Modeling Ionospheric Outflows and Their Effect on the Magnetosphere

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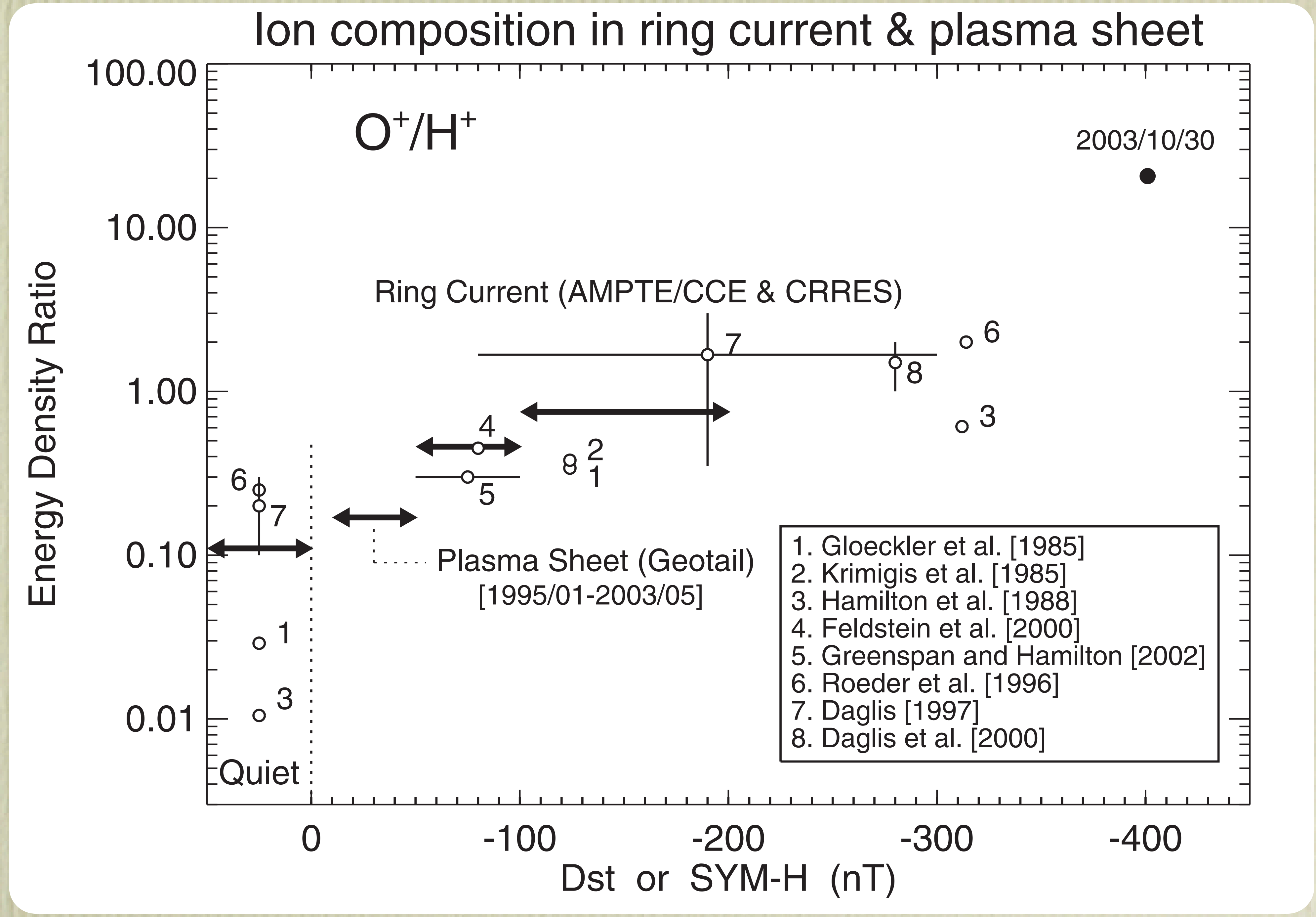
Outline

- Overview of observations of ionospheric plasma in the magnetosphere. O^+ is important!
- Describe observations of out-flowing plasma.
- Summary of efforts to model ionospheric outflow and to track its impact in the magnetosphere.
- Modeling ionospheric outflow and its effects in the Space Weather Modeling Framework (SWMF)
  - Modeling the outflow: Polar Wind Outflow Model (PWOM)
  - Tracking the outflow and impact: Multi-Species and Multi-Fluid BATS-R-US
  - Two Storm Cases: May 4, 1998 and March 31, 2001
- How magnetospheric composition can have a broader impact on the space environment system

Overview of Observations: Magnetosphere

- Early observations of O^+ in the inner magnetosphere were made by the polar-orbiting satellite 1971-089A during the December 16-18, 1971 geomagnetic storm (*Shelley et al.* [1972])
- ISEE 1 satellite composition data during 10 geomagnetic storms shows that O^+ can comprise 40-80% of total ion population within 15 Re (*Lennartsson et al.* [1981])
- GEOTAIL observations at 159 Re demonstrate that O^+ is present, albeit in small proportions, in the distant tail (*Seki et al.* [1996])
- *Kistler et al.* [2005] used Cluster data to show that the O^+:H^+ ratio can reach as high at 10:1 during a substorm
- Examining data from Dynamics Explorer and Polar satellites lead *Huddleston et al.* [2005] to conclude that the ionosphere is a sufficient source for magnetospheric plasma.



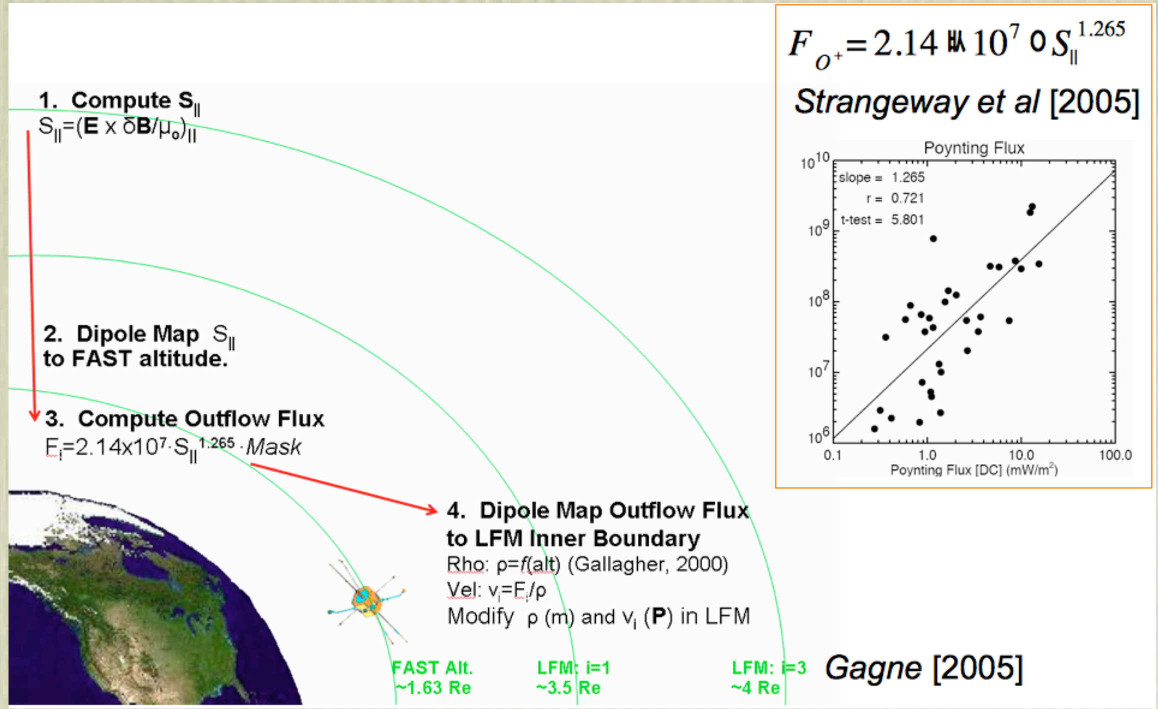
- *Nose et al.*, [2005]: O+:H+ Energy density ratio as a function of Dst or SymH.

Overview of Observations: Outflow

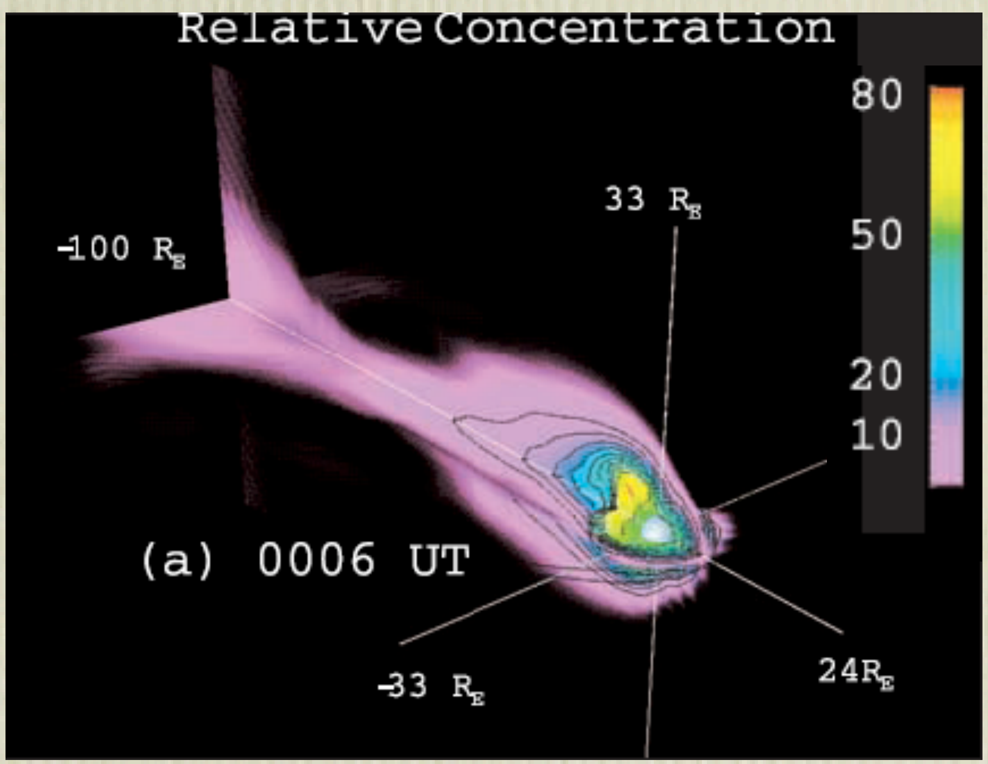
- Ionospheric H^+ Flux:
  - $2\text{-}20\times10^7$ $cm^{-2}s^{-1}$ at 1,400 km altitude as observed by ISIS-2 satellite (*Hoffman and Dodson*, [1980])
  - 20×10^7 $cm^{-2}s^{-1}$ at 2,000 km altitude as observed by DE-1 (*Nagai et al.*, [1984])
- Ionospheric O^+ Flux:
  - *Abe et al.*, [1996] use Akebono data and find that the O^+ flux is 1.5-2.0 times smaller than H^+ flux for $kp<5$.
  - They also find that for $kp\geq5$ the O^+ flux can exceed H^+ flux, and the flux in the noon sector is largest.
  - Centrifugal acceleration may contribute to O^+ acceleration (*Horwitz et al.*, [1994])
- *Strangeway et al.*,[2001] examined FAST data and found a connection between ion outflow and Poynting Flux
- The electron temperature has a significant impact on H^+ velocity (*Abe et al.*, [1993])

Inclusion of Outflow in Global Models of the Space Environment

- LFM
  - *Gagne* [2005] have used the calculated Poynting flux to set the inner boundary of the LFM model (see schematic to right)
  - Multi-Fluid efforts (Lyon, Wiltberger, and others) have also attempted to look at the impact of outflow.



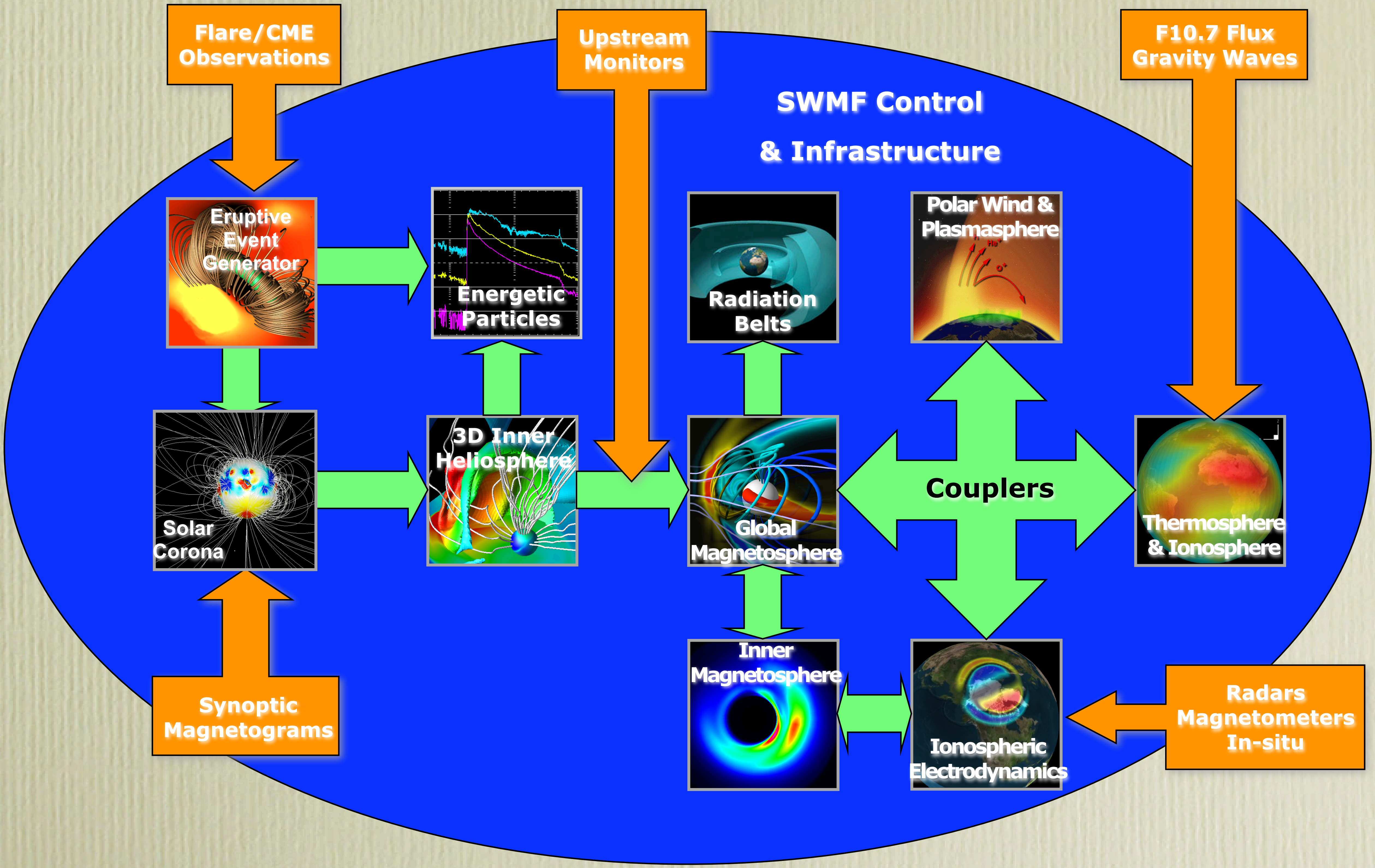
- Winglee
  - *Winglee* [2002] used a multi-fluid mhd model, and used centrifugal terms to fling plasma into the magnetosphere.
  - He found that the inclusion of O+ can actually reduce the cross polar cap potential.



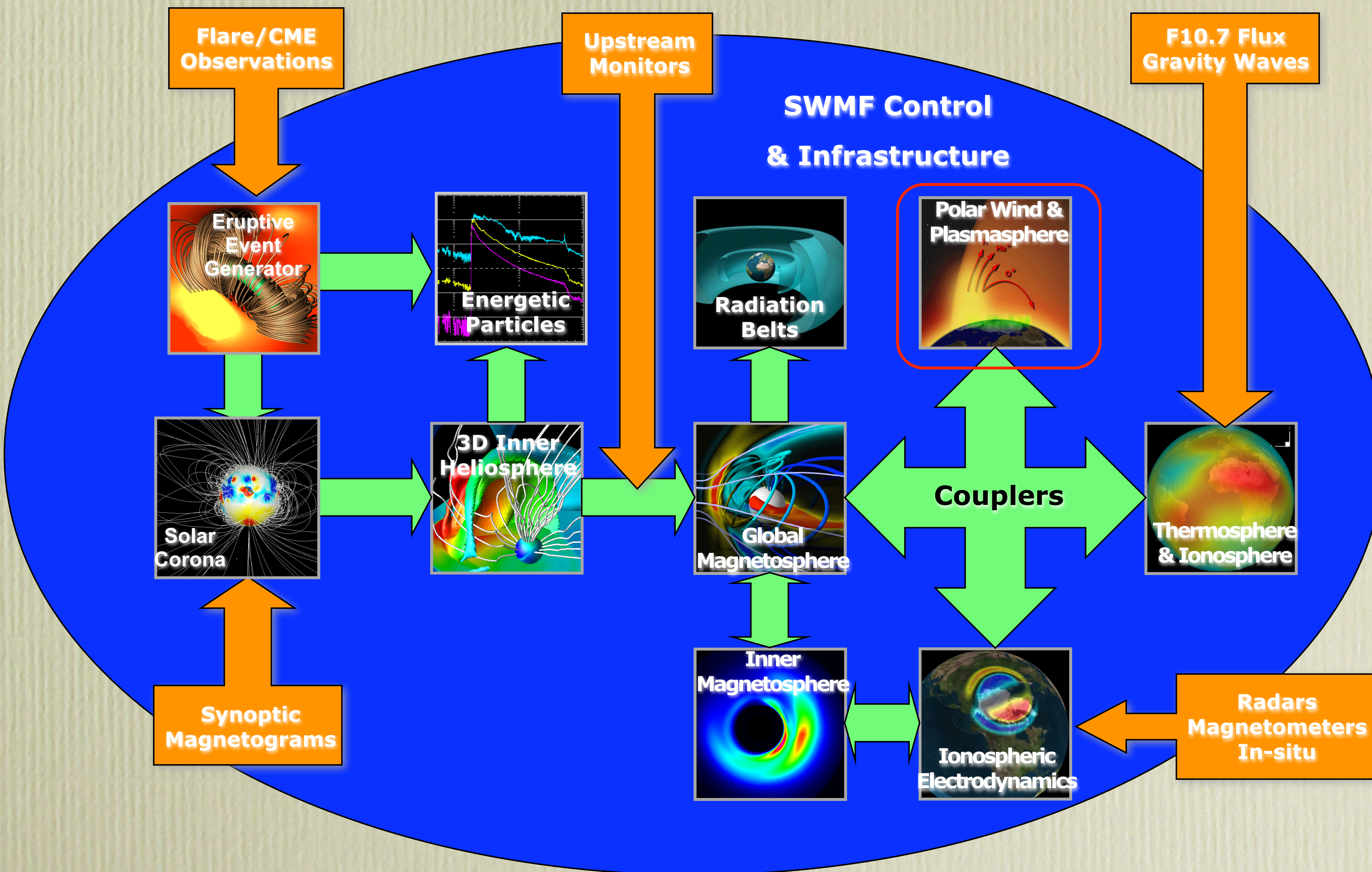
Ionospheric Outflow in SWMF

- Goals
  - To understand the global impacts on ionospheric outflow
  - Study how plasma is accelerated through the “gap” region between the ionosphere and magnetosphere
  - Examine the importance of ionospheric outflow on the magnetosphere during geomagnetic storms
- Outline
  - Provide a description my polar wind outflow model
  - Describe the relevant coupling mechanisms in the SWMF that connect the outflow model with the magnetosphere, ionosphere, and neutral atmosphere
  - Use the PWOM together with multi-fluid and multi-species MHD version of BATS-R-US model to study the fate and impact of ionospheric outflow during geomagnetic storms.

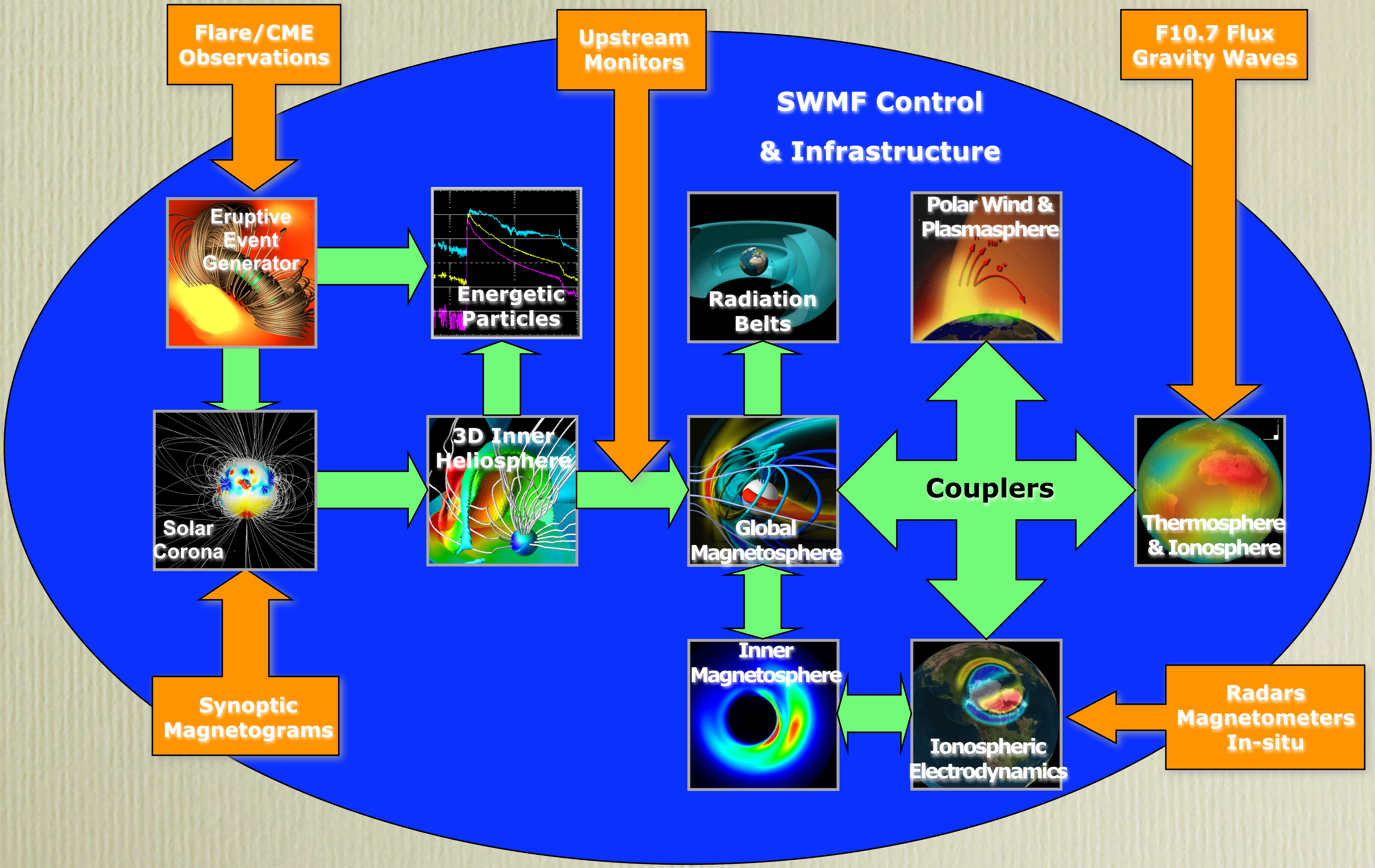
Space Weather Modeling Framework



Space Weather Modeling Framework

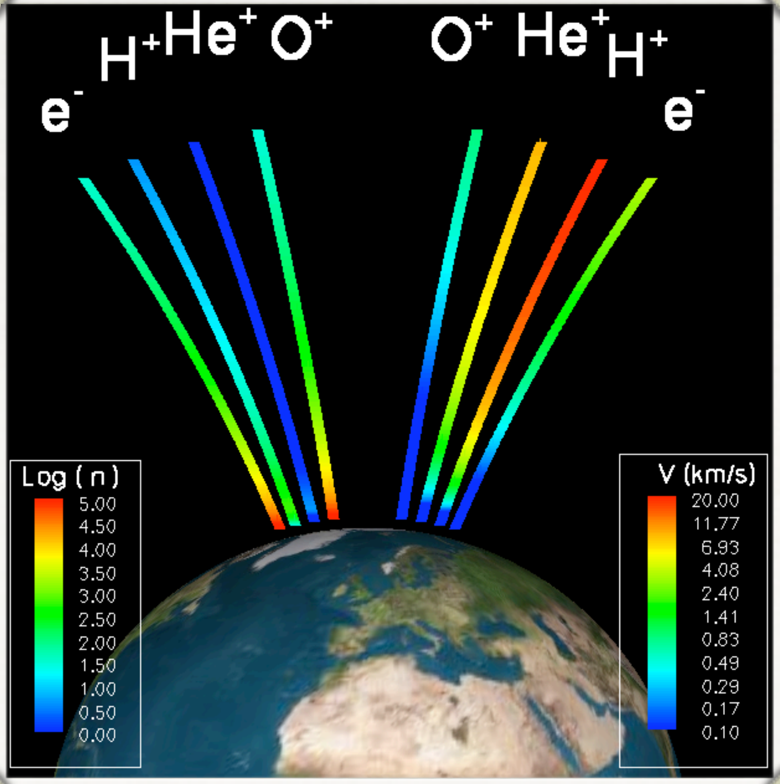


Space Weather Modeling Framework



Polar Wind Outflow Model (PWOM)

- PWOM solves the time-dependent gyrotropic field aligned transport equations for H+, O+, He+ and electrons
  - The lower boundary is at 200km, and the upperboundary is at a few Earth Radii
  - Multiple convecting field-lines solutions are obtained
- The neutral thermosphere model is externally specified (F10.7 and solar cycle effects can be included)
- Ion-neutral friction, FAC, centrifugal, charge exchange drag, topside heating, solar zenith angle effects, chemical sources and losses are included



Where we started

- Original model of Gombosi et al. [1985]:
  - Single stationary field-line with limited physics
  - Explicit first-order solver
  - No coupling with other physical regimes

What's New?

- New model: PWOM
- Multiple field-lines are considered
- Field-lines are able to convect throughout the polar cap
- Coupling with other models (numerical and empirical)
- Computing:
  - Field-lines are solved in parallel using the Message Passing Interface (MPI) on large cluster computers
  - Nightly test make sure that the code works on a variety of platforms
- New numerical schemes:
  - 2nd order Rusanov scheme with flux limiting
  - Explict, fully implicit, or point implicit options are available
- Saturn and Earth versions of PWOM are available.

Field-Aligned Transport Equations

Continuity

$$\frac{\partial}{\partial t}(A\rho_i) + \frac{\partial}{\partial r}(A\rho_i u_i) = AS_i$$

Momentum

$$\frac{\partial}{\partial t}(A\rho_i u_i) + \frac{\partial}{\partial r}\left(A\rho_i u_i^2\right) + A\frac{\partial p_i}{\partial r} = A\rho_i\left(\frac{e}{m_i}E_\| - g\right) + A\frac{\delta M_i}{\delta t} + Au_iS_i$$

Energy

$$\frac{\partial}{\partial t}\left(\frac{1}{2}A\rho_i u_i^2 + \frac{1}{\gamma_i - 1}Ap_i\right) + \frac{\partial}{\partial r}\left(\frac{1}{2}A\rho_i u_i^3 + \frac{\gamma_i}{\gamma_i - 1}Au_ip_i\right) = A\rho_i u_i\left(\frac{e}{m_i}E_\| - g\right) + \frac{\partial}{\partial r}\left(A\kappa_i\frac{\partial T_i}{\partial r}\right) + A\frac{\delta E_i}{\delta t} + Au_i\frac{\delta M_i}{\delta t} + \frac{1}{2}Au_i^2S_i$$

Ambipolar E-Field

$$E_\| = -\frac{1}{en_e}\left[\frac{\partial}{\partial r}\left(p_e + \rho_e u_e^2\right) + \frac{A'}{A}\rho_e u_e^2\right] + \frac{1}{en_e}\frac{\partial}{\partial r}\left(\sum_i \frac{m_e}{m_i}\left[\left(u_e - u_i\right)S_i - \frac{\delta M_i}{\delta t}\right] + \frac{\delta M_e}{\partial t}\right)$$

Equations: Electrons

Continuity

$$n_e = \sum_i n_i$$

Momentum

$$u_e = \frac{1}{n_e}\left(\sum_i n_i u_i - \frac{j}{e}\right)$$

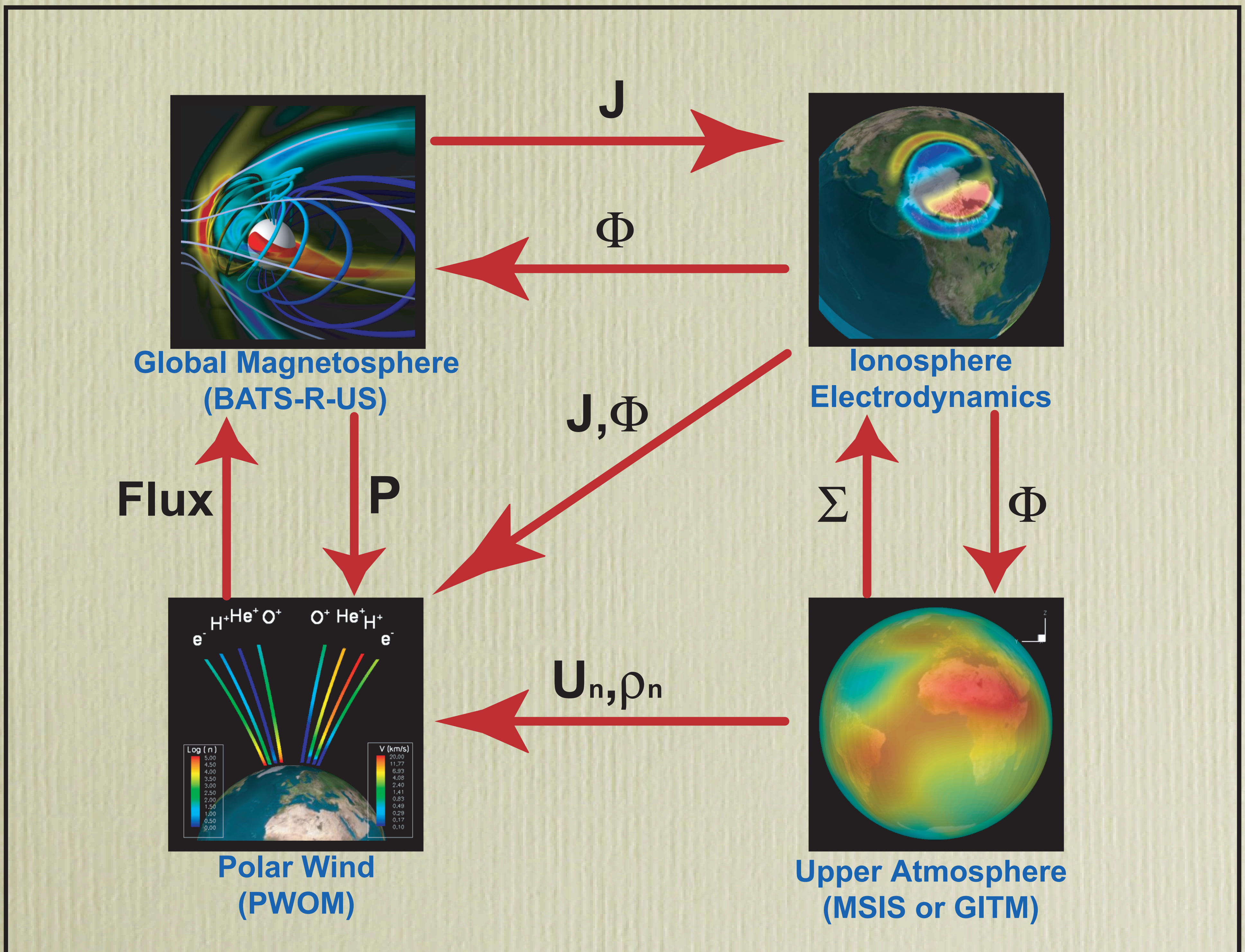
$$j = j_0 \frac{A_0}{A}$$

Temperature

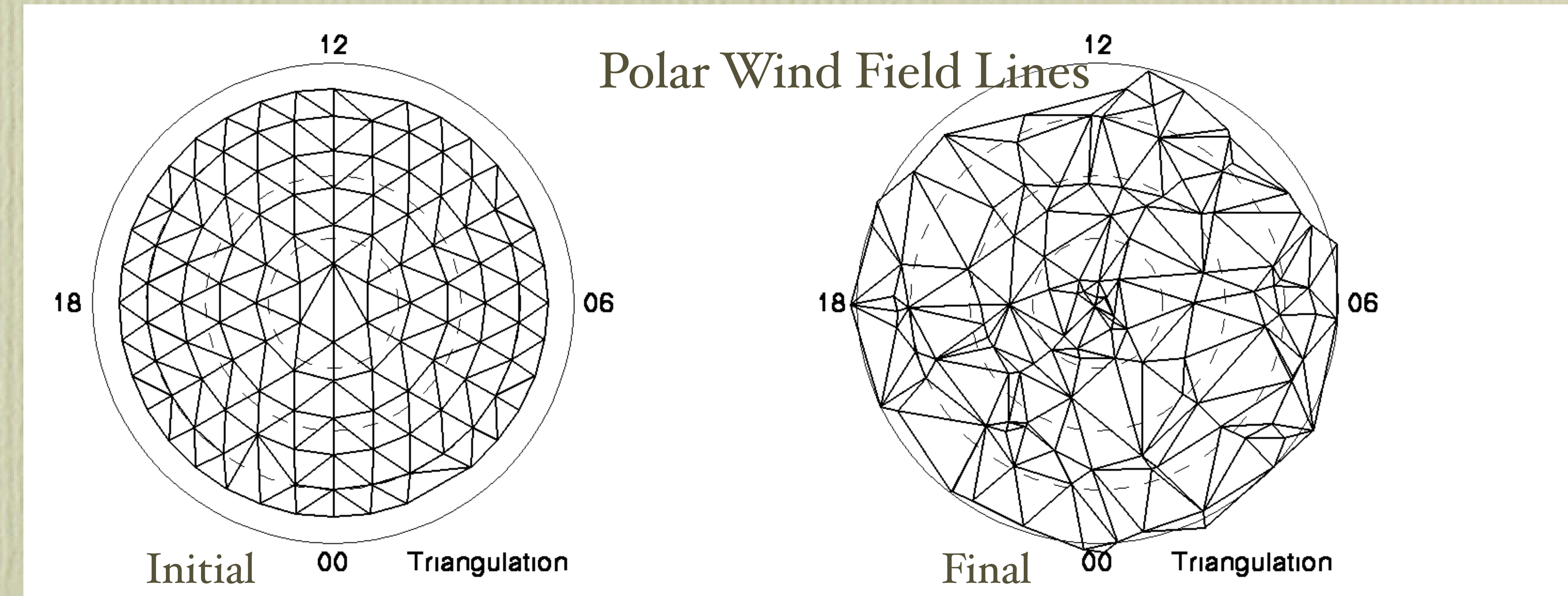
$$\rho_e \frac{\partial T_e}{\partial t} = (\gamma_e - 1)\,\frac{m_e}{kA}\frac{\partial}{\partial r}\left(A\kappa_e \frac{\partial T_e}{\partial r}\right) - \rho_e u_e \frac{\partial T_e}{\partial r} -$$

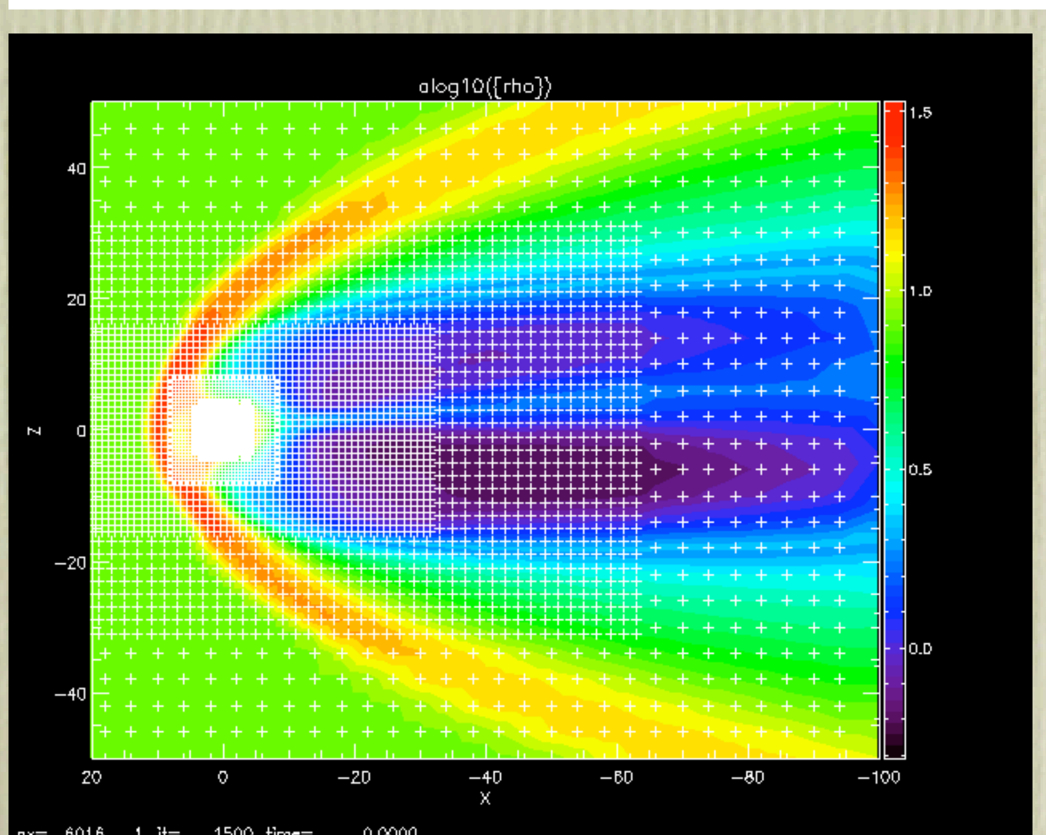
$$T_e\left[S_e + \frac{\gamma_e - 1}{A}\rho_e \frac{\partial}{\partial r}(A u_e)\right] + (\gamma_e - 1)\,\frac{m_e}{k}\frac{\delta E}{\delta t}$$

PWOM – SWMF Coupling



Simulation Grids





Multi-Fluid BATS-R-US Equations

$$\frac{\partial \rho_s}{\partial t} + \nabla \cdot (\rho_s \mathbf{u}_s) = S_{\rho_s}$$

$$\frac{\partial \rho_s \mathbf{u}_s}{\partial t} + \nabla \cdot (\rho_s \mathbf{u}_s \mathbf{u}_s + I p_s) = n_s q_s (\mathbf{u}_s - \mathbf{u}_+) \times \mathbf{B} + \frac{n_s q_s}{n_e e} (\mathbf{J} \times \mathbf{B} - \nabla p_e) + S_{\rho_s \mathbf{u}_s}$$

$$\frac{\partial p_s}{\partial t} + \nabla \cdot (p_s \mathbf{u}_s) = -(\gamma - 1) p_s \nabla \cdot \mathbf{u}_s + S_{p_s}$$

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{u}_+ \times \mathbf{B}) = 0$$

$$\mathbf{u}_e = -\frac{\mathbf{J}}{e n_e} + \mathbf{u}_+ \qquad \mathbf{u}_+ = \frac{\sum_s n_s q_s \mathbf{u}_s}{e n_e}$$

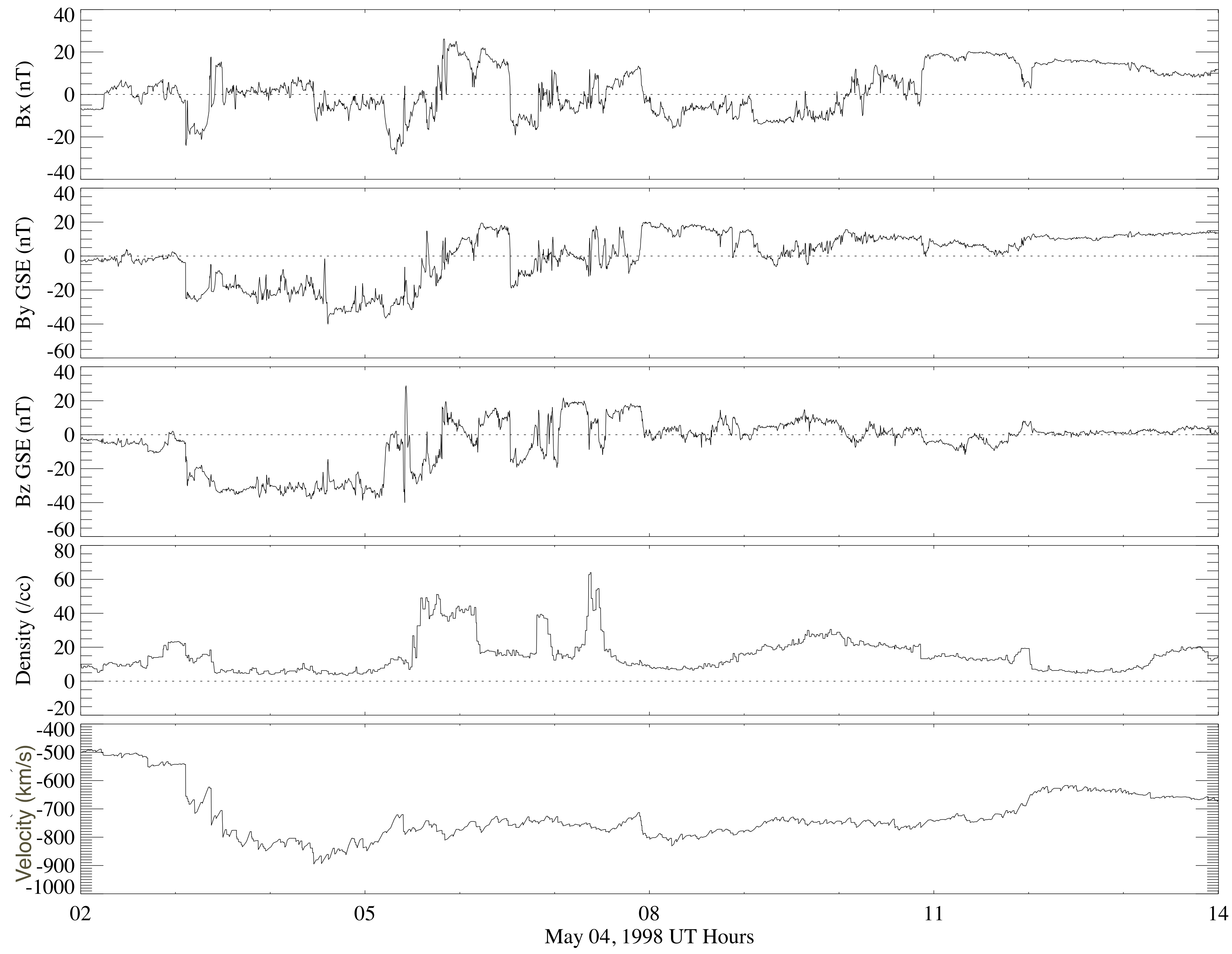
Glocer et al.,[2009] submitted to JGR

- Notes on Multi-Fluid Equations:
  - They cannot be written in conservative form.
  - Resistivity is neglected.
  - The Hall term and the gradient of the electron pressure are neglected in the induction equation.

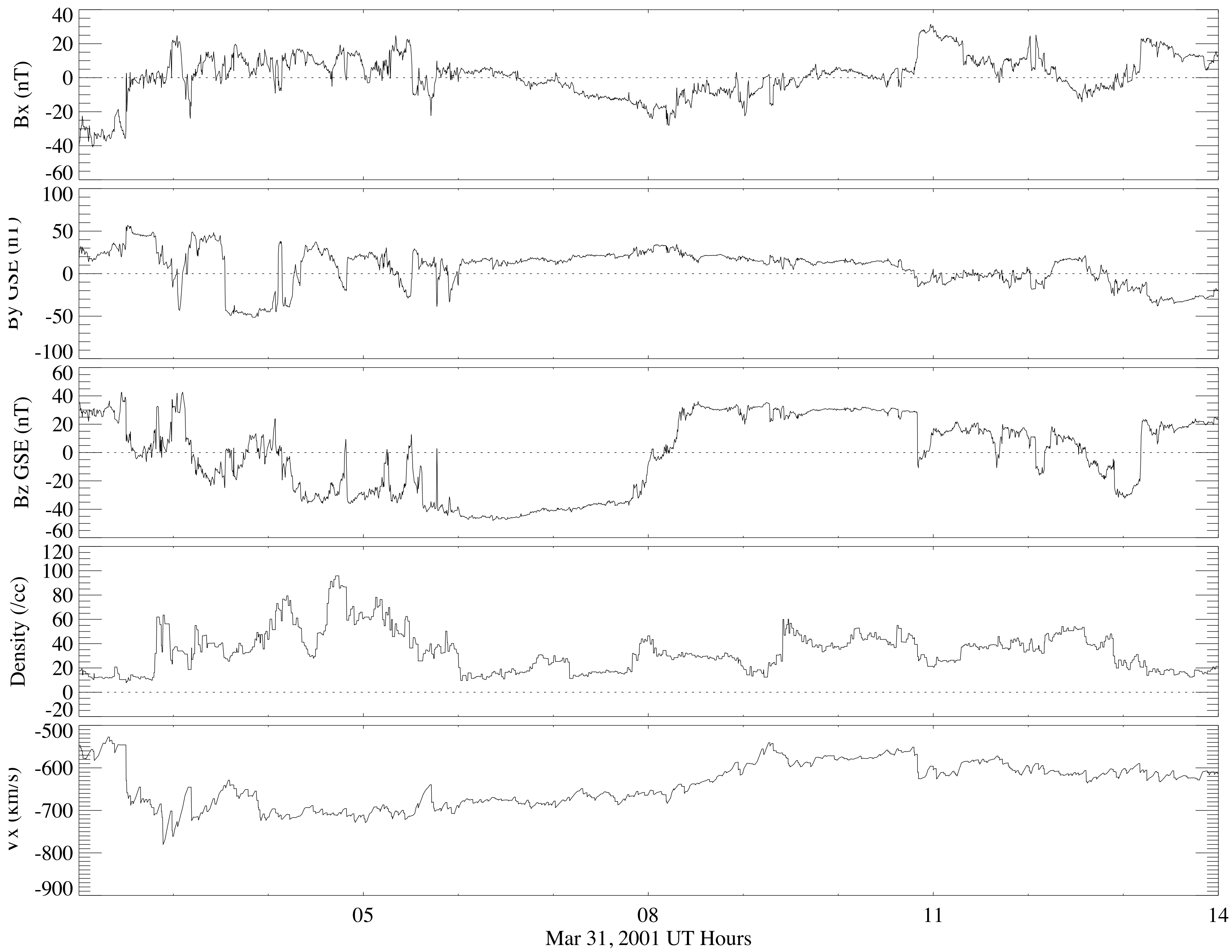
Modeling Geomagnetic Storms

- We apply our newly coupled model to two geomagnetic storms: the May 4, 1998 and March 31 2001 events.
- Three cases are considered for each event:
  1. Multi-Fluid MHD (with outflow), where each ion fluid moves under its own continuity, momentum, and energy equation
  2. Multi-Species MHD (with outflow), where each ion species has its own continuity equation, but uses a common momentum and energy equation.
  3. Single-fluid MHD (without outflow) as a reference solution.
- The impact of ionospheric outflow on the magnetosphere is explored by looking at:
  - Indicies: Dst and CPCP
  - Magnetospheric composition
  - Specific satellite data (GOES and CLUSTER)

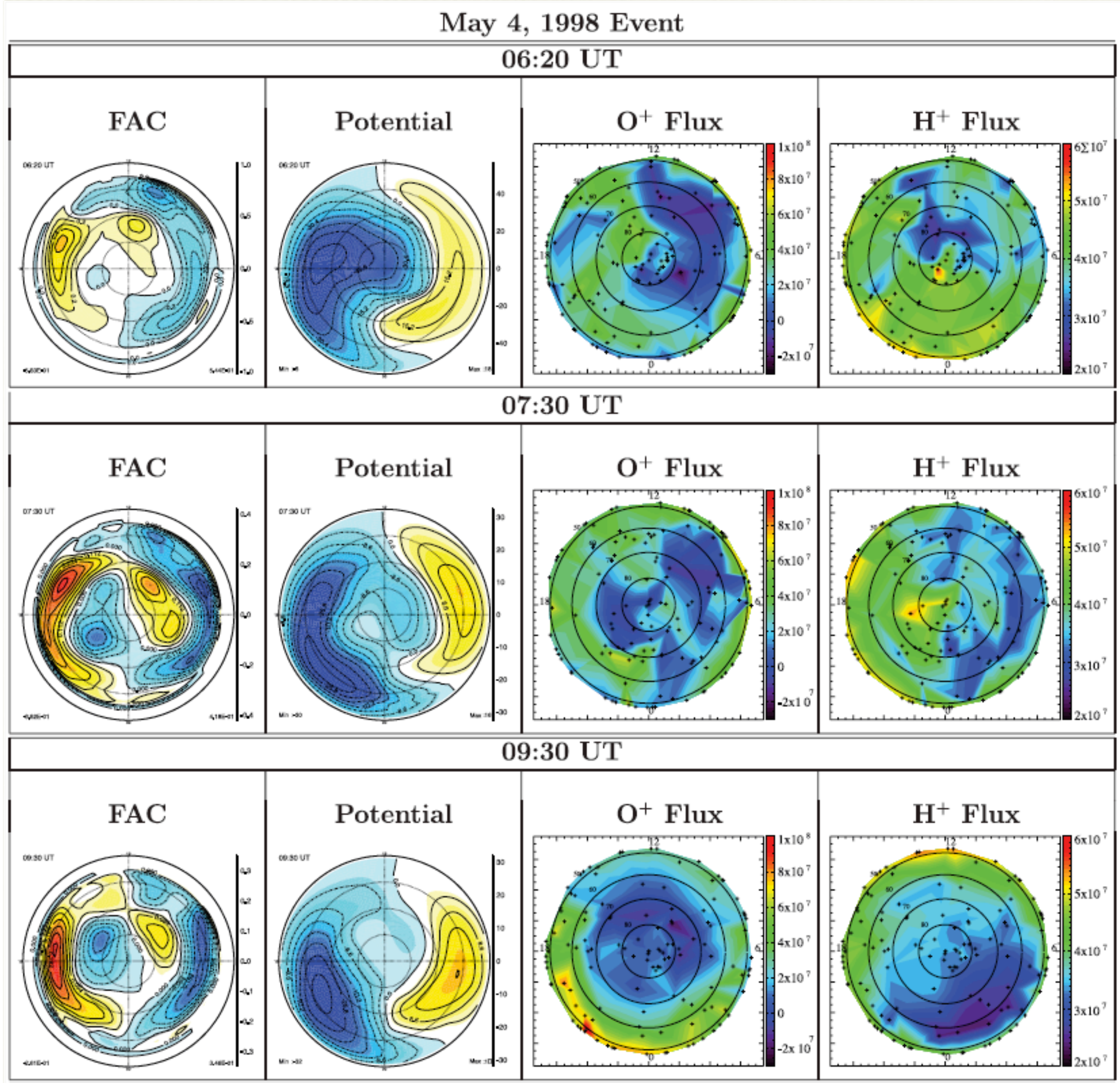
May 4, 1998: Solar Wind



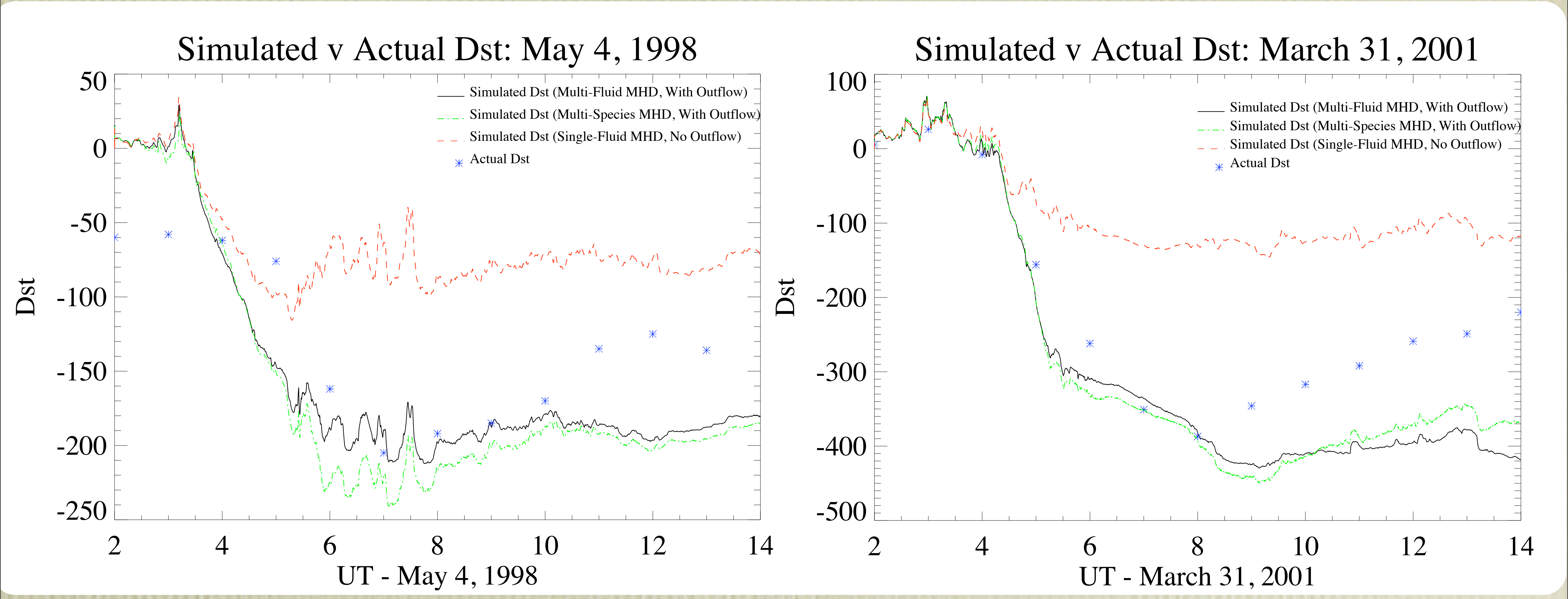
March 31, 2001: Solar Wind



Outflow During May 4, 1998 Event

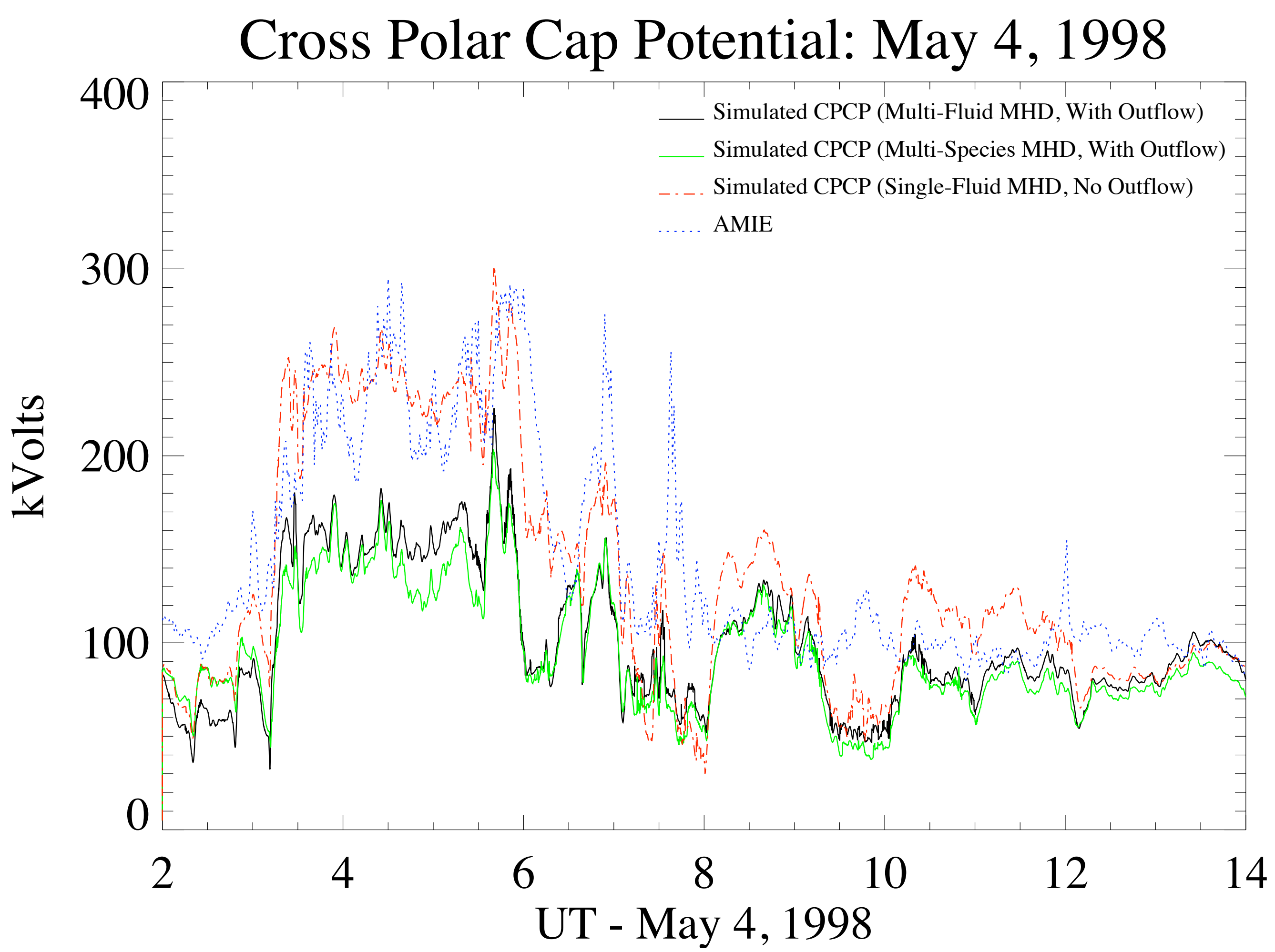


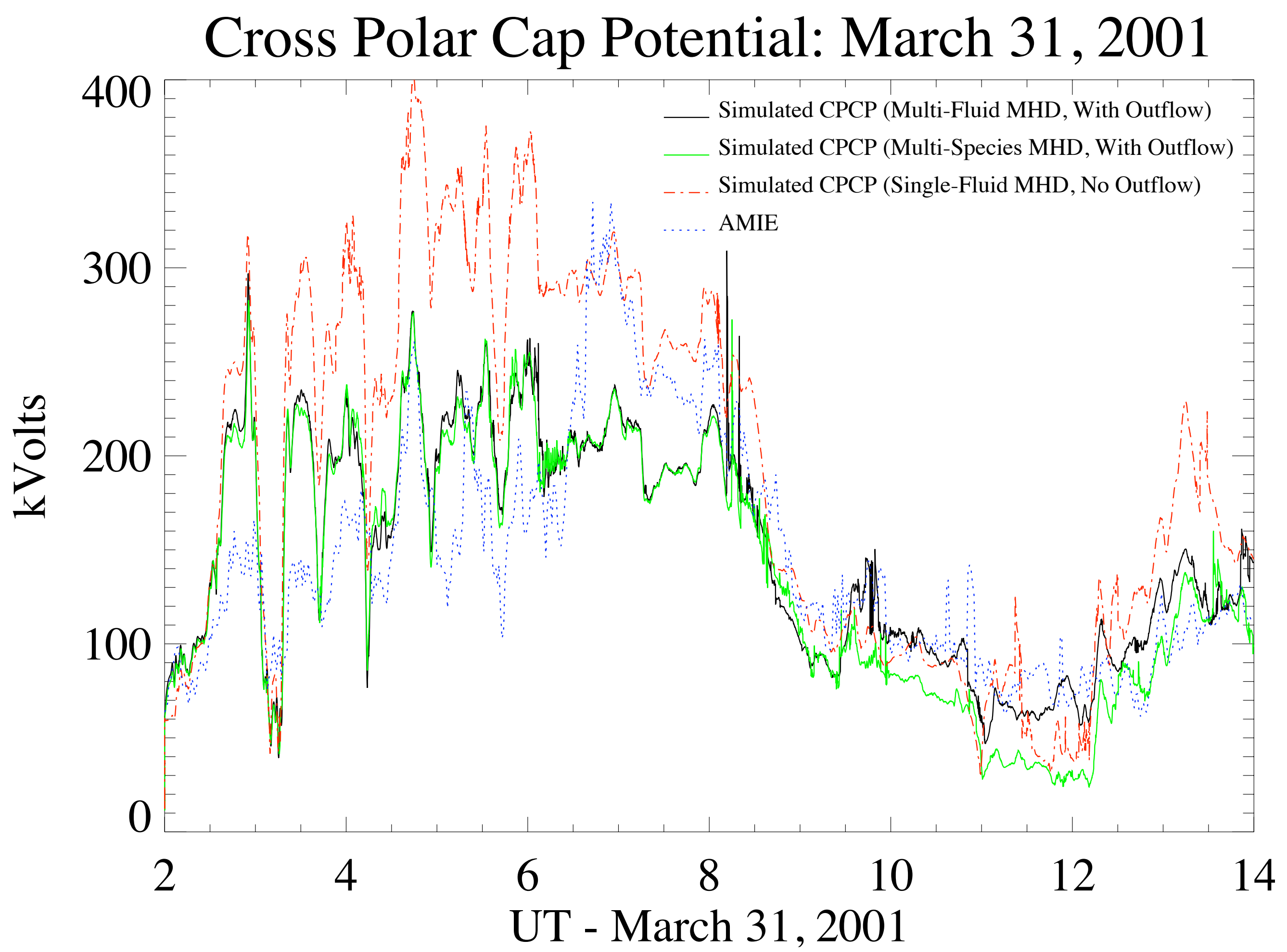
Dst Index for Events



- The multi-fluid and multi-species simulations (with outflow) yield a much more negative Dst than the single-fluid simulation (without outflow).
- Multi-fluid and multi-species give very similar, but not identical, Dst calculations.

CPCP Index for Events

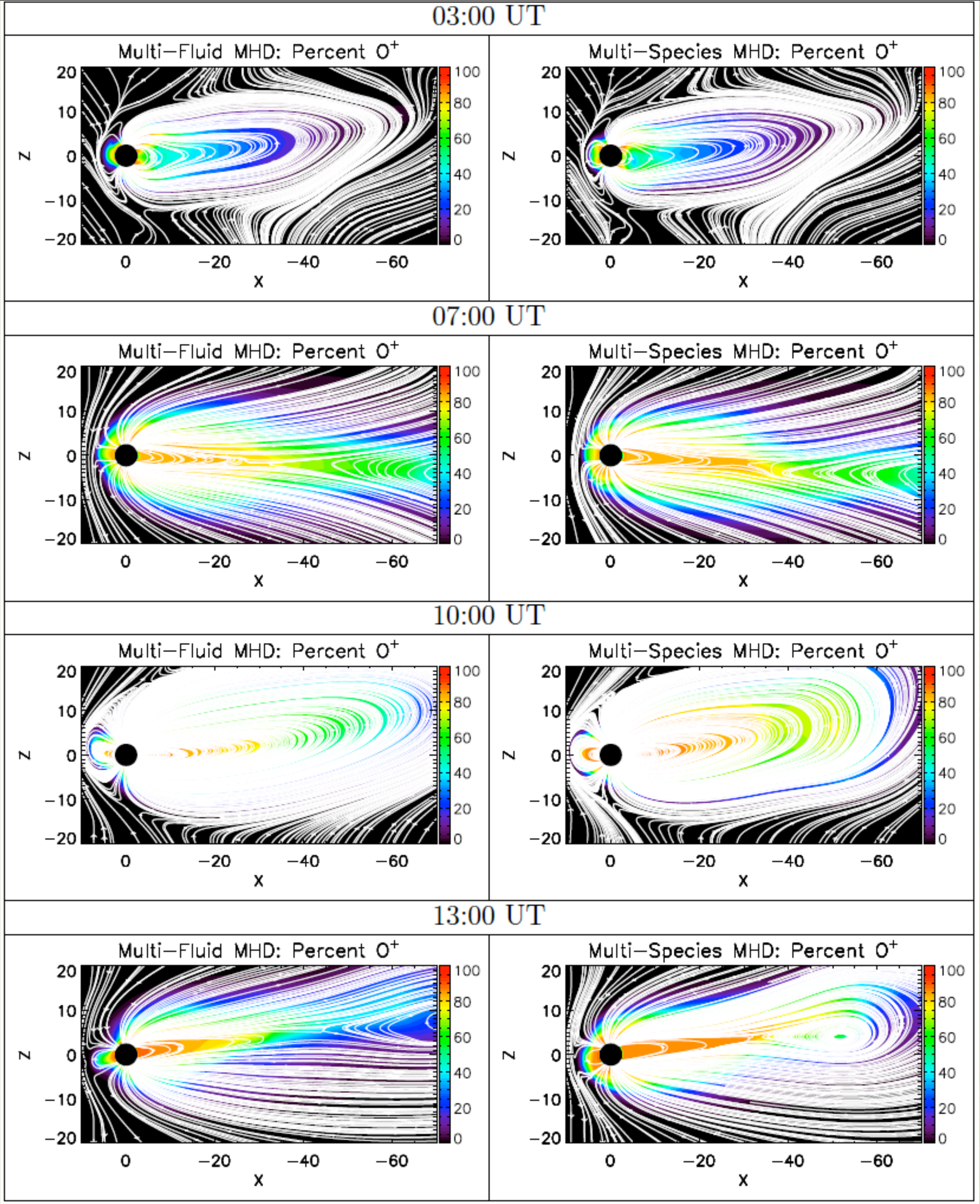




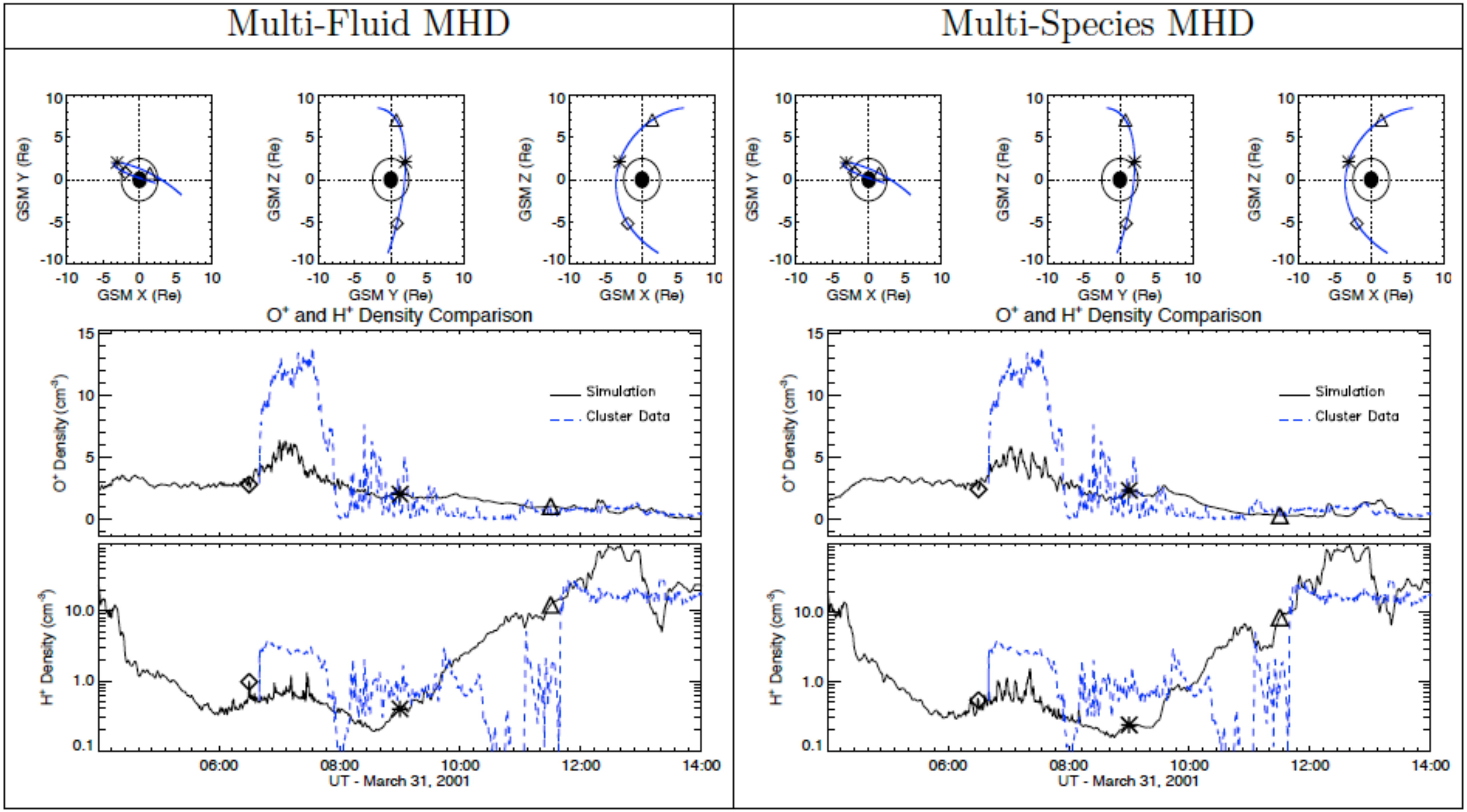
- The multi-fluid and multi-species simulations (with outflow) yield a significantly reduced CPCP compared to the single-fluid simulation (without outflow).
- Multi-fluid and multi-species give very similar, but not identical, CPCP calculations.

March 31, 2001 Event

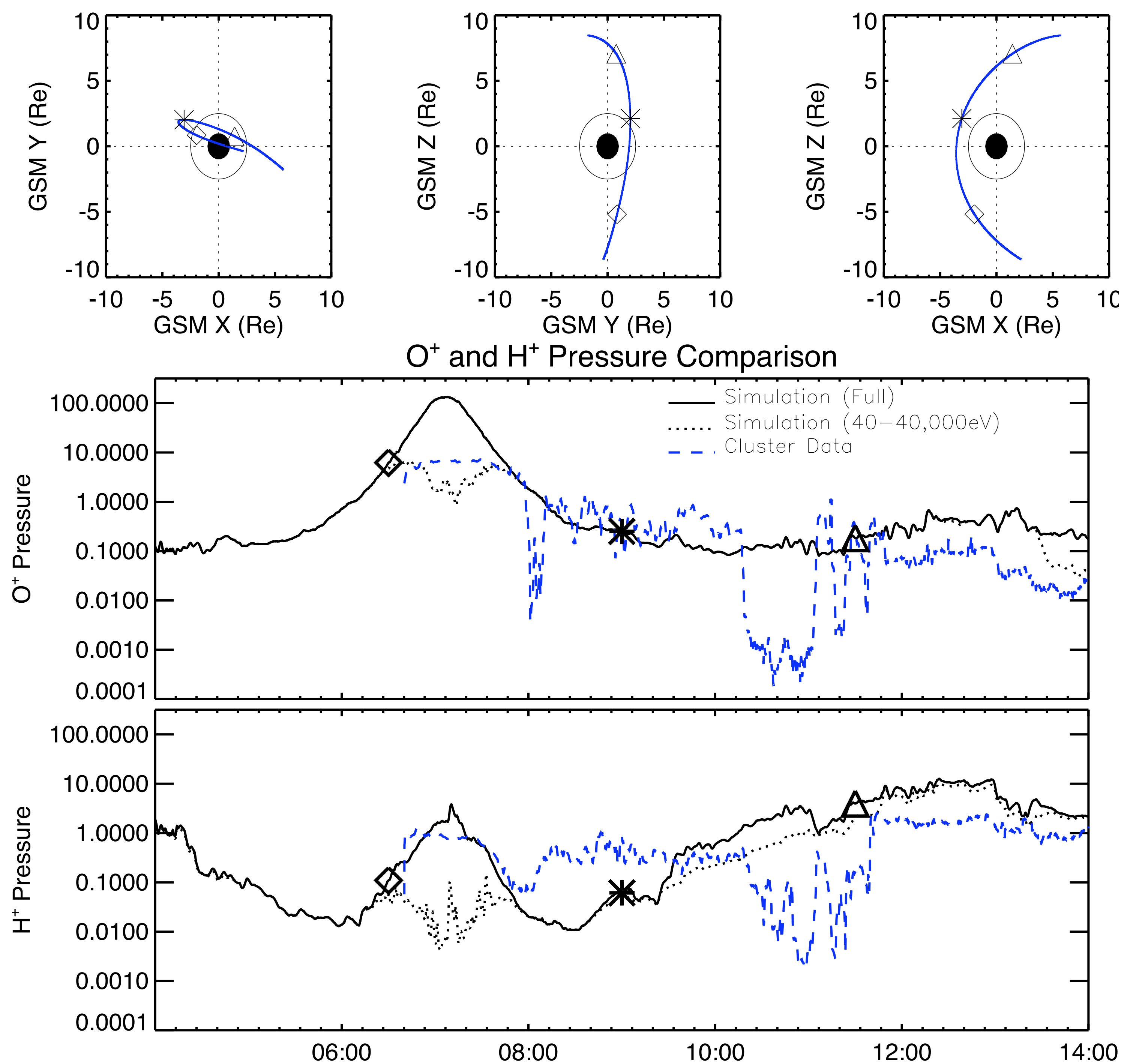
- We compare multi-fluid (left) and multi-species (right) results.
- Similar results are found in the inner magnetosphere, but differences begin to arise in the tail.



March 31,2001 Composition Comparison: CLUSTER

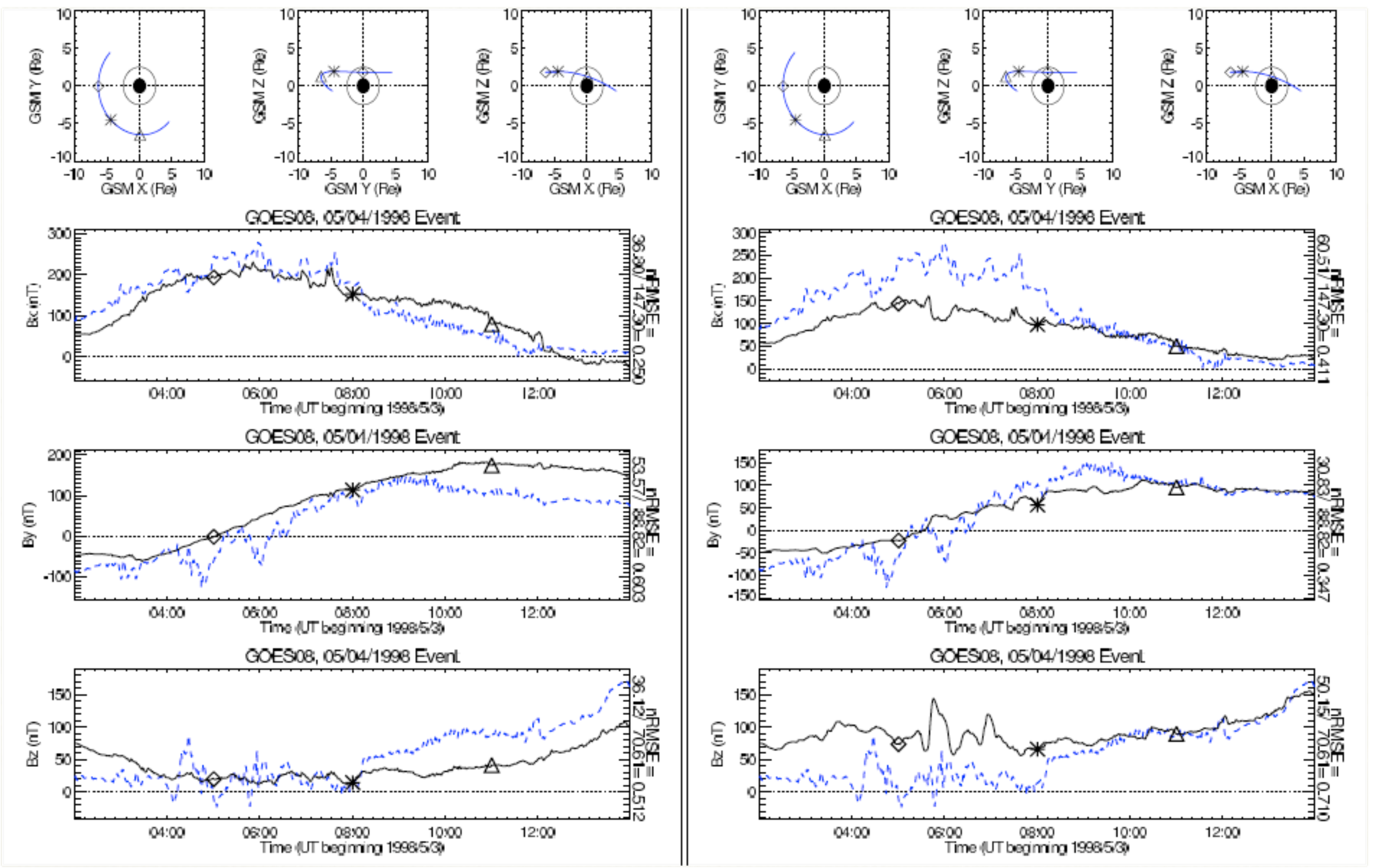


March 31, 2001 Pressure Comparison: CLUSTER



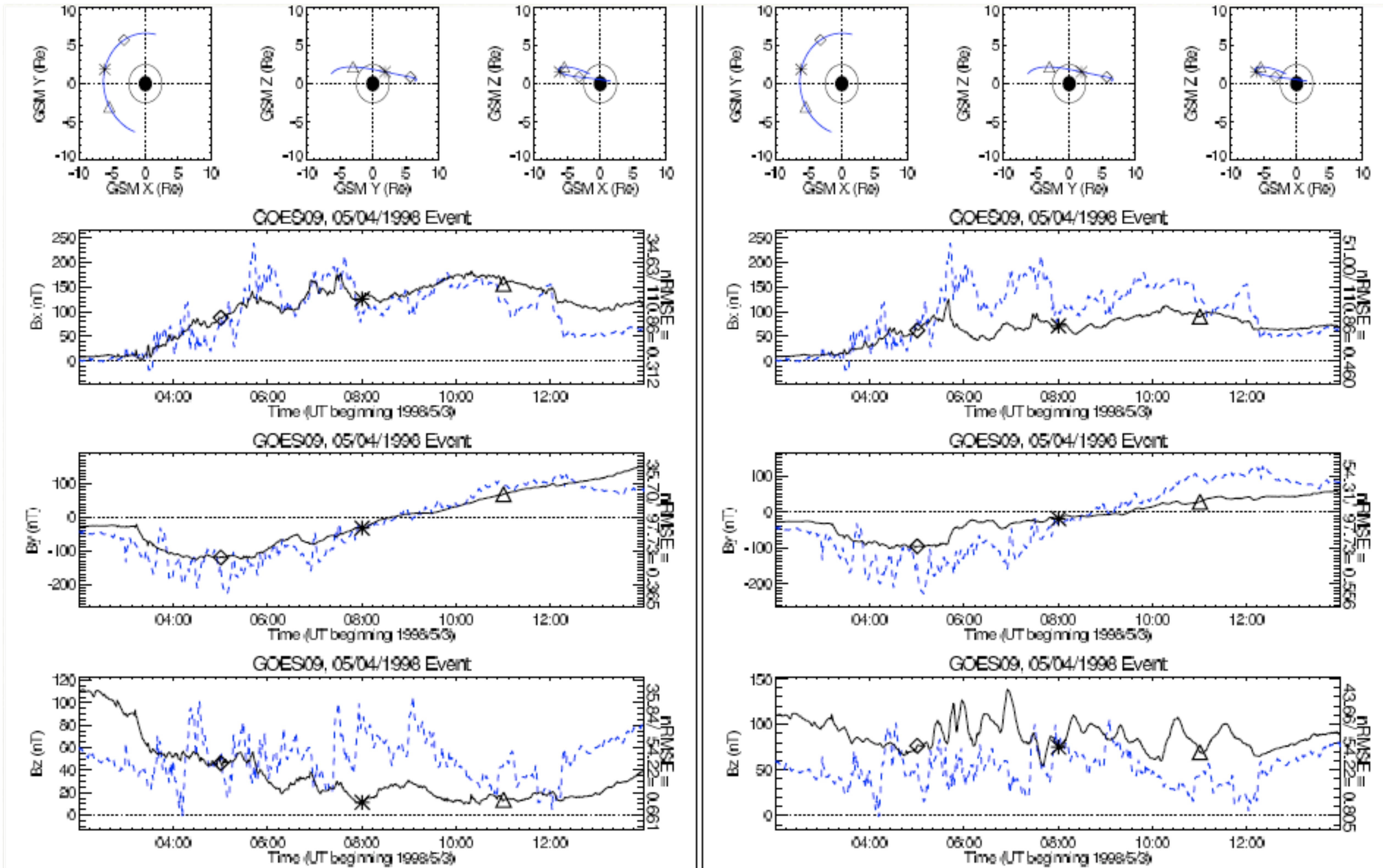
May 4, 1998 Event: GOES08

With Outflow | Without Outflow



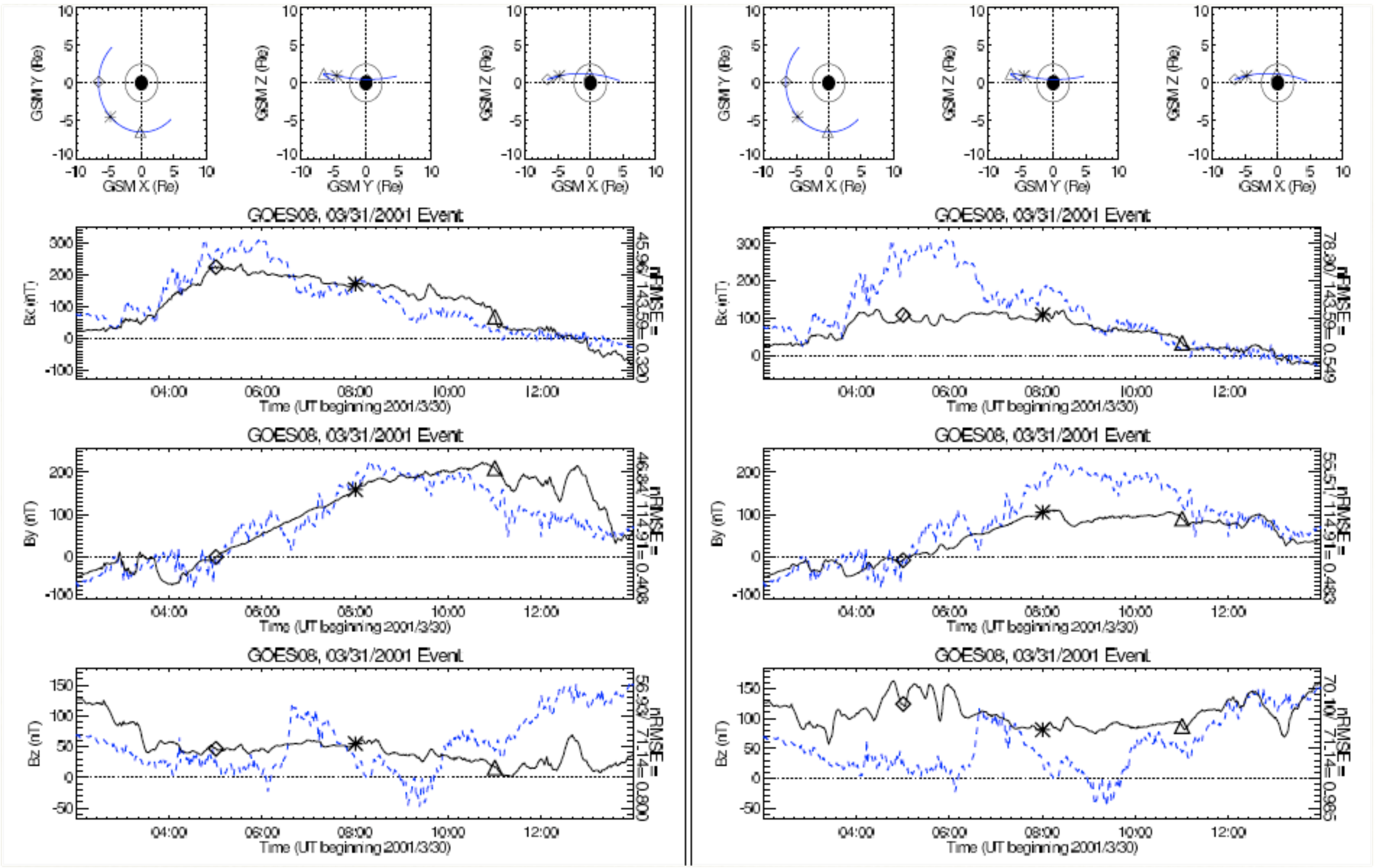
May 4, 1998 Event: GOES09

With Outflow / Without Outflow



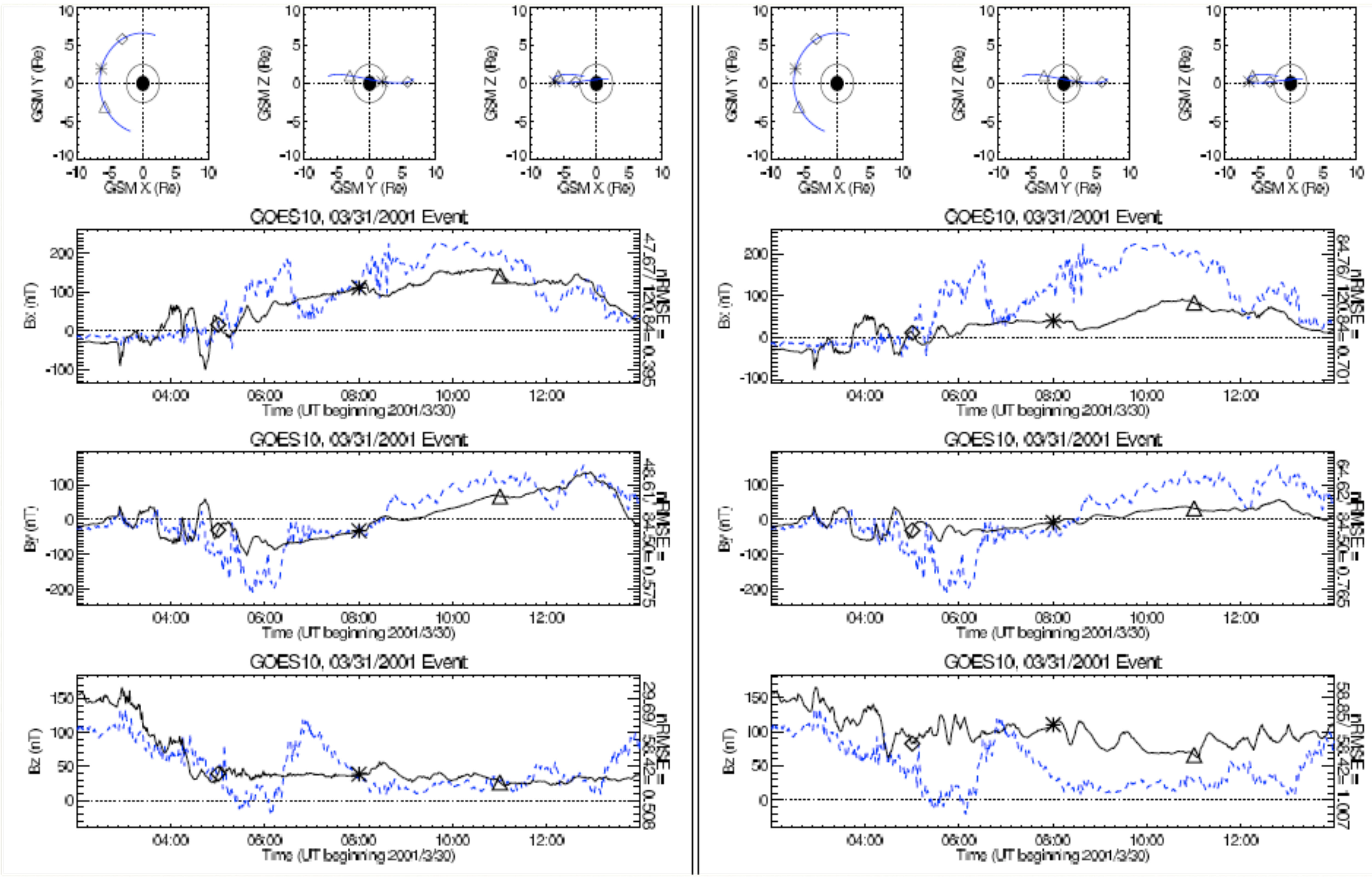
March 31, 2001 Event: GOES08

With Outflow Without Outflow



May 4, 1998 Event: GOES10

With Outflow | Without Outflow



Summary of Satellite B-Field Comparisons

Event	Satellite	RMS Error in $|B|$			RMS Error in Elev Θ		
		M-F MHD	M-S MHD	MHD	M-F MHD	M-S MHD	MHD
May 4, 1998	GOES 08	0.200	0.195	0.244	0.674	0.649	0.769
	GOES 09	0.226	0.214	0.299	0.743	0.728	1.094
March 31, 2001	GOES 08	0.222	0.180	0.312	0.831	0.631	0.983
	GOES 10	0.364	0.326	0.443	0.474	0.488	1.060

- The above table summarizes the RMS error in magnetic field magnitude and elevation angle for multi-fluid and multi-species MHD (with outflow) and single-fluid MHD without outflow.
- The multi-fluid and multi-species MHD simulations generally yield better comparisons than the single fluid MHD simulations with the GOES satellite data.
- In general, the largest improvement appears in the elevation angle.

The Mechanisms for Improvements

- Why is the rms error in the geomagnetic field so strongly reduced?
  - The ionospheric outflow gets energized in the inner magnetosphere, strengthening the ring current (see stronger Dst) and raising the plasma beta.
  - Heavy ions lead to lower Alfvén speeds which can alter the reconnection.
- Why is the CPCP consistently reduced?
  - Mass loading the magnetosphere affects the momentum transfer between the solar wind and the magnetosphere (*Winglee* [2002]).
  - Improved magnetic field calculation yields more accurate determination of the FACs, and increased mass density at inner boundary changes the precipitation.
  - Outflow leads to stronger ring current, which enhances shielding.

Multi-Fluid v Multi-Species MHD

- Similarities:
  - Both approaches yield very similar Dst and CPCP indicies.
  - The density and composition in the inner magnetosphere are also comparable.
- Differences:
  - The solution in the magnetotail and near sub-solar point demonstrate significant differences in topology, density, and composition.
  - These differences seem to grow over the simulations.
- Conclusions:
  - The most important factor is whether the outflow is included.
  - Multi-Species MHD is sufficient if you are only interested in indicies, density, composition, or B-Field in the inner magnetosphere.
  - Multi-Fluid MHD is necessary if you are interested in other regions, or for studying the separate dynamics of ions.

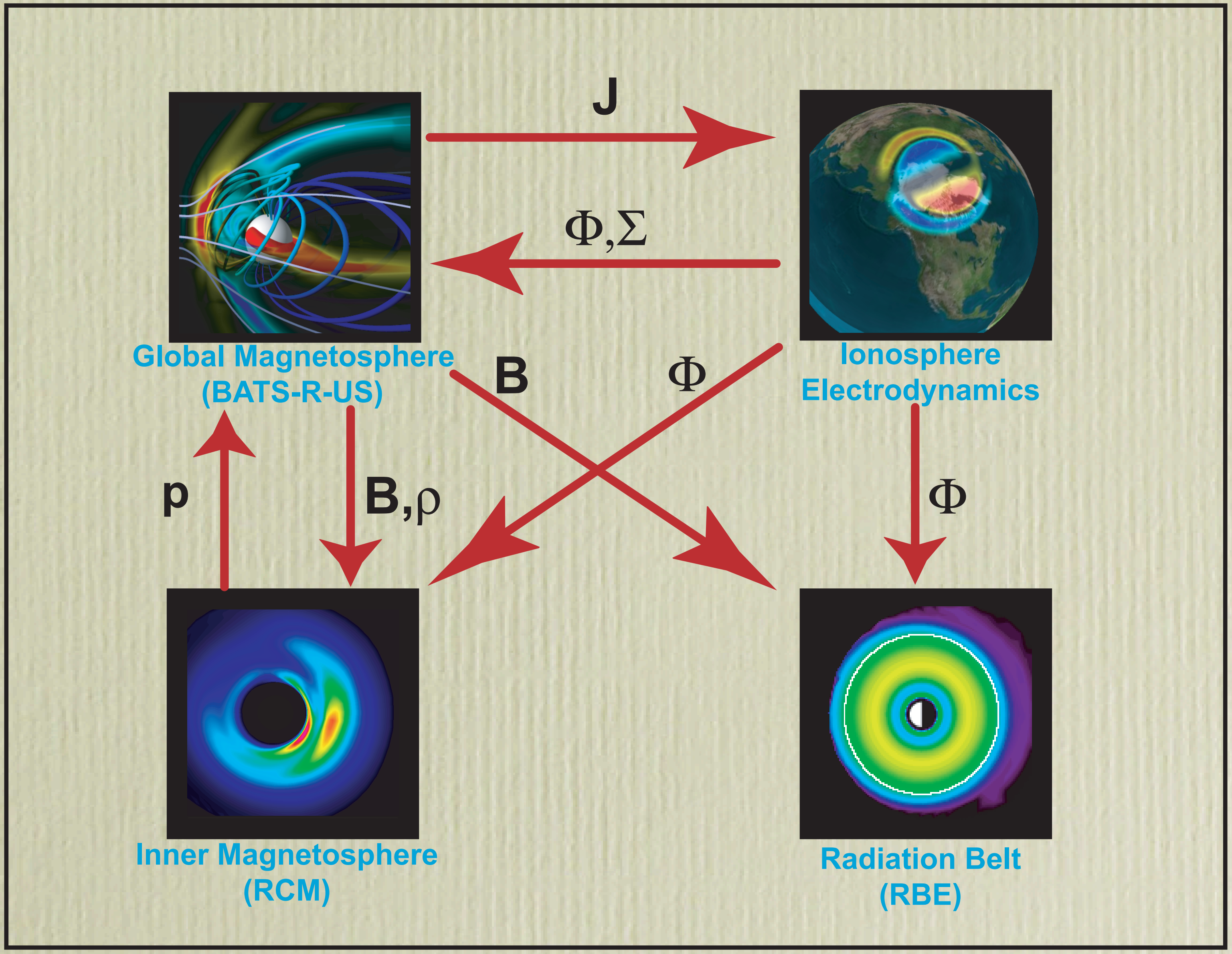
Summary

- PWOM can model time-dependent multi-fluid (H^+, O^+, He^+ and e^-) plasma flows along magnetic field lines between ~200 km altitude and the inner boundary of the global magnetosphere model (~2.5 Re).
- Expanded BATS-R-US: Multi-Fluid and Multi-Species MHD.
- We have used these models to study the May 4, 1998 and March 31, 2001 geomagnetic storms.
- We include a wide array of data model comparisons including geomagnetic indices (Dst and CPCP), magnetic field comparisons, and composition measurements.
- These results are written up in two papers:
    - The first paper details the PWOM model and the multi-species MHD simulations. (*Glocer et al*., "Modeling ionospheric outflows and their impact on the magnetosphere, initial results" [2009], in JGR)
    - The second paper details the multi-fluid MHD model and simulations. (Glocer et al., "Multi-Fluid BATS-R-US: magnetospheric composition and dynamics during geomagnetic storms, initial results" [2009], submitted to JGR)

The Broader Impact of Outflow

- Does ionospheric outflow have an effect on the larger space environment system?
- In the SWMF (and other models), the MHD magnetosphere code acts as a “spine”. Changes to the MHD result should therefore extend to other models.
- Example:
  - Potential impact on the radiation belts.

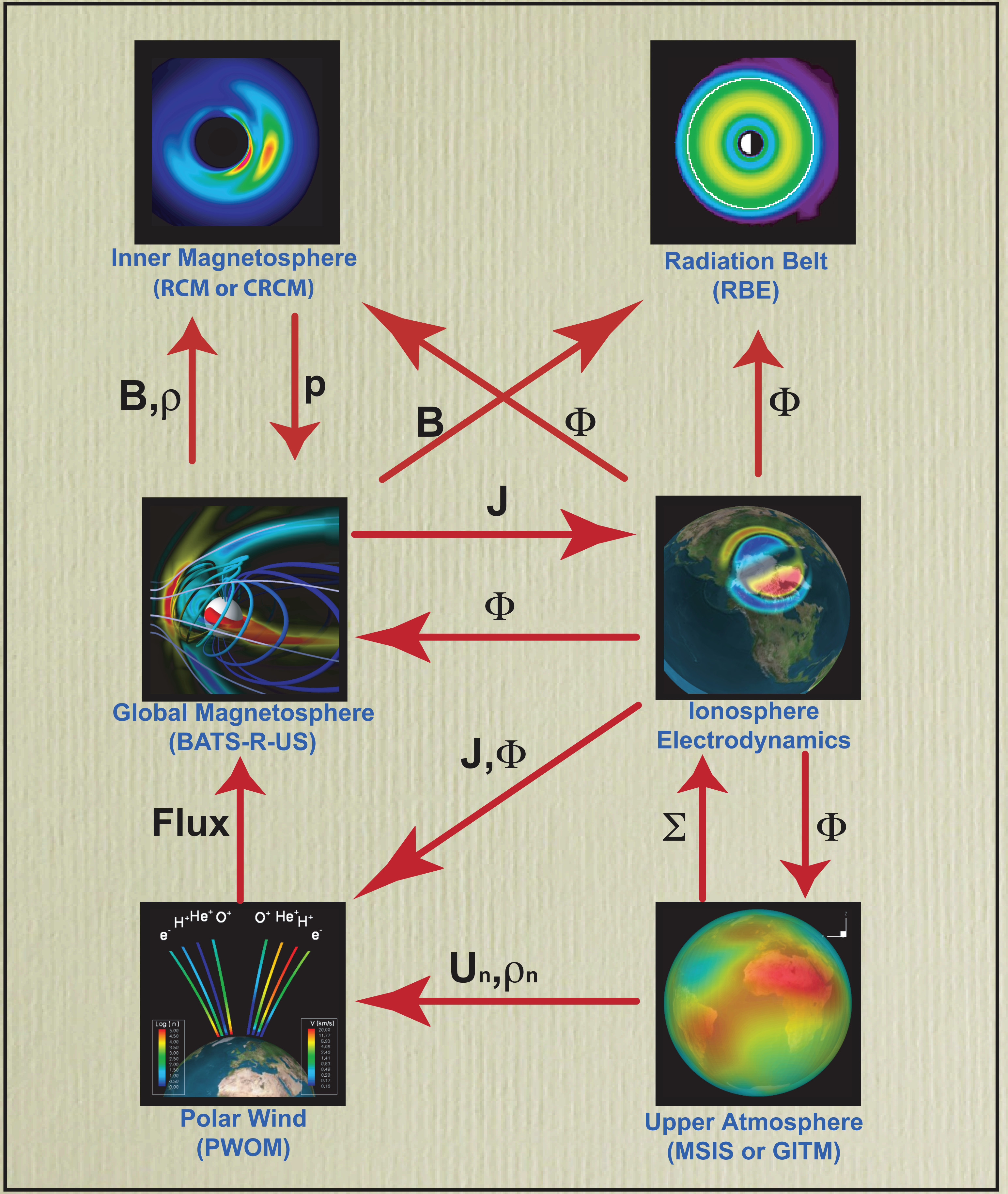
Radiation Belt Model Coupling



Glocer et al., [2009] (JASTP)

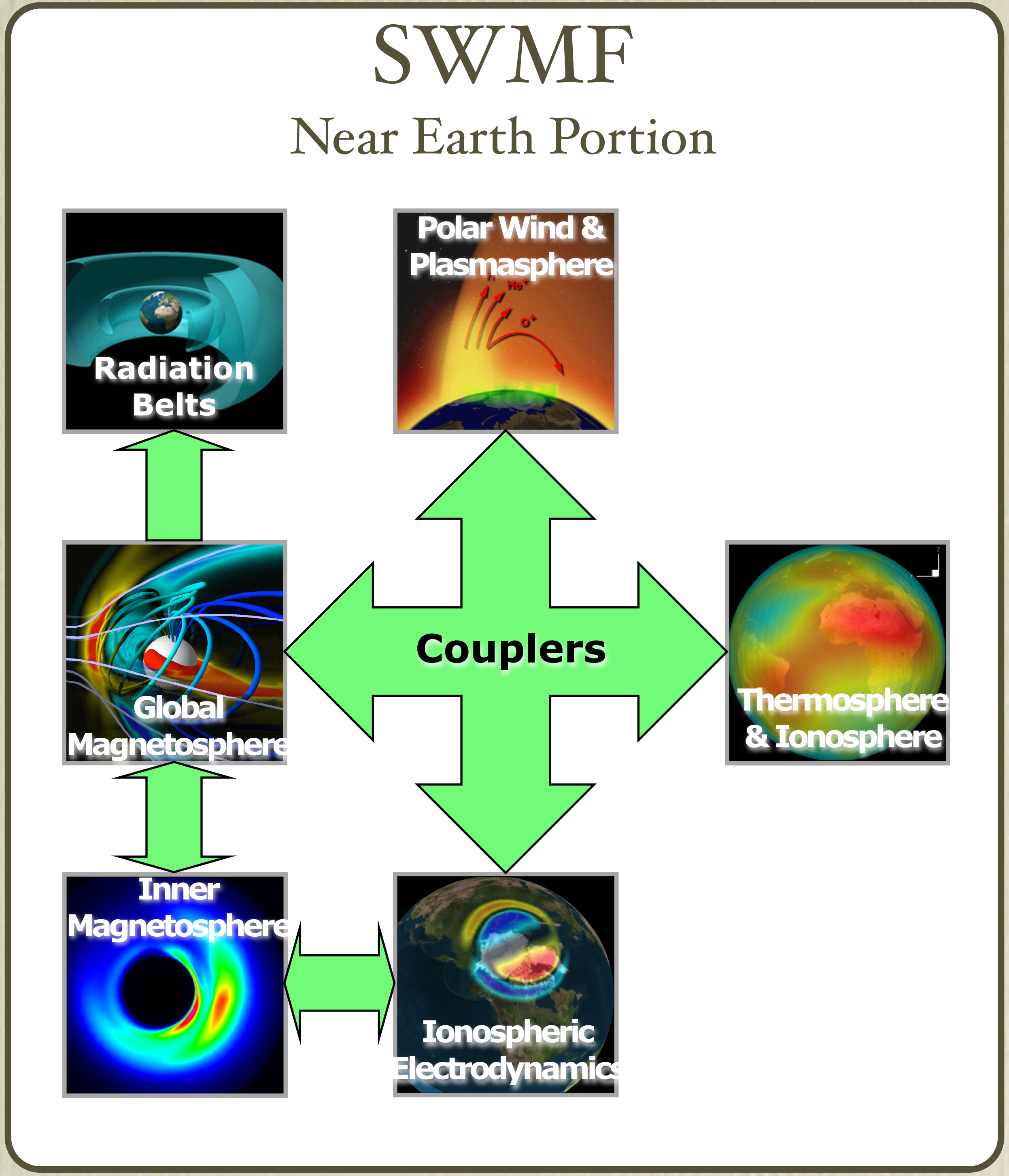
Radiation Belt Model Coupling

Radiation Belt Model Coupling



Ionospheric Outflow Affects Space Environment System

- Improvement in the magnetic field:
  - Radiation Belts, Inner Magnetosphere, and Global Magnetosphere
- Reduction in CPCP (ionospheric potential):
  - Ionosphere Electrodynamics, Inner Magnetosphere, Thermosphere/ Ionosphere,Global Magnetosphere
- Stronger ring current (as measured by Dst):
  - Inner Magnetosphere and Global Magnetosphere
- **Ionospheric outflow impacts the entire system!!**



Conclusions

- Ionospheric plasma is important to magnetospheric processes, and needs to be taken into account in global models.
- We have included a polar wind outflow model into the SWMF.
- We have implemented multi-fluid and multi-species MHD versions of BATS-R-US to track the changing composition and impacts.
- The ionosphere must be taken into account as a plasma source, and not just as a resistive layer.
- The consequences for the broader system may be significant.

Thank you!