Validation of Magnetospheric Magnetohydrodynamic Models

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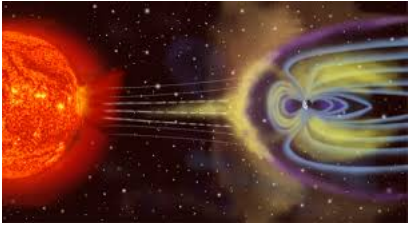
Special Recognition



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- Dr. Art Poland
- Dr. Ruixin Yang

Outline

1. Introduction
    - Motivation
    - Experiments
    - Space Weather
2. Magnetospheric Magnetohydrodynamics
    - Earth's Magnetosphere
    - Magnetohydrodynamics
    - Magnetospheric MHD Models
3. Validation
    - Overview
    - Validation Methods
4. Experiments
    - B_z Reversal
    - Preconditioning
    - Extreme Conditions
5. Summary
    - Future Work

Motivation

1. Interest in using MHD models for operational forecasting; very little validation is done.
   - Most common: in-situ data analysis.
   - Comprehensive inter-model comparison is not done.
2. Want understanding of MHD magnetosphere sensitivity to initial solar wind conditions.
   - Sensitivities not looked into yet.
3. Want a better understanding of MHD model differences.
   - New tool in analyzing two model outputs: Differences.

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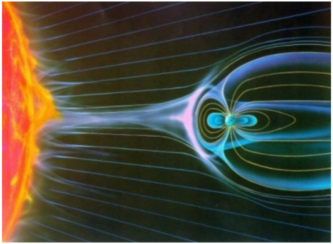
Summary

1. This new inter-model difference comparison, with future work will offer a new perspective to model developers in understanding reasoning behind results from in-situ data analysis.
2. MHD models are very sensitive in response to initial conditions. Found regions of inconsistencies in these numerical models. For example high compression gave three very different results.
3. Differences between models are large. The ring current has an effect on the BATS-R-US output and more validation is still needed to determine the causes of these differences. For example, changes in preconditioning times.

Experiments

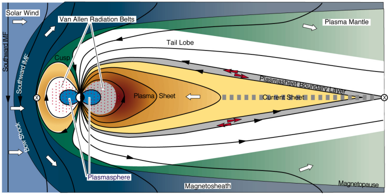
1. Response to a change in solar wind B_z from positive to negative. (Addresses all motivations)
2. The influence of preconditioning on MHD magnetospheric models. (Addresses motivations 1 and 3)
3. How magnetospheric MHD models differ in their response to extreme solar wind conditions. (Addresses all motivations)

Space Weather



Space weather: The term used to describe the current state of the space environment involving the influence of particles traveling outward from the Sun on objects in the heliosphere, magnetosphere, ionosphere and thermosphere (Thompson, 2000)

Earth's Magnetosphere



- Shape determined from a balance between kinetic pressure from the solar wind and magnetic pressure from Earth's magnetic field.
- IMF direction has most influence on magnetospheric response.
- Fluctuates between a bell and teardrop shape.
- Reconnection most supported theory for energy transfer in magnetosphere.

Magnetohydrodynamics

Magnetohydrodynamics

- Start with Boltzmann equation for single species.
- Invoke conservation of Mass, Momentum, Energy.
- Conservation equations summed over all species, treated as a single fluid.
- Use Maxwell's Equations:
  - Gauss' Law.
  - Gauss' Law for Magnetism.
  - Faraday's Law.
  - Ampere's Law.

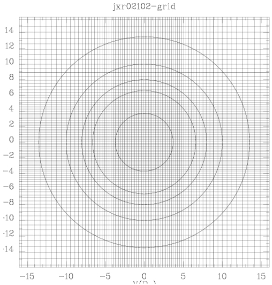
Ideal MHD

- The time derivative of E is small
- Isotropic Pressure
- Charge neutrality
- Neglect small terms
- Single ion flow with collision term approximation
- Perfect conductivity

Implementation

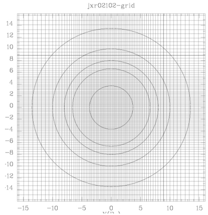
- Grid Choice
- Discretization

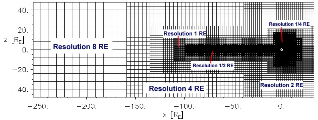
Modeling



- Grid Choice: Uniform/Stretched Cartesian, SAMR
- Boundary/Initial Conditions
- Discretization: Finite Differences, Finite Volumes, Finite Elements.

Chosen MHD Models





OpenGGCM

- Stretched cartesian grid.
- Solves resistive MHD. (Not neglecting magnetic diffusivity)
- Conservative finite difference.

BATS-R-US/SWMF

- Block adaptive grid.
- Solves ideal MHD.
- Finite volumes.
- SWMF adds Rice Convection Model.

- **Verification** analyses ensure that the numerical implementation of the mathematics are correct.
  - Verification done extensively by model developers.
- **Validation** analysis encompasses many ways of looking at model outputs.
  - 15 methods used (*Sargent*, 2003).

Validation

- Animation
- **Comparison to other models**
- Degenerative tests
- Event validity
- Extreme condition test
- Face validity
- Historical data validation
- Historical methods
- Internal validity
- Multistage validation
- Operational graphics
- **Parameter variability - sensitivity analysis**
- Predictive validation
- Traces
- Turing tests

- **Comparison to other models**: The results from other already validated models are used to determine a new models' validity.
- **Parameter variability - sensitivity analysis**: Changing the input and internal values of a model to determine the effect of the models output/behavior.

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1. Response to a change in solar wind B_z from positive to negative. (Addresses all motivations)
2. The influence of preconditioning on MHD magnetospheric models. (Addresses motivations 1 and 3)
3. How magnetospheric MHD models differ in their response to extreme solar wind conditions. (Addresses all motivations)

Experiment Setup

- B_z reversal from positive to negative at 00:30 out of 06:00.
- Other input variables kept at 11 year means.

Table : Chosen values for CCMC run 1

Run Num.	ρ $[cm^{-3}]$	T $[K]$	U_x $[km/s]$	B_z $[nT]$
1	5.76	101289	-442	+3.1 to -3.0 at 00:30

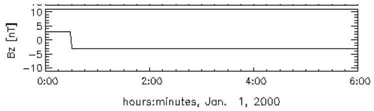


Figure : CCMC run 1 plot of input time series

Input Variable Selection

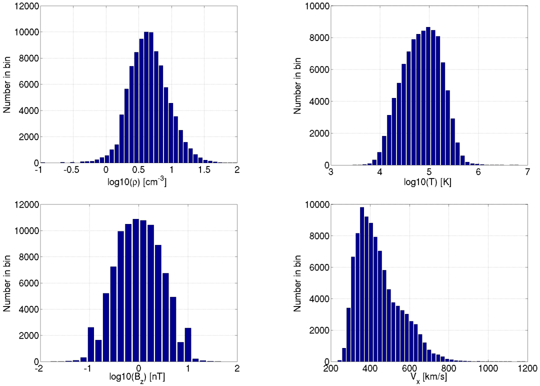
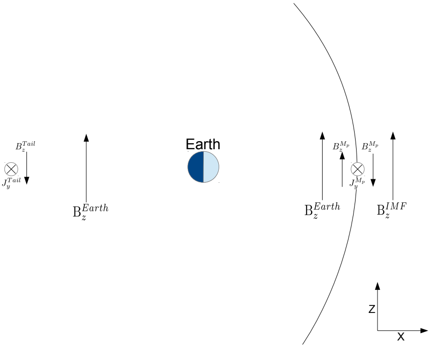


Figure : Jan 1, 2000 to Jan 1, 2011 Histograms of ACE Data

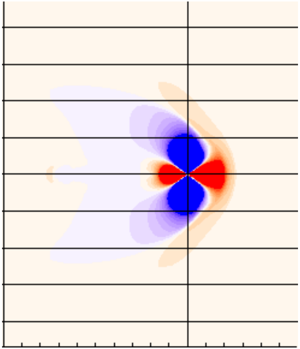
B_z Analysis: Magnetopause locations

- Important for satellite operations. Avoid crossing from magnetosphere into solar wind.
- For this experiment:
  - No ring current and northward IMF B_z
  - No ring current and southward IMF B_z
  - Included ring current and northward IMF B_z
  - Included ring current and southward IMF B_z

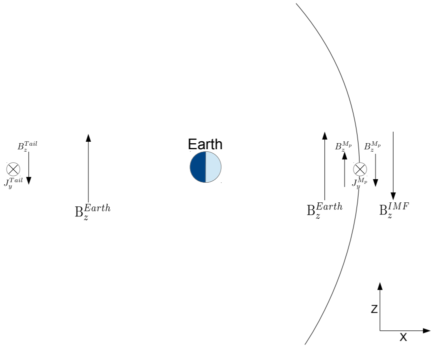
No ring current and northward IMF B_z

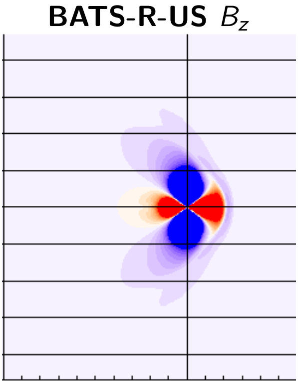


BATS-R-US B_z

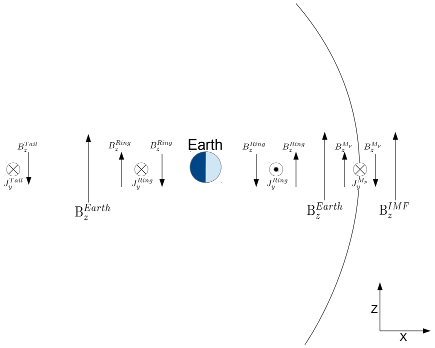


No ring current and southward IMF B_z

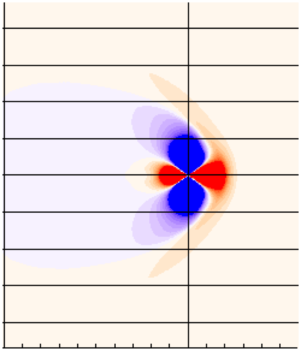




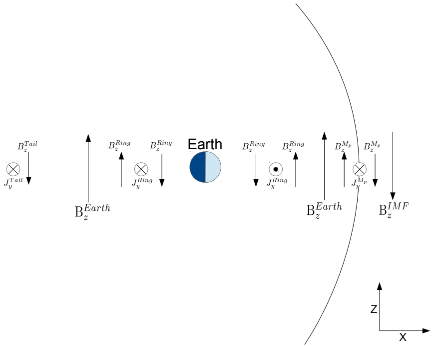
Included ring current and northward IMF B_z

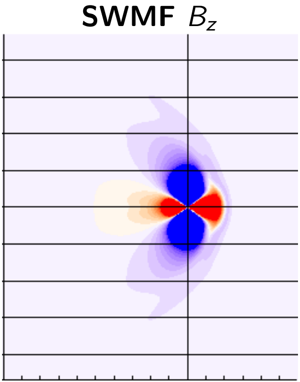


SWMF B_z



Included ring current and southward IMF B_z





B_z Differences

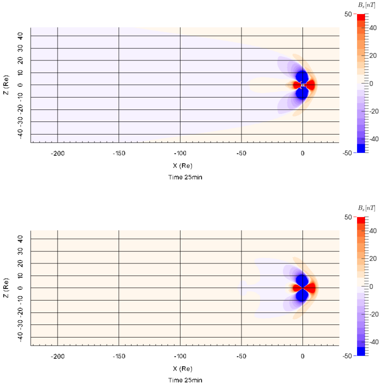


Figure : OpenGGCM (top) and BATS-R-US (bottom) northward IMF B_z

B_z Differences

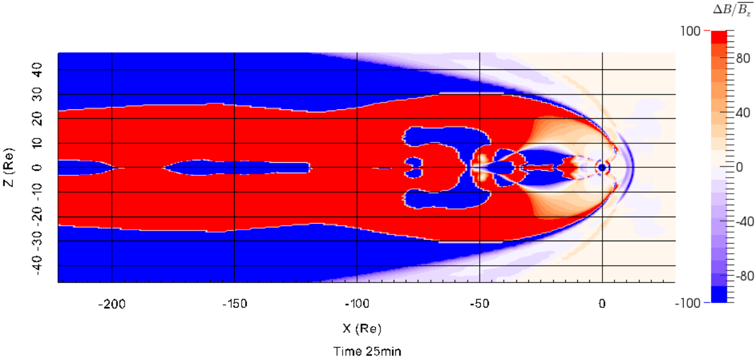
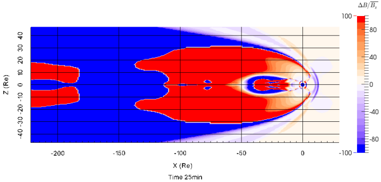


Figure : OpenGGCM - BATS-R-US B_z Percent Diff

B_z Differences



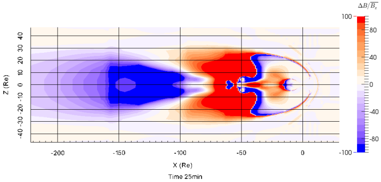


Figure : OpenGGCM - SWMF (top) and BATS-R-US - SWMF (bottom) northward IMF B_z differences

B_z Differences

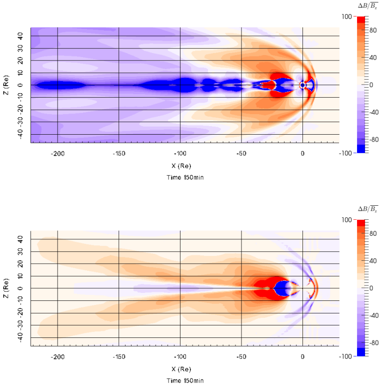
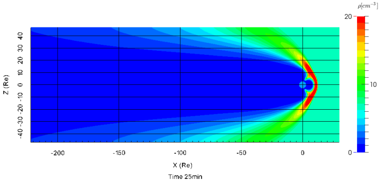


Figure : OpenGGCM - SWMF (top) and BATS-R-US - SWMF (bottom) southward IMF B_z differences

ρ Differences



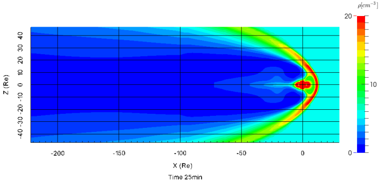


Figure : OpenGGCM (top) and SWMF (bottom) ρ

ρ Differences

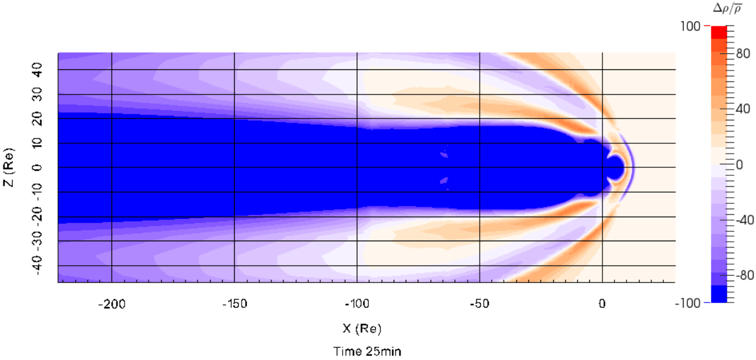
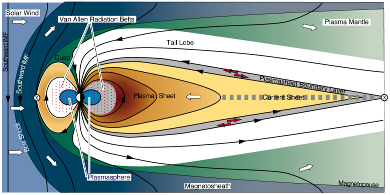
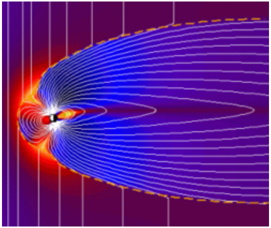


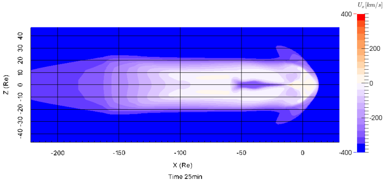
Figure : OpenGGCM - SWMF ρ Percent Diff

Expected U_x


Solar Wind
Van Allen Radiation Belts
Plasma Mantle
Tail Lobe
Southward IMF
Southward IMF
Cusp
Plasmasheet Boundary Layer
Plasma Sheet
Current Sheet
Bow Shock
Plasmasphere
Magnetosheath
Magnetopause



U_x Plots



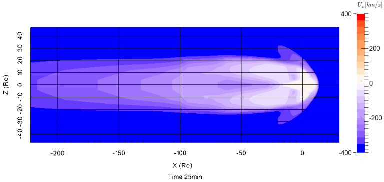


Figure : BATS-R-US (top) and SWMF (bottom) U_x

U_x Differences

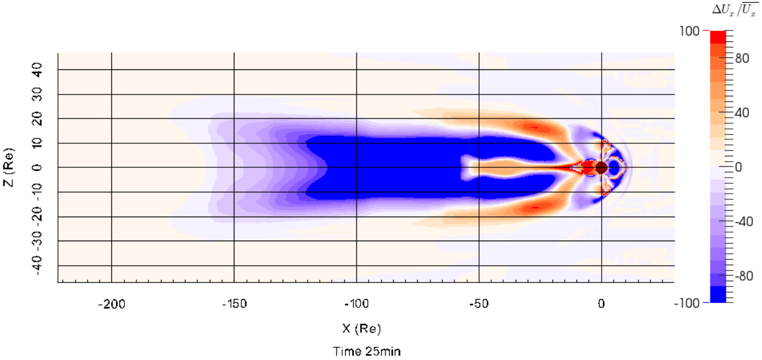


Figure : BATS-R-US - SWMF U_x Percent Diff

B_z Reversal Conclusions

For a reversal in IMF B_z, the following occur in the models:

- The OpenGGCM magnetopause is closest to Earth as it has the weakest magnetic pressure near-Earth.
- In positive IMF B_z conditions, the ring current pushes the SWMF magnetopause farther Sunward than the BATS-R-US.
- In negative IMF B_z conditions, the SWMF magnetopause is farther Earthward than the BATS-R-US.
- The differences in magnetopause positions between the BATS-R-US and SWMF are due to the effects of the ring current addition to the magnetosphere in the SWMF model.
- Densities are highest with the SWMF and lowest with the OpenGGCM.
- The OpenGGCM tail velocities are largely different from the BATS-R-US and SWMF.

Preconditioning Definition

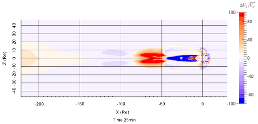
Definition: Magnetospheric model pre-conditioning takes an initial state, then the model is iterated through time and conditions are slowly changed to meet the initial conditions set by the user.

- Earth's magnetic field is set as a dipole, mirror dipole at $16R_e$. Plasma temperature and density initially set to 5000 $[K]$ and 0.1 $[cm^{-3}]$ respectively.
- OpenGGCM: Uses 2 hours of preconditioning that includes 30 minutes with negative Bz.
- BATS-R-US/SWMF: Uses a local time stepping scheme where an approximate steady state is reached after 2500 iteration steps.

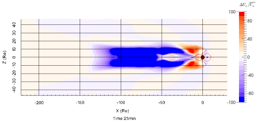
Experiment Setup

- First run: B_z reversal at 00:30 (early reversal)
- Second run: Delay B_z reversal until 02:00 (late reversal)
- Take equal data sample sizes matching the reversal times.
- Compare models with themselves at two different reversal times.

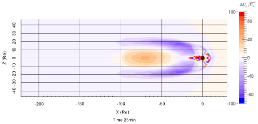
Model Outputs



- OpenGGCM



- BATS-R-US



- SWMF

Preconditioning Conclusions

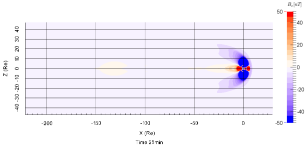
For changes in the preconditioning time of magnetospheric MHD models the following shows that there is a significant sensitivity to preconditioning time and supports that there is a need for a more detailed analysis:

- Longer preconditioning time allowed the magnetosphere to relax more giving different positions for the magnetopause with all three models.
- The OpenGGCM magnetopause position differences were wider than that of SWMF or BATS-R-US.
- There were large differences for all three models before the B_z reversal.
- The differences in the current sheet region for the OpenGGCM were similar before and after the reversal.
- The BATS-R-US and SWMF differences decreased after the B_z reversal to near zero.

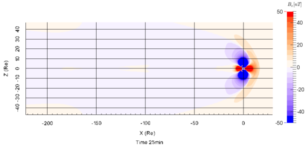
Experiment Setup

Table : Chosen values for CCMC runs 3 and 4

Run Num.	ρ	T	Vx	B_z
3	11	101289	-604	-3.0
4	2	101289	-320	3.1



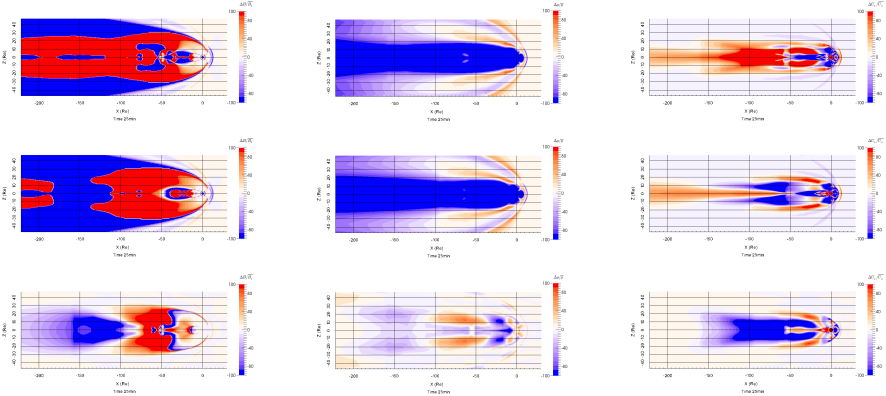
Run 3 - High Compression



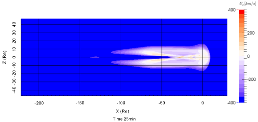
Run 4 - Low Compression

Low Compression - Model Output

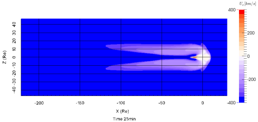
B_z Percent Diff | **ρ Percent Diff** | **U_x Percent Diff**



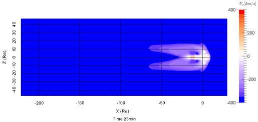
High Compression - Model Output



- OpenGGCM



- BATS-R-US



- SWMF

Extreme Conditions Conclusions

For extreme conditions in the solar wind, the following occurs in the magnetosphere:

- The OpenGGCM has a large region of Earthward U_x in the current sheet region that grows as time progresses in a compressed environment.
- The BATS-R-US is either completely stable or stops in a compressed environment.
- In a compressed environment the SWMF will eventually oscillate.
- The OpenGGCM has the highest tailward velocities in a compressed environment.
- The ring current reduced the maximum velocities in the SWMF.
- The OpenGGCM has the highest B_z in a compressed environment.
- All three models have similar magnetopause positions in a low compression environment.
- The OpenGGCM current sheet velocities are largest in a low compression environment.

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Summary

1. This new inter-model difference comparison, with future work will offer a new perspective to model developers in understanding reasoning behind results from in-situ data analysis.
2. MHD models are very sensitive in response to initial conditions. Found regions of inconsistencies in these numerical models. For example high compression gave three very different results.
3. Differences between models are large. The ring current has an effect on the BATS-R-US output and more validation is still needed to determine the causes of these differences. For example, changes in preconditioning times.

Future Work

- Expand to more magnetospheric models.
- Increased preconditioning time can allow more stability in the magnetosphere. Research is needed to better understand a more appropriate preconditioning time.
- Expand to different types of conditions.
- Correlate model differences to real-time outputs for forecasters.

Thank you.

Appendix - MHD

- Conservation of Mass.
  $\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$
- Conservation of Momentum.
  $\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u}) + \nabla \cdot P - \rho_q \mathbf{E} - \mathbf{J} \times \mathbf{B} - \rho \mathbf{g} = 0$
- Conservation of Energy.
  $\frac{\partial \epsilon}{\partial t} + \nabla \cdot (\epsilon \mathbf{u} + P \cdot \mathbf{u} + \mathbf{q}) - \mathbf{J} \cdot \mathbf{E} - \rho \mathbf{u} \cdot \mathbf{g} = 0$
- Maxwell's Equations:
  - Gauss' Law.
    $\nabla \cdot \mathbf{E} = \frac{\rho_q}{\epsilon_0}$
  - Gauss' Law for Magnetism.
    $\nabla \cdot \mathbf{B} = 0$
  - Faraday's Law.
    $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
  - Ampere's Law.
    $\nabla \times \mathbf{B} = \mu_0 (\mathbf{J} + \epsilon_0 \frac{\partial \mathbf{E}}{\partial t})$

Appendix: Ideal MHD

To simplify the single fluid MHD equations, the following assumptions were made:

- The time derivative of E is small
  $\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$
- Isotropic Pressure
  $\nabla \cdot P = \nabla p$
- Charge neutrality
  If net charge balances, then $\rho_q = 0$
- Neglect small terms
  If p_e is small, then any term involving P_q can be neglected
- Single ion flow with collision term approximation
  $\mathbf{J} = \sigma(\mathbf{E} + \mathbf{u} \times \mathbf{B})$
- Perfect conductivity
  $\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{uB} - \mathbf{Bu}) = 0$