Forecasting Space Weather: Progress and Challenges

Tamas Gombosi

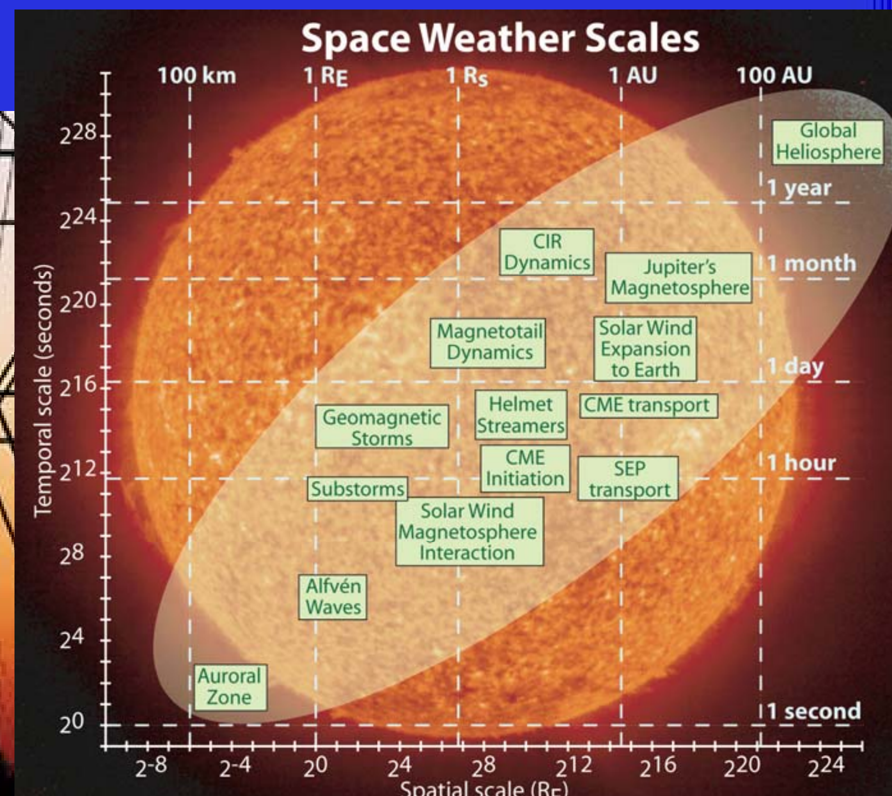
Center for Space Environment Modeling
University of Michigan

Outline

- A few remarks about space weather
- State of space weather forecasting
- Physics based models
- Model coupling and frameworks
- Improving physics models
- Validation and verification
- Uncertainty quantification
- Validation examples
- Data assimilation
- Summary

Space Weather

Conditions in geospace that can have adverse effects on space-borne and ground-based technological systems and can endanger human life or health.



Data Streams Used for Space Weather Forecasting (NOAA SWPC)

- GOES (NOAA)
  - Energetic Particles
  - Magnetic Field
  - Solar X-ray Flux
  - Solar EUV Flux
  - Solar X-Ray Images
- POES (NOAA)
  - High Energy Particles
  - Total Energy Deposition
  - Solar UV Flux
- GROUND STATIONS
  - Magnetometers (NOAA/USGS)
  - Thule Riometer and Neutron monitor (USAF)
  - SOON Sites (USAF)
  - RSTN (USAF)
  - Telescopes and Magnetographs
  - Ionosondes (AF, ISES, …)
  - GPS (CORS)
- SOHO (ESA/NASA)
  - Solar EUV Images
  - Coronagraphs
- ACE (NASA)
  - Solar wind speed, density, temperature and energetic particles
  - Magnetic field strength and direction

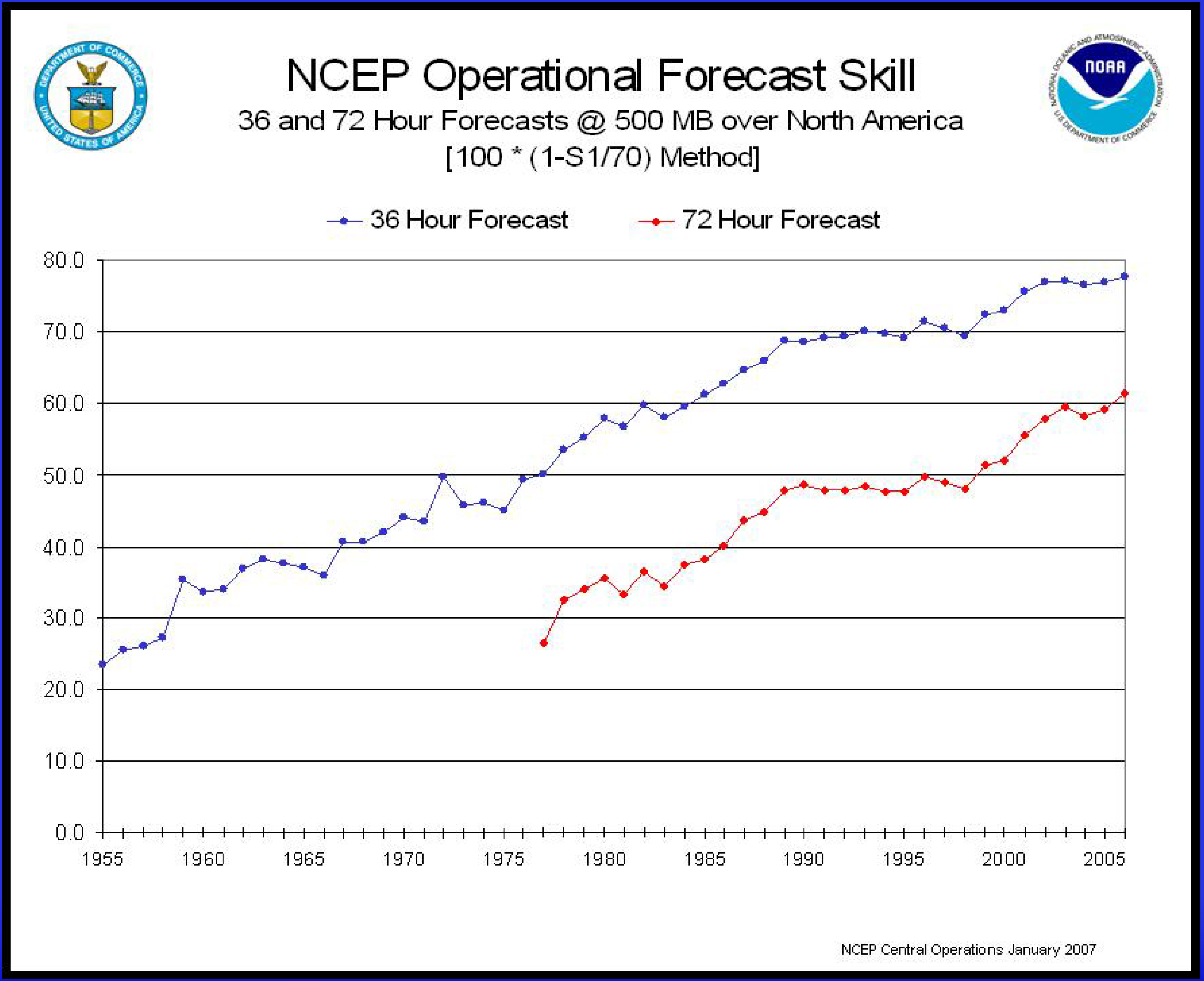
Models/Tools Used for Space Weather Forecasting (NOAA SWPC)

- Empirical/Synoptic Models:
  - D-region Absorption Prediction
  - Global D-region Absorption Prediction (experimental)
  - STORM Time Empirical Ionospheric Correction Model
  - US Total Electron Content Map – USTEC
  - Costello Geomag Activity Index – Predicts Kp
  - Wang–Sheeley Model
  - Relativistic Electron Forecast Model
- Physics-based models
  - ENLIL – experimental runs will start in 2010 (maybe)

How Far Behind Are We?

Numerical Weather Forecasting	Physics-Based Space Weather Models
1904: Vilhelm Bjerknes (Norway) suggests the idea of numerical weather forecast	1995: NSWP Strategic Plan envisions Sun-to-Earth model chain
1922: Lewis Richardson (UK) publishes “Weather Prediction by Numerical Process”	1998: GGCM Concept Report (“MHD spine” plus modules)
1950: Jule Charney (US) makes successful 24h forecasts for North America	2000: First coupled Sun-to-Mud simulation is published (Groth et al., JGR)
1955: Start of operational regional numerical weather forecasting	2002: CCMC starts real-time magnetosphere runs on an experimental basis
1974: Operational global weather models (hydrostatic, spectral)	2004: SWMF is transitioned to CCMC
1991: Operational data assimilation (1DVAR)	2007: First operational regional data assimilation model (USU GAIM)
1998: Operational coupled ocean-atmosphere weather model	2010: First operational regional numerical model

Skill Score Evolution



CSEM — Center for Space Environment Modeling

University of Michigan

Physics-Based Regional Space Weather Models

Domain	Physics	Institution(s)
Convection zone to corona	Radiation MHD	UC Berkeley
Corona*	MHD with parametrized sources	Predictive Science Inc., U. Michigan
Inner heliosphere* ($15R_\odot$–10AU)	MHD	SWPC (Odstrcil), U. Michigan, GSFC (Usmanov), UAH
Inner heliosphere	Kinetic (exospheric solar wind)	BIRA-IASB (Belgium)
Solar energetic particles*	Field-aligned transport	U. Arizona, GSFC, UNH, UAH, U. Michigan, APL
Outer heliosphere*	MHD + 4 neutral fluids	UAH, U. Michigan/GMU
Global magnetosphere*	MHD, multifluid MHD	Dartmouth, UNH, U. Michigan, U. Washington, U. Nagoya, U. Kyushu, FMI (Finland)
Radiation belts*	Adiabatic invariants	GSFC, LANL, Dartmouth, UCLA
Ring current*	Drift physics on closed field lines	Rice, GSFC, U. Michigan
Plasmasphere*	Field-aligned transport	U. Michigan
Ionospheric outflow*	Multifluid transonic flow along open field lines	USU, U. Michigan
Ionosphere-thermosphere*	3D HD and chemistry	NCAR, SWPC, U. Michigan
Ionospheric electrodynamics*	Height integrated potential field	Many
Whole atmosphere	3D HD and chemistry with vertical coupling	NCAR, SWPC

*Coupled together with SWMF

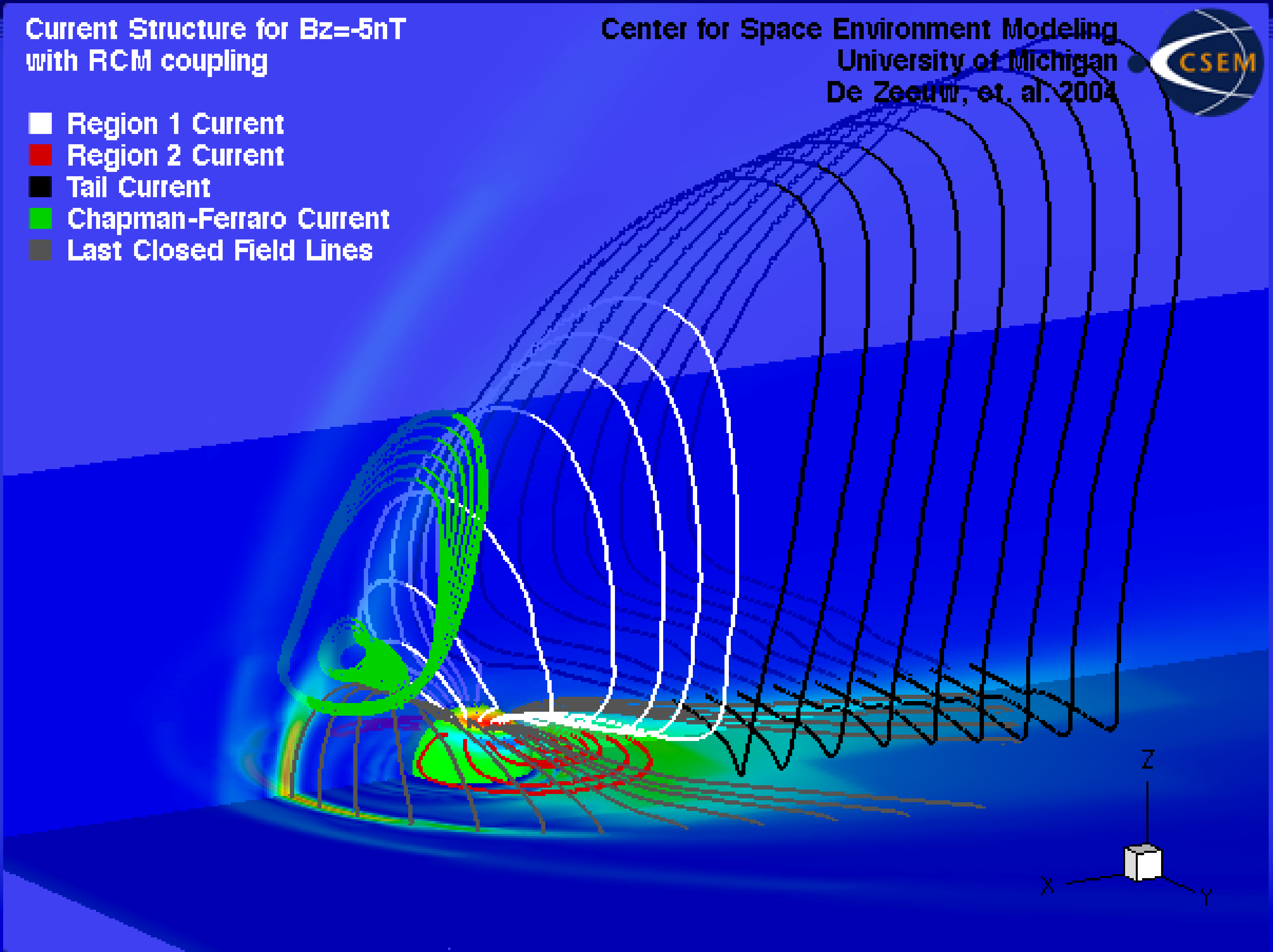
Model Coupling and Frameworks

- CISM: Model coupling based on object oriented programming using existing packages
  - Intelligent Data Channels (InterComm)
  - Program Control (HPCALE)
  - Data Manipulation and Interpolation -Couplers (Overture)
- CSEM: Space Weather Modeling Framework
  - Single executable
  - Similar architecture as used by ESMF (can be run under ESMF)
- OpenGGCM: Direct coupling

Ideal MHD

- Ideal MHD is the lowest order fluid approximation describing the behavior of space plasmas.
- Ideal MHD completely neglects the microphysics.
  - Any discretization will introduce numerical dissipation.
  - Numerical transport coefficients (resistivity, diffusivity, viscosity, etc) are usually larger than the physical values of these coefficients.
- Nevertheless, ideal MHD based numerical simulations give a qualitatively realistic description of most space weather phenomena.

Example: Magnetospheric Current Systems



Better Physics: It Comes from Ohm's Law

Average velocity of positive charges

Electron-ion velocity difference

$$\mathbf{E} + \mathbf{u}_+ \times \mathbf{B} - \eta_e \mathbf{j} = -\frac{\mathbf{j}}{en_e}\times\mathbf{B} - \frac{1}{en_e}\nabla p_{e\perp} - \frac{\mathbf{B}}{en_e}\nabla_\parallel\left(\frac{p_{e\parallel}-p_{e\perp}}{B}\right) - \frac{p_{e\parallel}-p_{e\perp}}{en_e}\nabla_\parallel \mathbf{b}$$

Hall term

Ambipolar electric field

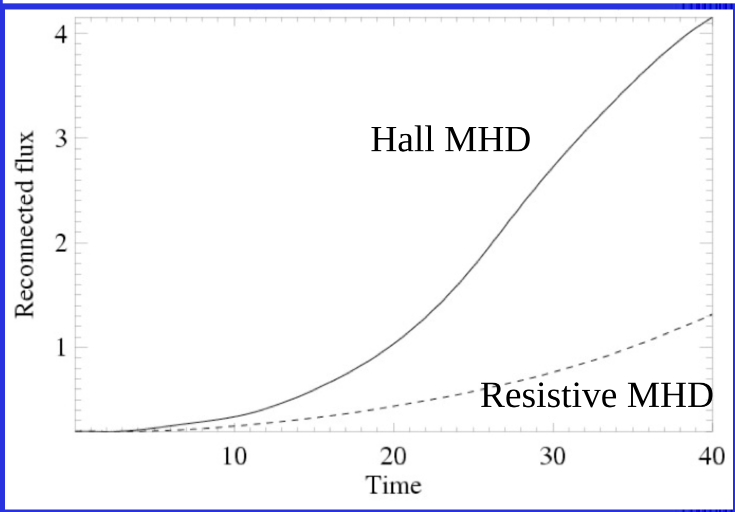
Adiabatic focusing

- In general $\mathbf{u}_+$ and $\mathbf{u}_i$ are not equal (multifluid)
- The Hall term introduces a new "resistivity" and new waves (whistler, drift, reconnection)
- One needs to solve the electron energy equation(s) to get the ambipolar electric field and adiabatic focusing effects

Hall MHD

- Two fluid (electron, ion) Hall MHD with isotropic pressure is the lowest order self-consistent description of magnetized plasmas where reconnection is important.
- The Hall term decouples the ion and electron motion on length scales comparable to the ion inertial length and the electrons remain magnetized while the ions become unmagnetized.
- Numerical challenges:
  - The induction equation contains a second order spatial derivative that is not a Laplace operator. Higher order accuracy is difficult to achieve, especially at resolution changes.
  - The whistler wave is the fastest wave speed and the CFL condition yields $\Delta t \propto \Delta x^2$.

The GEM challenge



The GEM challenge on reconnection physics concluded that Hall physics is the minimum physics needed to achieve fast reconnection (Birn et al.: JGR, 106, 3715, 2001).

Anisotropic Pressure on Closed Field Lines

- Chew-Goldberger-Low (1956) double adiabatic relations:

$$\frac{B^2 p_\parallel}{n^3} \propto \text{const}; \quad \frac{p_\perp}{Bn} \propto \text{const}; \quad \Longrightarrow \quad p = \frac{1}{3}\left(p_\parallel + 2p_\perp\right) \neq \text{const}$$

- If $u_\parallel=0$ the CGL relation becomes $\frac{n}{B} \propto \text{const}; \quad T_\parallel \propto \text{const}; \quad \frac{T_\perp}{B} \propto \text{const}$
- In general, the conservation of adiabatic invariants reduces the number of independent physical quantities (Gombosi: GRL, 18, 1181, 1991):

$$\frac{n}{B} \propto \frac{1}{u_\parallel}; \quad T_\parallel \propto \frac{1}{u_\parallel^2}; \quad \frac{T_\perp}{B} \propto \text{const}$$

- The assumption of constant pressure along closed magnetic field lines (radiation belts, ring current, plasmasphere, coronal loops, etc) is inconsistent with conservation of adiabatic invariants.

Multifluid MHD

$$\boxed{\frac{\partial \rho_\alpha}{\partial t} + \nabla \cdot (\rho_\alpha \mathbf{u}_\alpha) = \frac{\delta \rho_\alpha}{\delta t}}$$

$$\boxed{\begin{aligned} {}_\alpha \frac{\partial \mathbf{u}_\alpha}{\partial t} + \rho_\alpha (\mathbf{u}_\alpha \cdot \nabla) \mathbf{u}_\alpha + \nabla p_{\alpha\perp} - eZ_\alpha n_\alpha \mathbf{w}_\alpha \times \mathbf{B} + \frac{Z_\alpha n_\alpha}{n_e} (\nabla p_{e\perp} - \mathbf{j} \times \mathbf{B}) \\ = eZ_\alpha n_\alpha \eta_e \mathbf{j} + \rho_\alpha \mathbf{g} - (p_{\alpha\parallel} - p_{\alpha\perp}) \nabla_\parallel \mathbf{b} - \frac{Z_\alpha n_\alpha}{n_e} (p_{e\parallel} - p_{e\perp}) \nabla_\parallel \mathbf{b} \\ -\mathbf{B} \nabla_\parallel \left(\frac{p_{\alpha\parallel} - p_{\alpha\perp}}{B} \right) - \frac{Z_\alpha n_\alpha}{n_e} \mathbf{B} \nabla_\parallel \left(\frac{p_{e\parallel} - p_{e\perp}}{B} \right) + \rho_\alpha \frac{\delta \mathbf{u}_\alpha}{\delta t} \end{aligned}}$$

$$\boxed{\frac{\partial p_{\alpha\parallel}}{\partial t} + (\mathbf{u}_\alpha \cdot \nabla) p_{\alpha\parallel} + p_{\alpha\parallel} (\nabla \cdot \mathbf{u}_\alpha) + 2 p_{\alpha\parallel} \mathbf{b} \cdot \nabla_\parallel \mathbf{u}_\alpha + \tfrac{4}{5} \mathbf{b} \cdot \nabla_\parallel \mathbf{h}_\alpha + \tfrac{2}{5} \nabla \cdot \mathbf{h}_\alpha = \frac{\delta p_{\alpha\parallel}}{\delta t}}$$

$$\boxed{\frac{\partial p_{\alpha\perp}}{\partial t} + (\mathbf{u}_\alpha \cdot \nabla) p_{\alpha\perp} + 2 p_{\alpha\perp} (\nabla \cdot \mathbf{u}_\alpha) - p_{\alpha\perp} \mathbf{b} \cdot \nabla_\parallel \mathbf{u}_\alpha - \tfrac{2}{5} \mathbf{b} \cdot \nabla_\parallel \mathbf{h}_\alpha + \tfrac{4}{5} \nabla \cdot \mathbf{h}_\alpha = \frac{\delta p_{\alpha\perp}}{\delta t}}$$

$$\mathbf{w}_\alpha = \mathbf{u}_\alpha - \mathbf{u}_+; \quad \mathbf{u}_+ = \sum_{\alpha = ions} \frac{Z_\alpha n_\alpha}{n_e} \mathbf{u}_\alpha$$

Gray-Diffusion Radiation Model

- Gray assumption by integrating over the entire spectrum
- Zeroth moment (in direction) of radiation intensity relates radiation energy to radiation flux
- First moment (in direction) of radiation intensity relates radiation flux to radiation pressure
- Close system by assuming directional isotropy: $p_{rad}=E_{rad}/3$
- More assumptions:
  - Diffusion limit: large optical depth, i.e. small photon mean free path (photons diffuse through random walk)
  - Fluid velocity is small compared to speed of light.
- Non-equilibrium solutions are allowed

Gray-Diffusion Radiation Model with HD/MHD

- The equations of gray-diffusion radiation in SWMF: (conservation of mass, momentum, energy, radiation energy)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot [\rho \mathbf{u}\mathbf{u} + pI] + \nabla p_{rad} = 0$$

$$\frac{\partial E}{\partial t} + \nabla \cdot [(E+p)\mathbf{u}] + \mathbf{u} \cdot \nabla p_{rad} = \kappa_{\mathrm{P}} c (E_{rad} - a T_{\mathrm{e}}^4),$$

$$\frac{\partial E_{rad}}{\partial t} + \nabla \cdot [E_{rad}\mathbf{u}] + p_{rad} \nabla \cdot \mathbf{u} = -\kappa_{\mathrm{P}} c (E_{rad} - a T_{\mathrm{e}}^4) + \nabla \cdot [\frac{c}{3\kappa_{\mathrm{R}}} \nabla E_{rad}]$$

- Planck mean opacity: $_P = _P(, T_e)$
- Rosseland mean opacity: $_R = _R(, T_e)$

Models

- A conceptual model consists of the mathematical (partial differential) equations that describe the physical system. It also includes initial and boundary conditions.
- The computational model is the computer program or code that implements the conceptual model. This may be finite-difference, finite-volume, finite-element, or other type of discretization. It includes the algorithms and iterative strategies. Parameters for the computational model include the number of grid points, algorithm inputs, and similar parameters.

Validation and Verification

- Verification: Are the equations being solved correctly?
  - Basic symmetries are preserved
  - Comparison with exact solutions to PDEs
    - Smooth
    - Discontinuous
  - Comparison with highly resolved problems for which exact solutions are not known (grid convergence)
    - “classic” test cases
    - controlled physically relevant problems
- Validation: Do the equations represent an adequate description of physics?
  - Statistical (can the code capture empirically seen trends?)
  - Dynamic validation (event studies)
- Uncertainty: A potential deficiency in any phase or activity of the modeling process that is due to the lack of knowledge.

Uncertainty Quantification

- Next step beyond traditional verification and validation
- Formal quantification of errors and uncertainties in the numerical simulations using statistical techniques
- There are many inputs to numerical simulations, each of which has an associated error or uncertainty
  - Initial conditions and boundary conditions
  - Physical parameters, such as equation of state and resistivity
  - Mesh parameters, such as grid resolution
  - Code tuning parameters, such as constants in a turbulence model, artificial viscosity constants, etc.
- Each of these uncertainties propagates through the simulation code to produce uncertainty in the output variables
- Must perform a large number of simulations varying all of the input parameters to see how the uncertainties propagate through the code

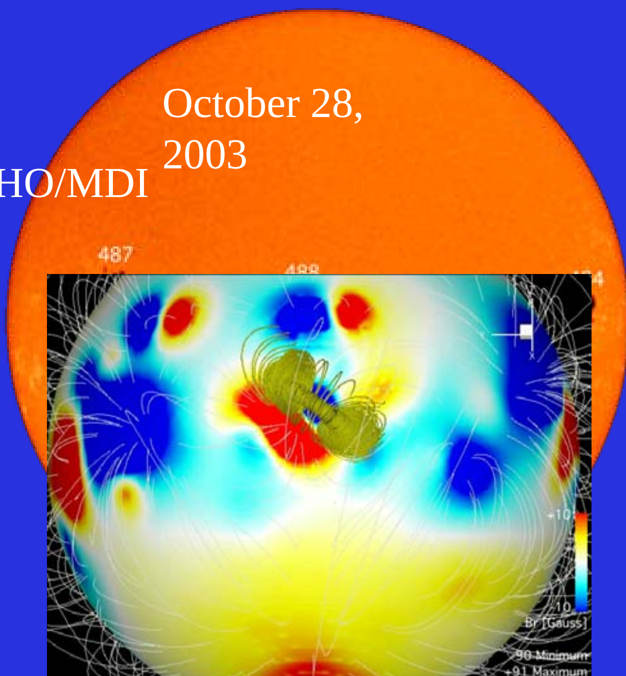
Goals of UQ

- To provide a formal framework for the quantification of errors and uncertainties in numerical simulations
  - Instead of a single output value, we obtain a probability distribution for each output quantity
- To perform a sensitivity analysis to determine which input uncertainties produce the largest output uncertainties
- To use observations to constrain the uncertainties of the input variables
- To predict the results of future observations with error bars
- To prioritize activities that best reduce uncertainty and increase confidence

Code Validation: Halloween Storms

SOHO/MDI

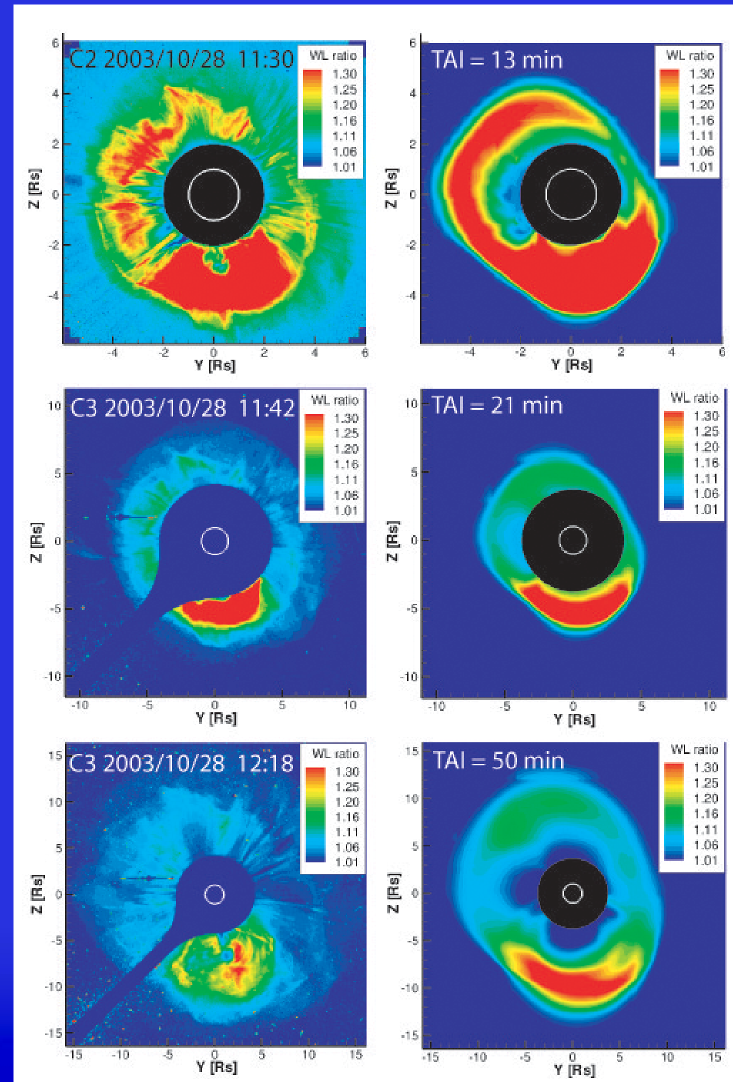
October 28, 2003

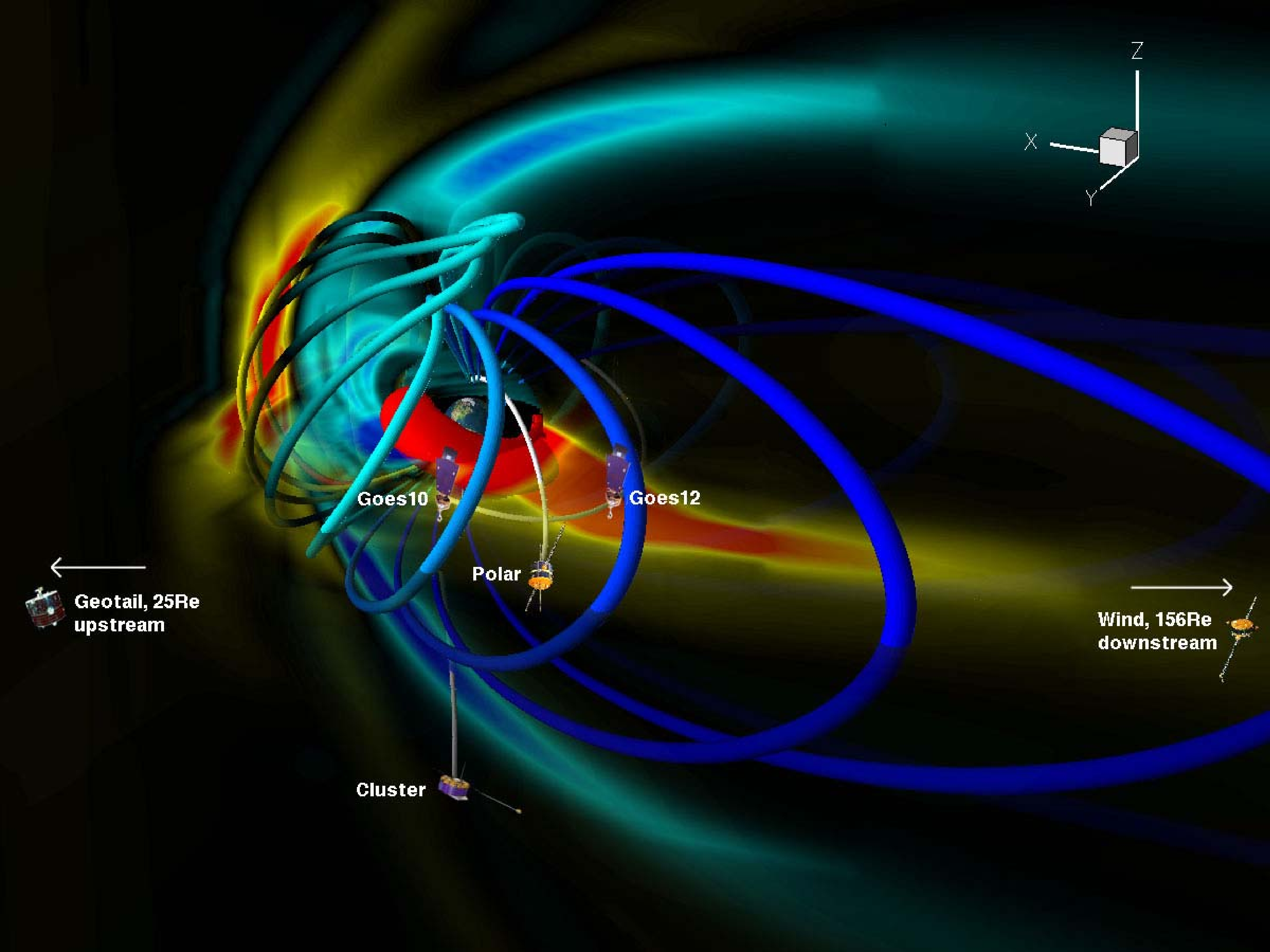


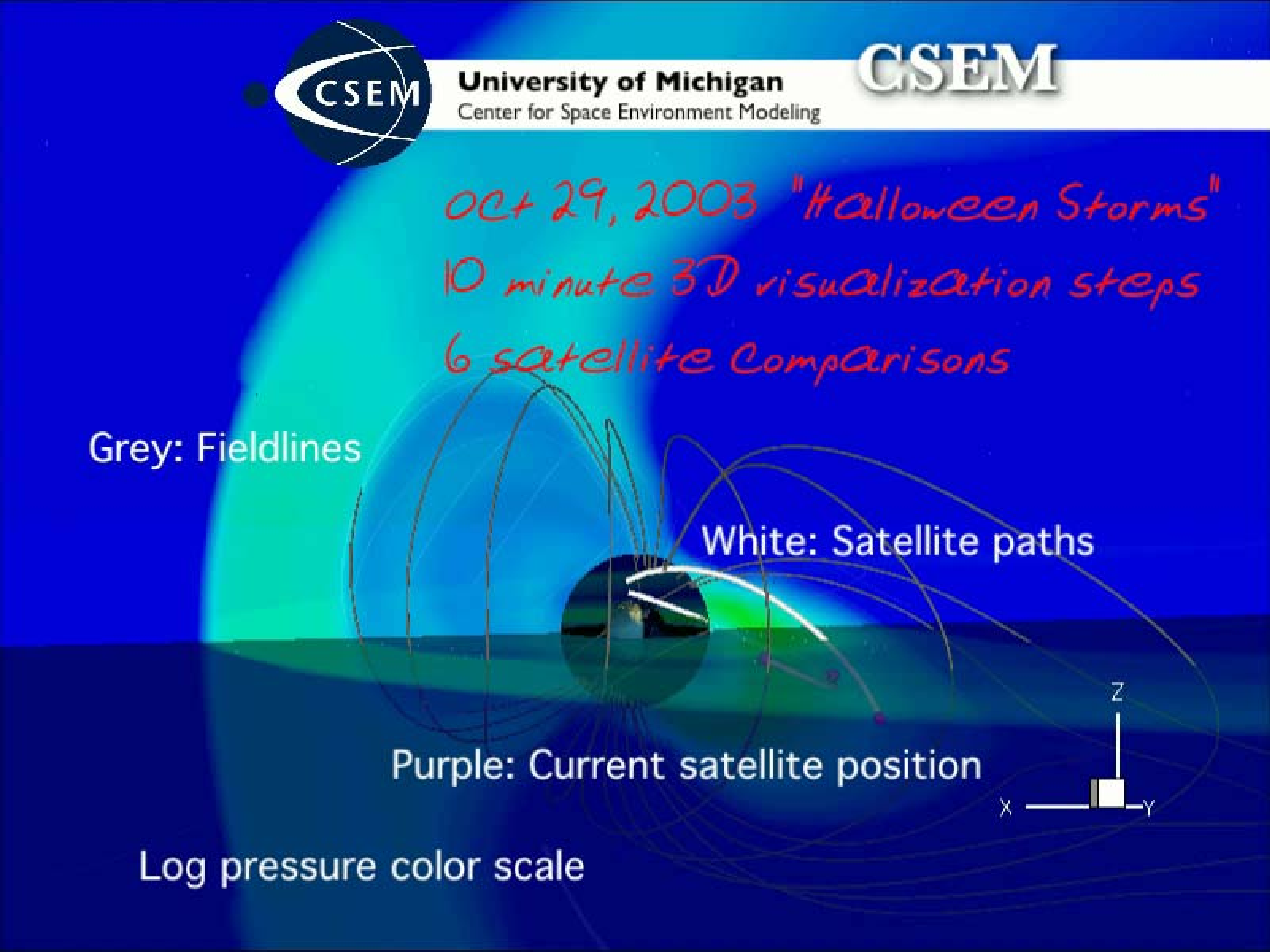
SWMF simulation

SOHO

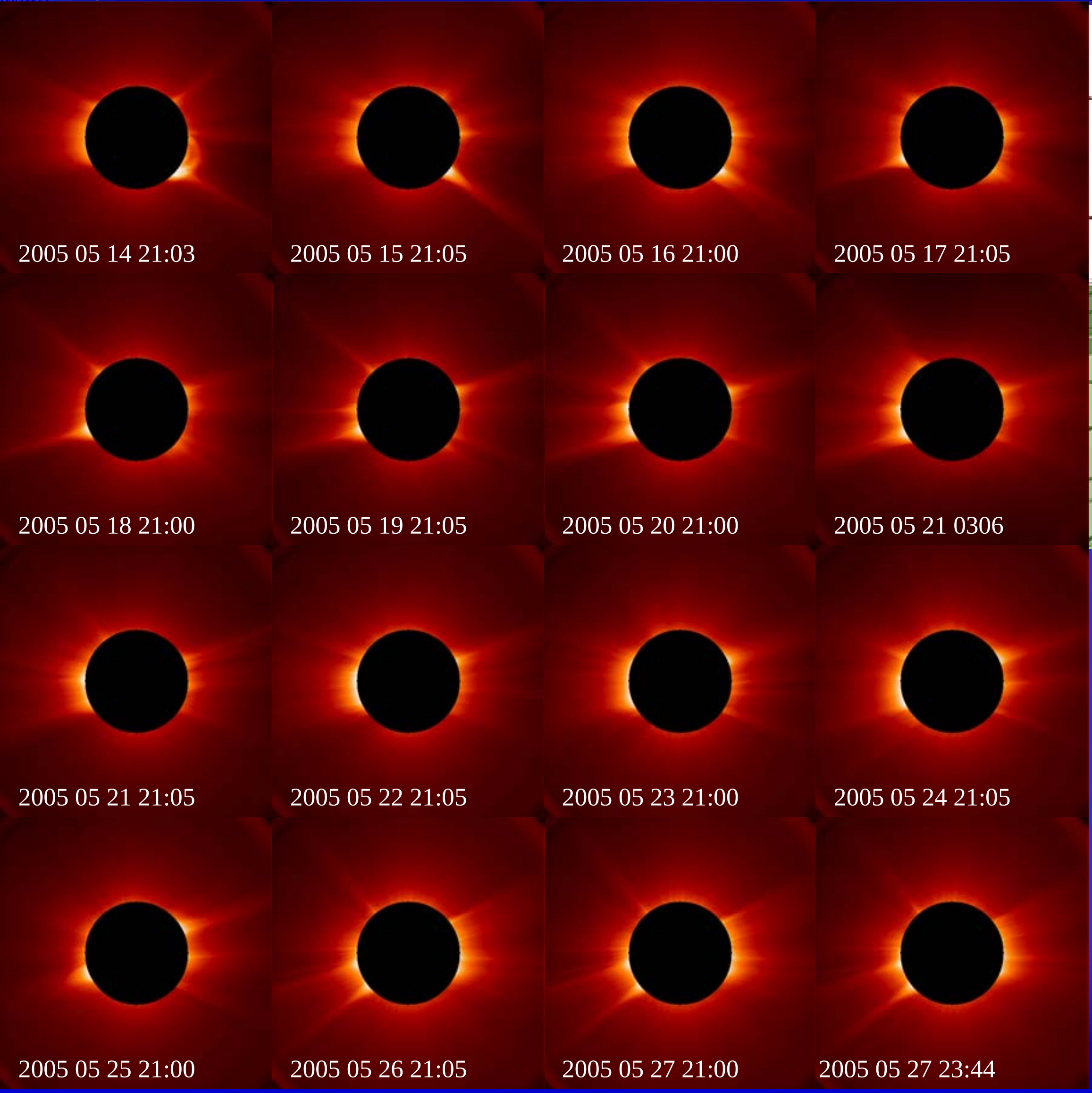
SWMF

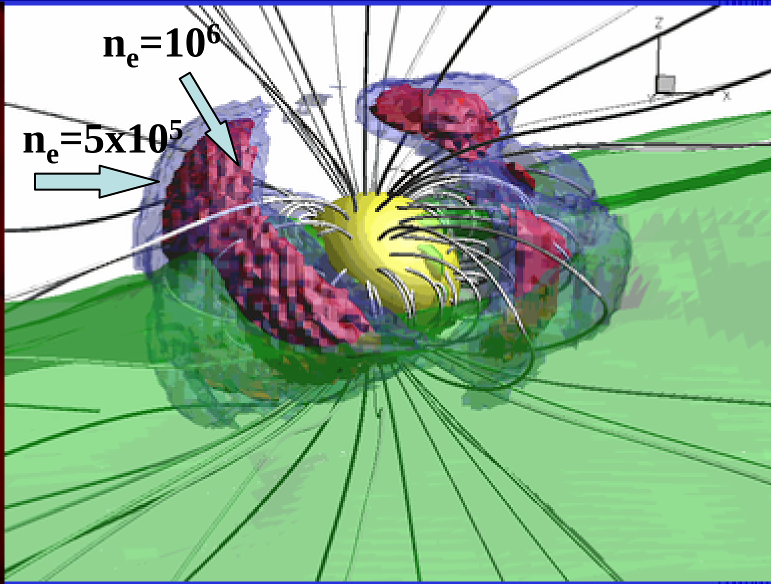



Z
X
Y
Goes10
Goes12
Polar
Geotail, 25Re
upstream
Wind, 156Re
downstream
Cluster


University of Michigan
Center for Space Environment Modeling
CSEM
Oct 29, 2003 "Halloween Storms"
10 minute 3D visualization steps
6 satellite comparisons
Grey: Fieldlines
White: Satellite paths
Purple: Current satellite position
Log pressure color scale
Z
X
Y

Tomographic Data Assimilation





Frazin et al., 2008

Summary

- Space weather forecast
  - Progress in basic understanding
  - First generation of end-to-end model chains
  - Physics-based nowcast is possible
  - Empirical models still outperform physics-based models
- Physics
  - Ohm's law
  - Multifluid
  - Moment equations
- Verification and validation
- Data assimilation is the next step
- UQ is on the horizon

Other Presentations from CSEM

- Gábor Tóth: Multi-ion Magnetohydrodynamics (Monday 10:00)
- Igor Sokolov: 4D model for MHD wave turbulence in the solar corona and solar wind (Tuesday, 14:25)
- Bart van der Holst: Breakout Coronal Mass Ejection or Streamer Blowout: the Bugle Eeffect (Tuesday 11:50)
- Darren De Zeeuw: The Virtual Model Repository (Friday, 9:25)