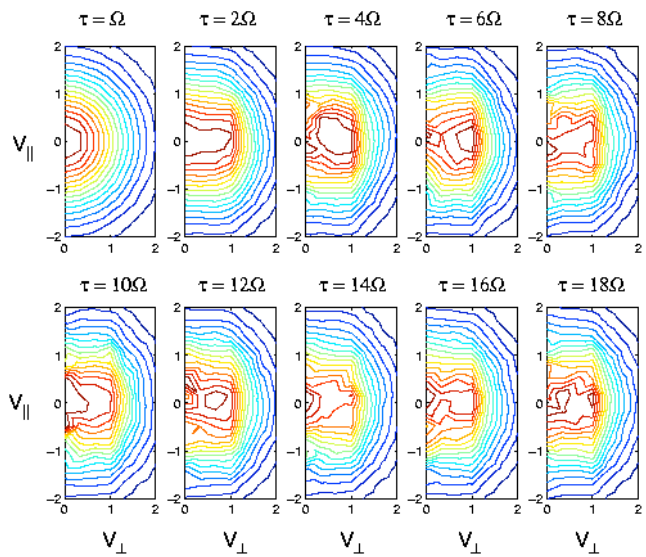


Future Plans to Study Magnetopause Waves and Associated Transport

- Particle Entry At Magnetopause Populates Plasma Sheet
- Observational Constraints on the Entry Process
- Mode Conversion of Compressional Foreshock Waves to Kinetic Alfven Waves



[Hasegawa et al., 2004]

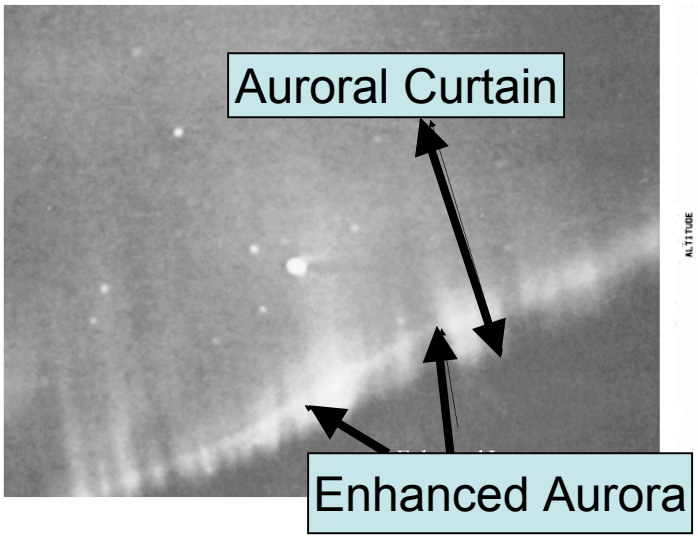


[Johnson et al., 2001]

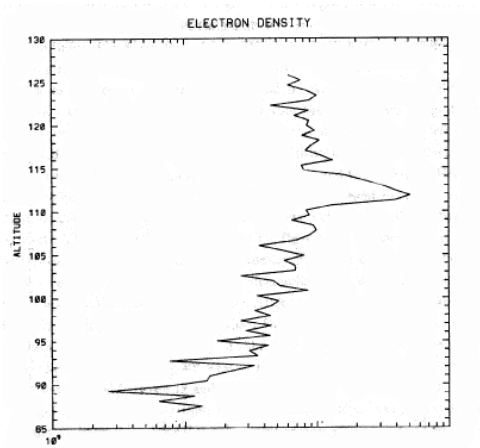
Planned Activities

- Theory-Data Comparisons
- Coupling Kelvin-Helmholtz Instabilities and Kinetic Alfven Waves
- Three-dimensional Hybrid Simulations

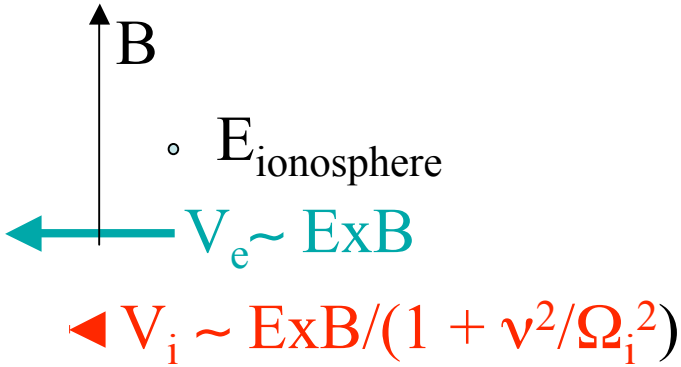
Cross-Field Current Instability Produces Enhanced Auroral Emissions



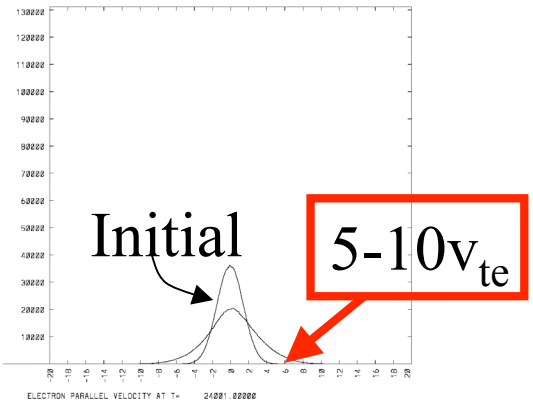
[Hallinan et al., 1985]



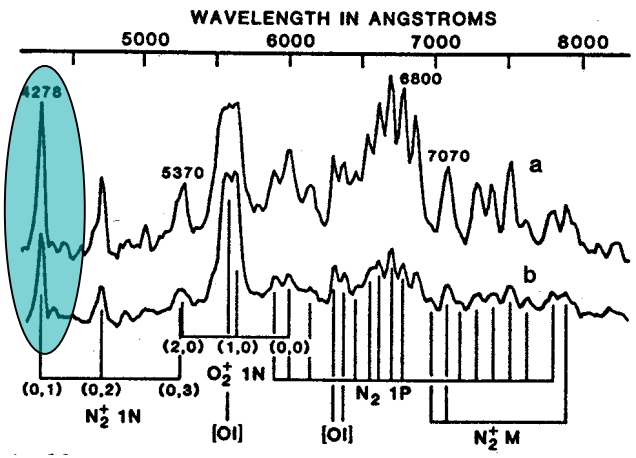
Bristow and Watkins, 1993



Electron Parallel Distribution $f_e(v_k)$



v_k / v_{te}



Cross-Field Current Instability
Increased Density
Reduced Ion Landau Damping
Localization
Electron Heating

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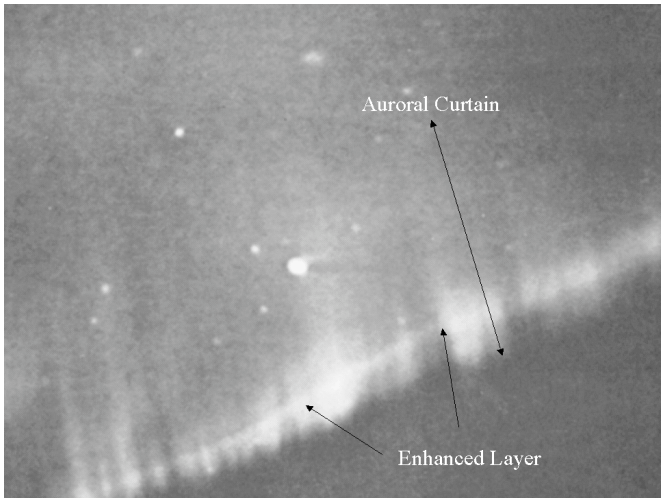
Planned Activities for Auroral Studies

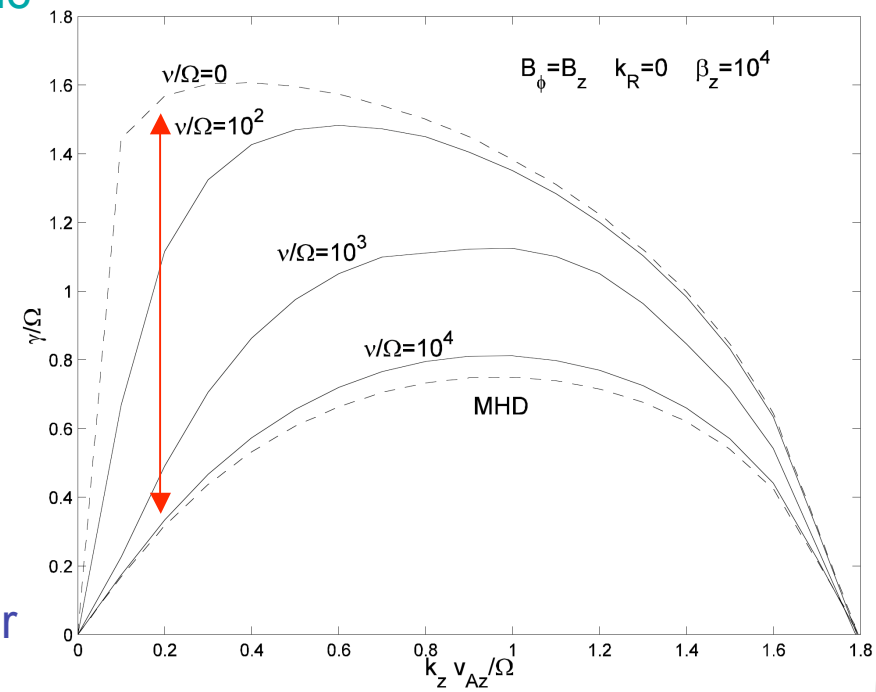
- Full particle simulations including ionospheric collisions and macroscale accelerating potential



[Hallinan et al., 1985]

Kinetic Effects Modify the Magnetorotational Instability

- Transport of Angular Momentum Due to MRI Allows Accretion to Occur
- MRI Growth Rate Modified by Kinetic Effects (Landau Fluid)
- Effective Astrophysics-Fusion Collaboration [Quateart (Berkeley), Stone (Princeton), Dorland (Maryland), Cowley (UCLA), Schekochihin (Cambridge)]



Sharma, Hammett, and Quateart, 2003

Future Plans

- Extend Landau Fluid Zeus from shearing box to global simulations
- Explore continuum/Eulerian code for 5-D kinetic-MHD

Collaborations

- C. Z. Cheng, National Space Program Office, Taiwan, Kinetic-MHD Model, Substorm Onset
- Sorin Zaharia, Los Alamos National Laboratory, Plasma Sheet Equilibria and Substorm Growth Phase
- A. T. Y. Lui and Simon Wing, Applied Physics Laboratory, Johns Hopkins University, Theory-Data Comparison of Substorm Onset and Kinetic Ballooning Instability, Observations of Plasma Sheet and Magnetopause Transport, Predictive Modeling of Geospace Indices
- Mark Engebretson, Augsburg College, MN, Theory-Data Comparison of Ion Cyclotron Observations
- Peter Chi, University of California, Los Angeles, Using Information-Theoretical Techniques to Define a ULF Wave Index
- Yu Lin, Auburn University, Magnetopause Physics
- Dirk Lummerzheim and Antonius Otto, University of Alaska, Fairbanks, Theoretical Modeling of Enhanced Aurora, Kinetic Effects on Magnetopause Simulations, Three Fluid Simulations (including the effect of neutrals)
- D. Gary and J. Lee, New Jersey Institute of Technology,Mechanisms of Solar Flares and Coronal Mass Ejections
- S. F. Martin, Helio Research, Roll Effect in Prominence Eruption
- Y. J. Moon, Korea Institute of Astronomy and Space Sciences,Statistical Studies of Solar Eruptions
- B. C. Low, HAO/National Center for Atmospheric Research,Magnetohydrostatic Equilibria in the Sun
- J. J. Aly, CEA, Service d'Astrophysique, France, Energetics of Force-free fields

Summary of Space Plasma Physics at PPPL

- Our Goal is to Understand Basic Plasma Physics in Space and Relate It to Observations
- Mutual Benefits for Space Physics and PPPL
  - Development of Codes and Theoretical Expertise
    - Equilibrium, MHD, kinetic-MHD, Wave Propagation, Gyrofluid, Gyrokinetic, and Full Particle Codes
  - Cross-Fertilization with Experiments
    - MRX
    - MRI
    - RF Heating
    - Information-Theoretical Techniques