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Toward A New Space Weather Model Suite

Space Plasma Theory and Modeling @ APL & collaborators

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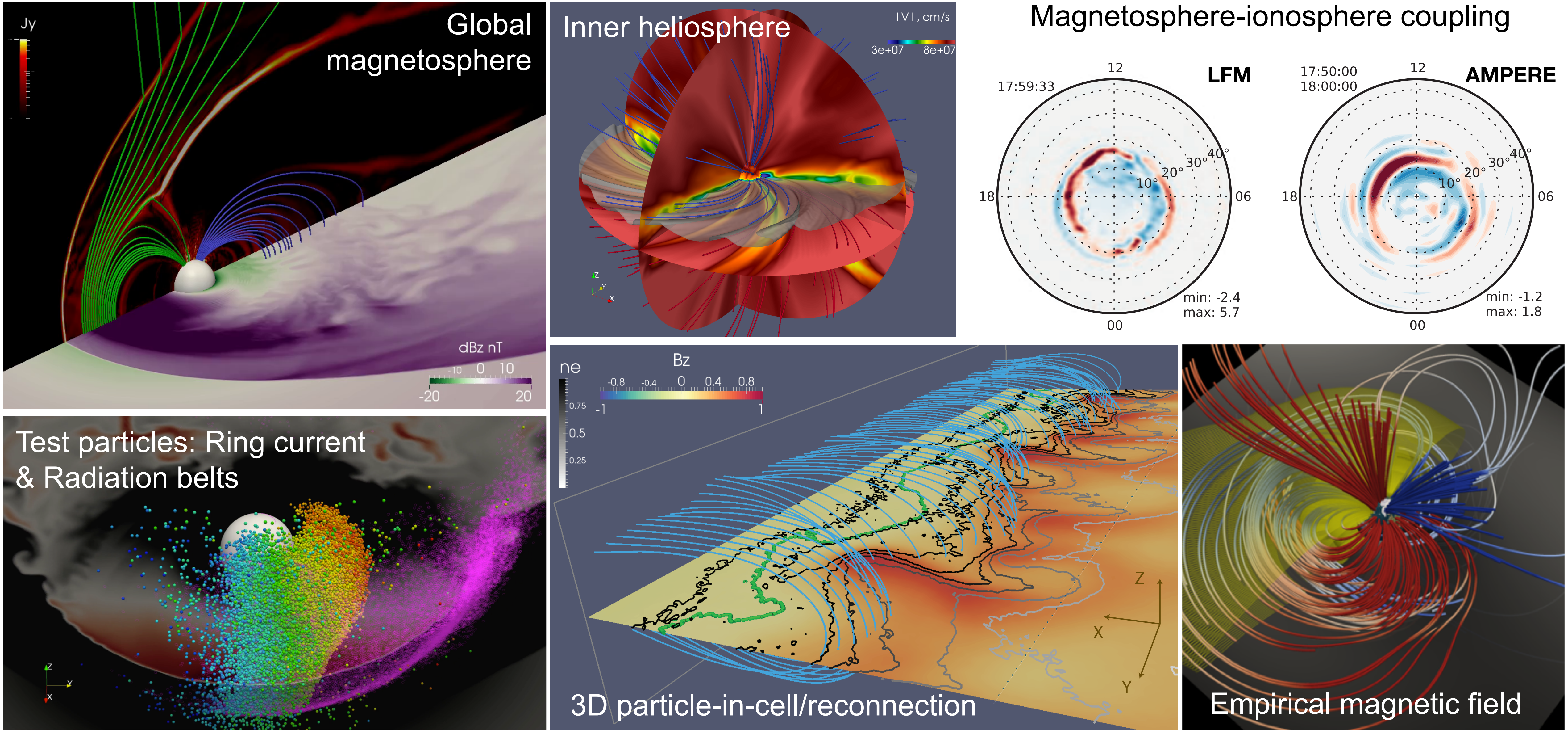
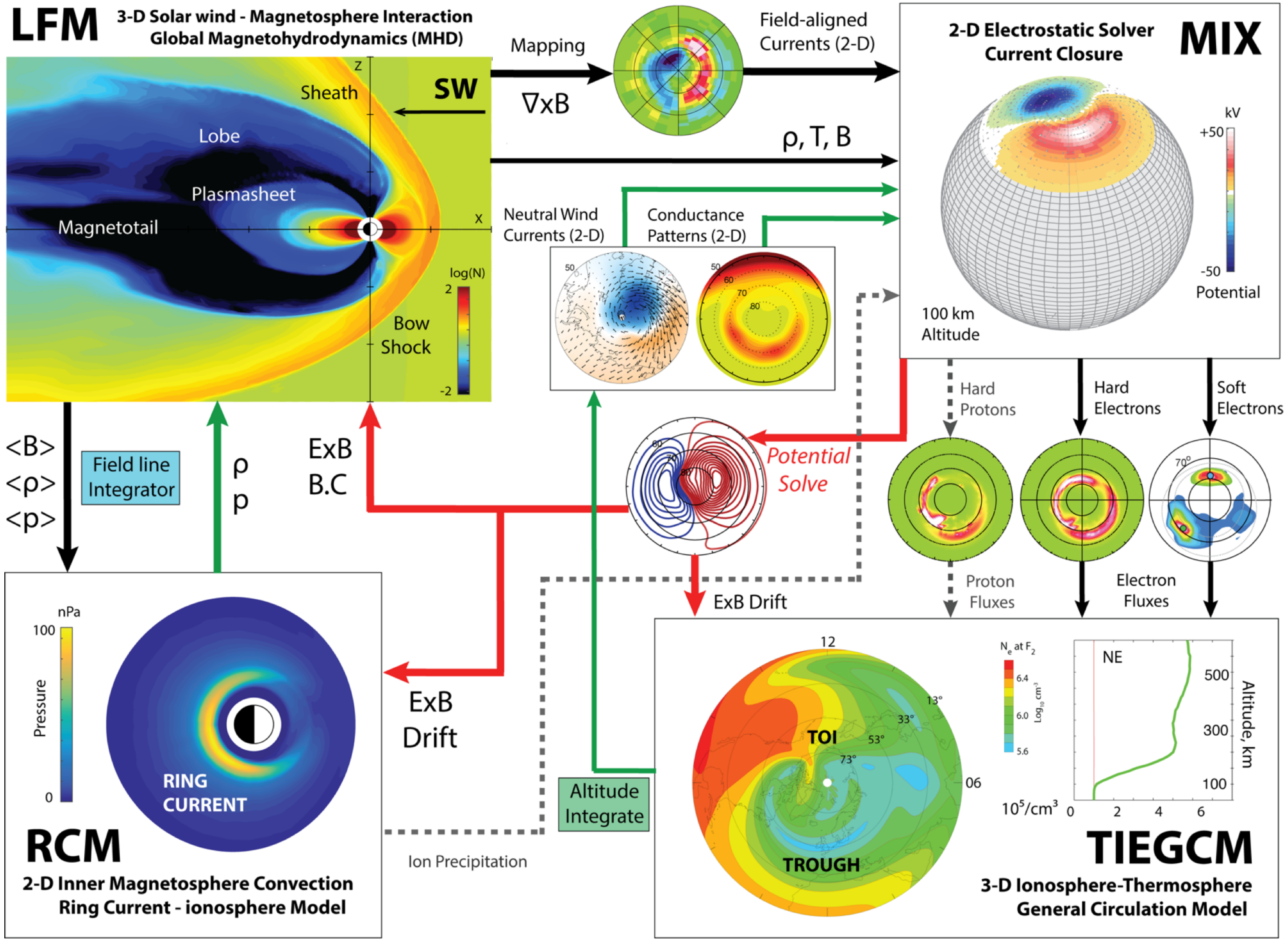
Outline
- Current model overview
- Research highlights
  - Geospace
  - Heliosphere
- Brief LFM (Lyon-Fedder-Mobarry) history
- Motivation for upgrade
- LFM overhaul project
- Future

APL space weather simulation toolbox



CMIT: Geospace modeling

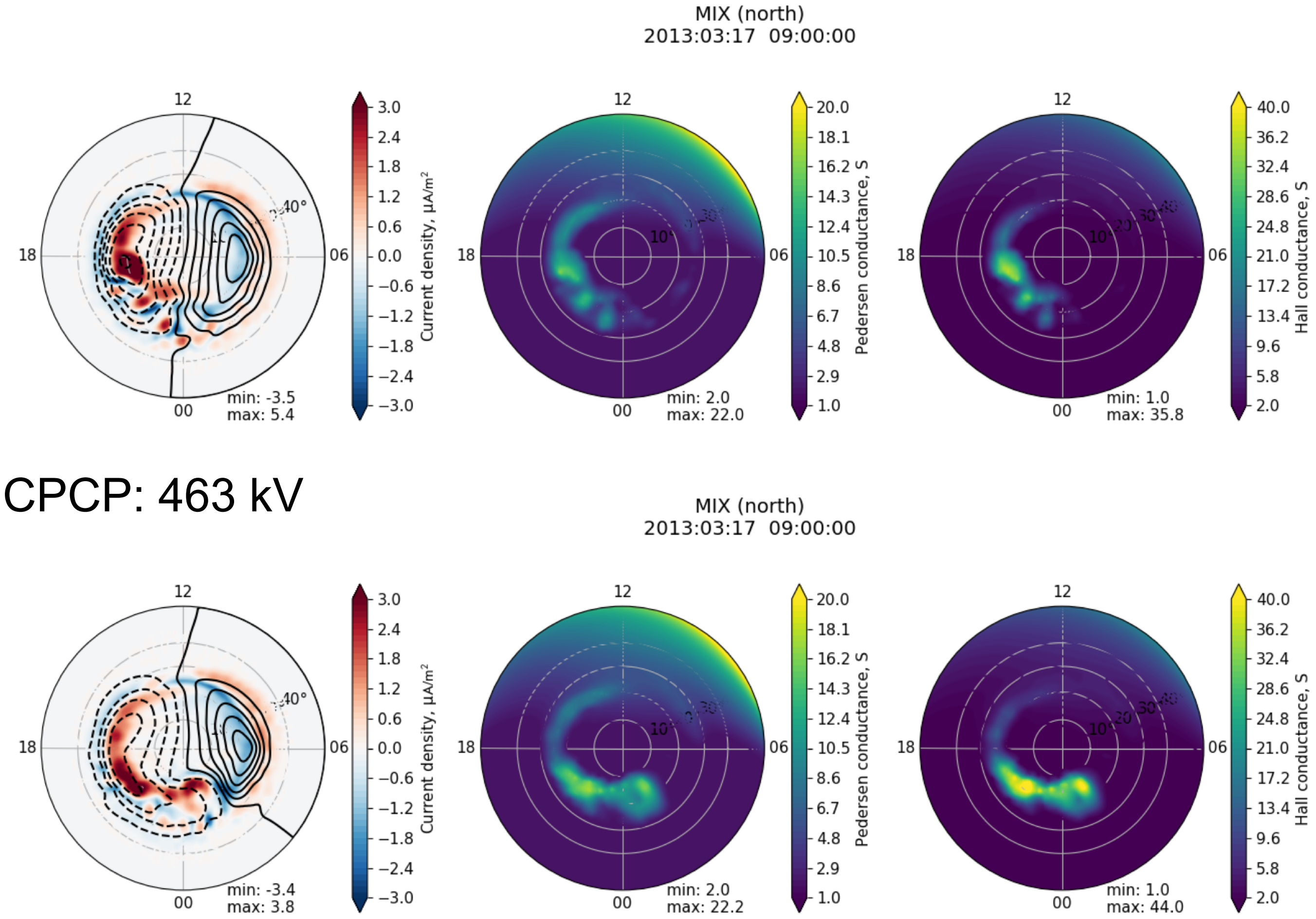


- Coupled Magnetosphere-Ionosphere-Thermosphere Model
- Includes global magnetosphere, ring current, precipitation, ionospheric electrodynamics, and ionosphere-thermosphere components
- Global magnetosphere LFM code is the backbone
- Coupling infrastructure built during the CISM project (in 2000's)
- Current state of the art in geospace modeling
- Continued collaboration among teams (APL, NCAR, HKU, Dartmouth, Rice)

Geospace research highlight #1

Fully coupled LFM-MIX-RCM-TIEGCM simulation of the 2013 St. Patrick's Day storm

Without ET



CPCP: 463 kV

With ET

CPCP: 383 kV

Merkin et al., AGU, 2017

- All major geospace components coupled
- Microscopic E-layer electrojet turbulence (ET) modifies ionospheric conductivity
- ET heating terms included directly in TIEGCM

Geospace research highlight #1

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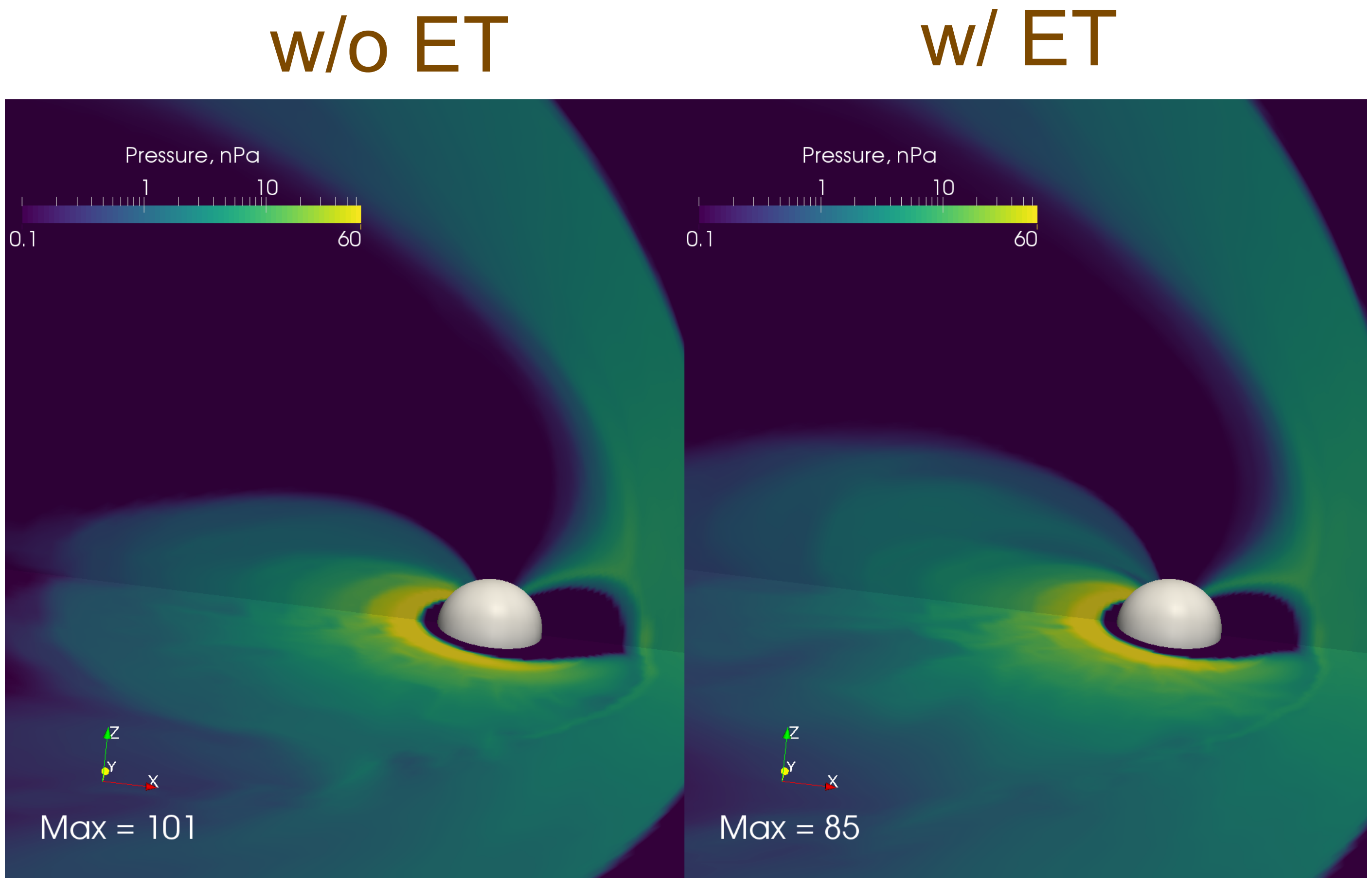
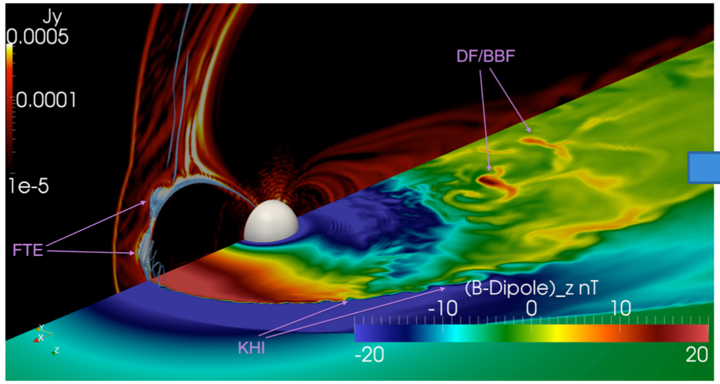


Merkin et al., AGU, 2017

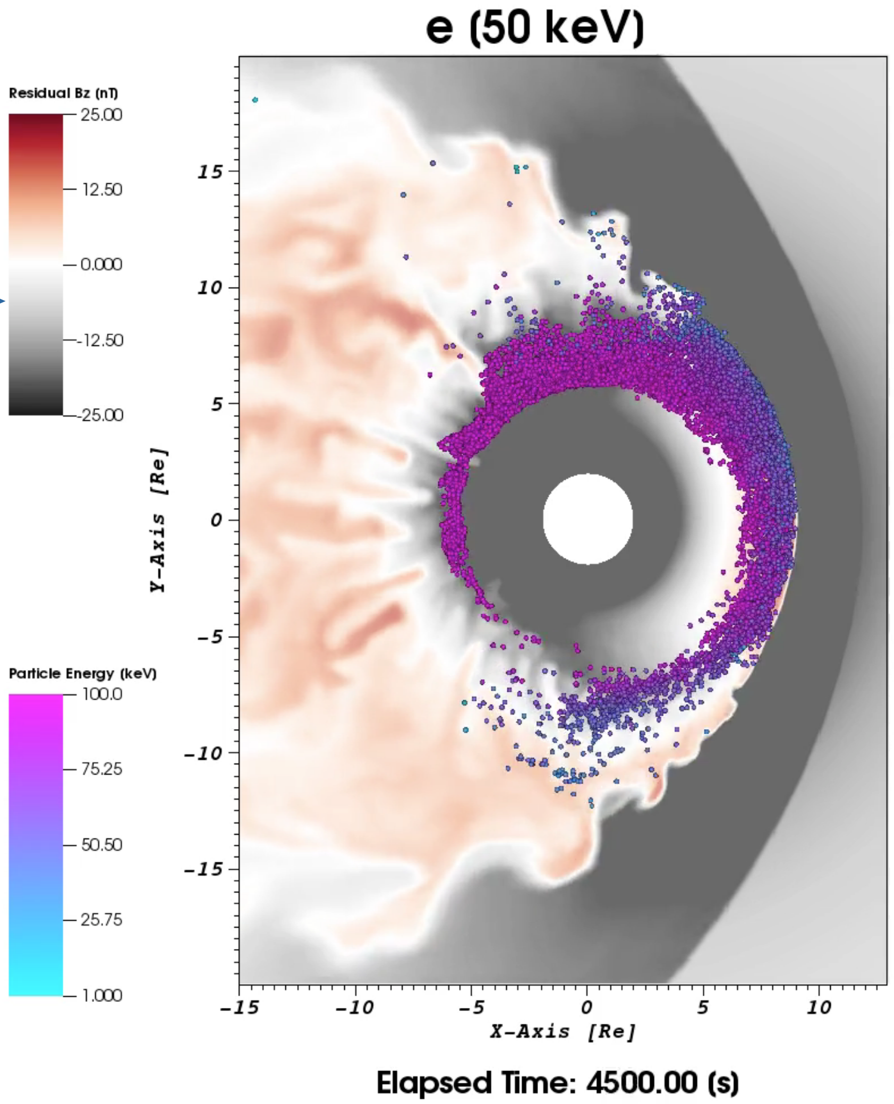
- Microscopic physics at 100km altitude has major macroscopic effects on magnetospheric plasmas at 60,000 km

Geospace research highlight #2

CHIMP + LFM: Particle Tracing in high-resolution MHD



CHIMP
Conservative Hamiltonian Integrator for Magnetospheric Particles



Example: Electron TP's initialized on MHD dipolarization front, Z=0 plane.

- How do energetic particles interact w/ mesoscale MHD flow structures?
- CHIMP
  - Evolve test particles (TPs) in MHD-generated EM fields
  - Post-proc step, interpolate from high-cadence saved MHD data
  - Full orbit/guiding center switching based on local field

Geospace research highlight #2

Modeling the Outer Radiation Belt w/ MHD+TP

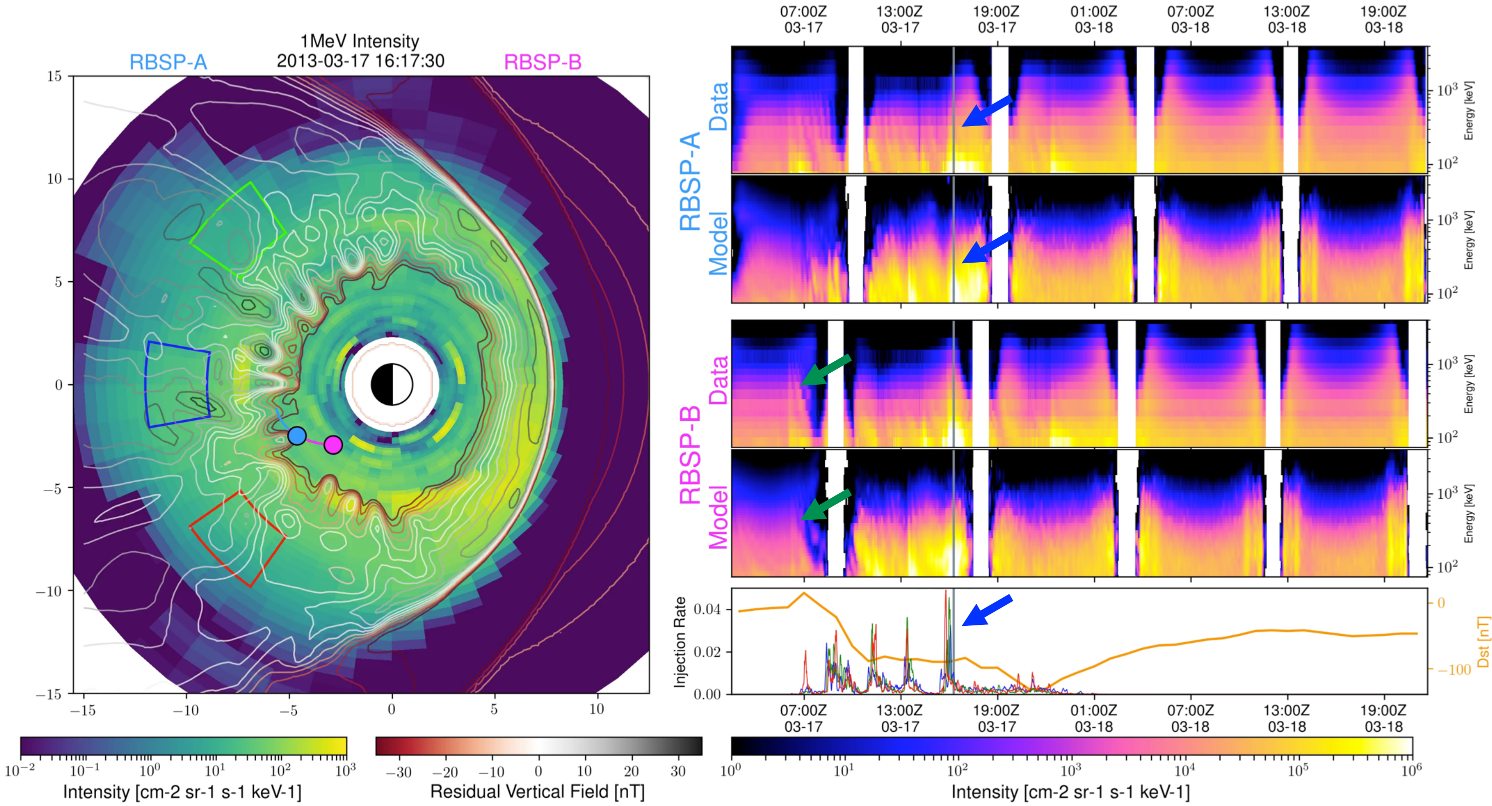
Sorathia et al., JGR, 2018

Framework

- Input: Solar wind/F10.7
- Global 3D MHD+RC
- TPs: Initial & injected population
- Use MHD flow data (n,T,V) to seed TPs
  - i.e., aim TP's at injection fronts
- Convert TPs to electron PSD

Application to March 2013 Storm

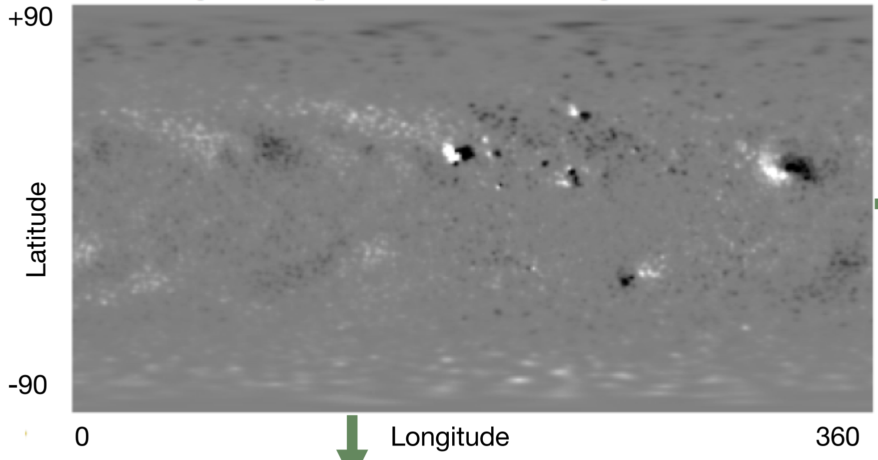
- Comparison w/ in situ RBSP measurements
- Reproduce global evolution
  - Cycle of depletion, recovery, enhancement
  - Ratio of pre- and post-storm intensities
- Reproduce localized (space+time) features
  - Compression/drift-echo signature of CME shock
  - Nightside injection signatures



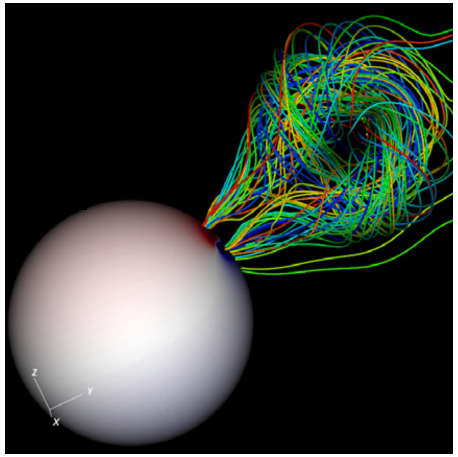
Model value ~ Output/Input
Input: Solar wind (@X=30) & F10.7
Output: RB Intensity (L,MLT)

LFM-helio: Inner heliosphere modeling

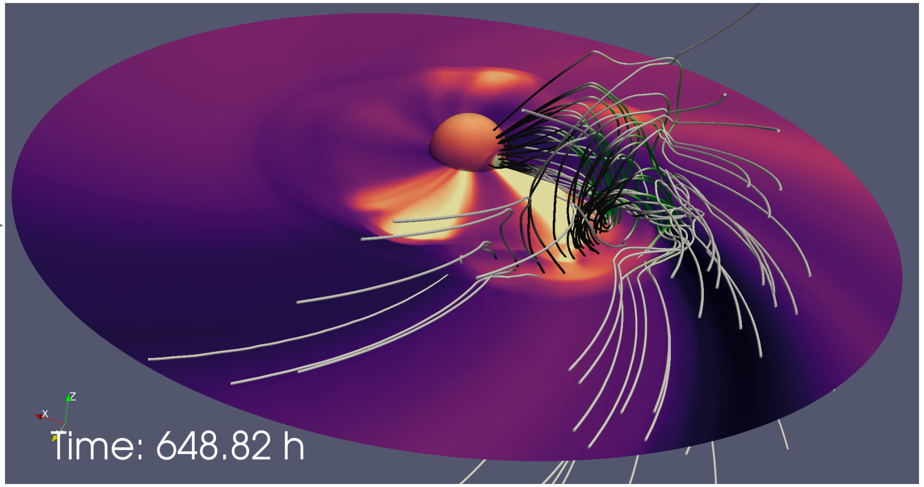
Photospheric maps (incl. ADAPT)



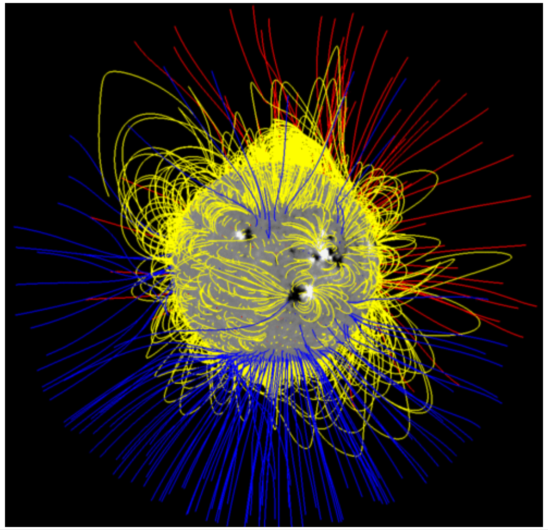
MAS corona



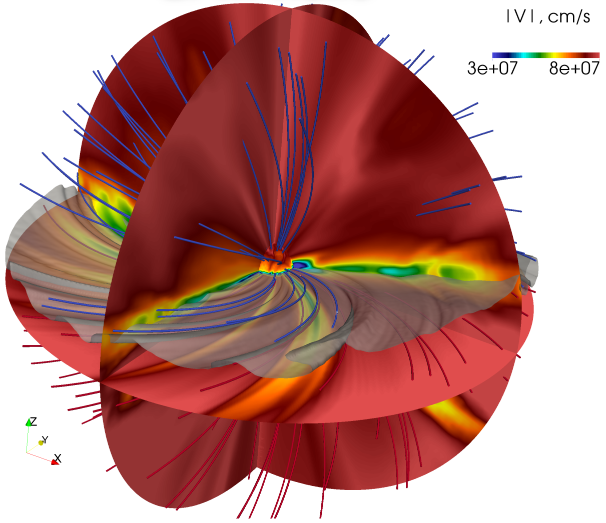
LFM-helio



WSA Corona



LFM-helio

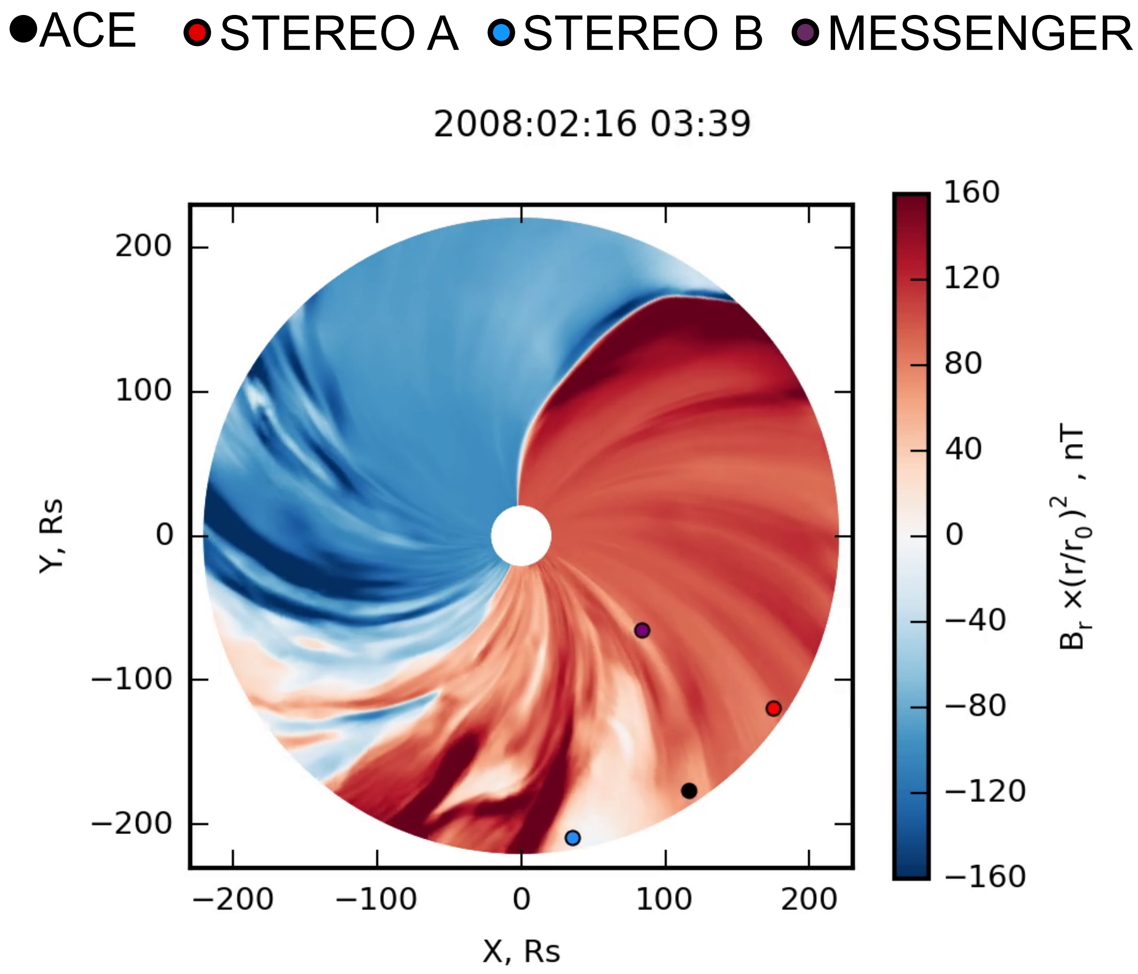


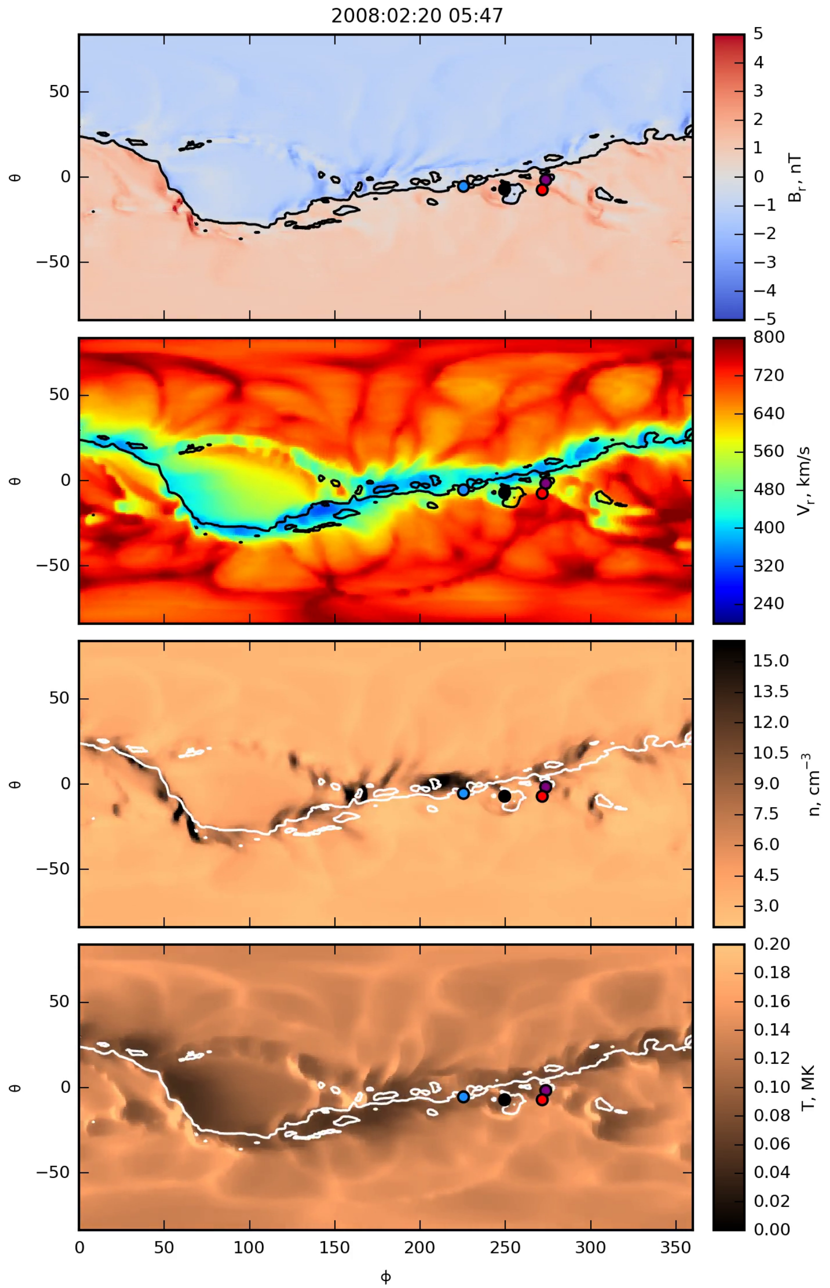
- LFM serves as backbone for the inner heliosphere modeling pipeline
- Modeling is time-dependent
- ADAPT/WSA-driven for quiet heliosphere
- Coupled with MAS for CME propagation

Helio research highlight #1

ADAPT/WSA-driven time-dependent background solar wind

- HCS moves around
- Transient SW velocity streams
- Complex HCS crossings/ transitions

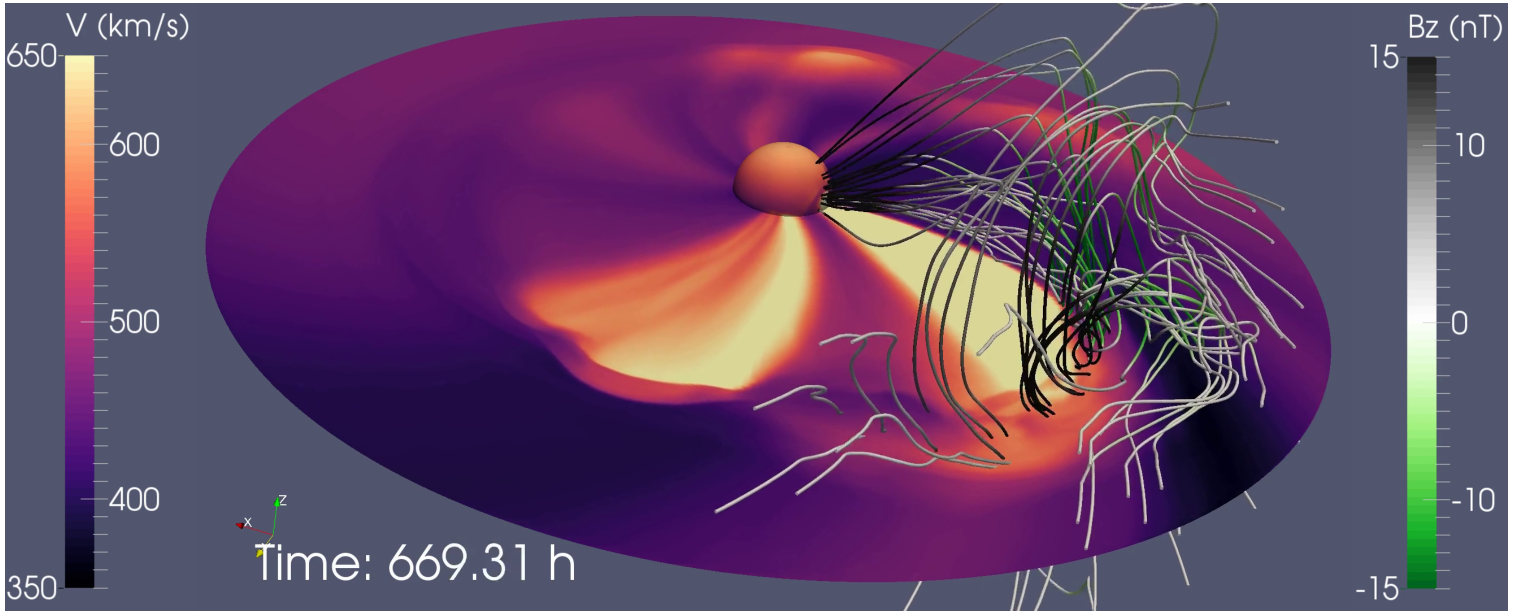




Merkin et al., JGR, 2016a

Helio research highlight #2

MAS-driven CME propagation: First-principles from eruption to Earth



LFM-helio driven by the MHD-around-a-sphere (MAS) code.
Work done in collaboration with Predictive Science Inc.

Merkin et al., ApJ, 2016b

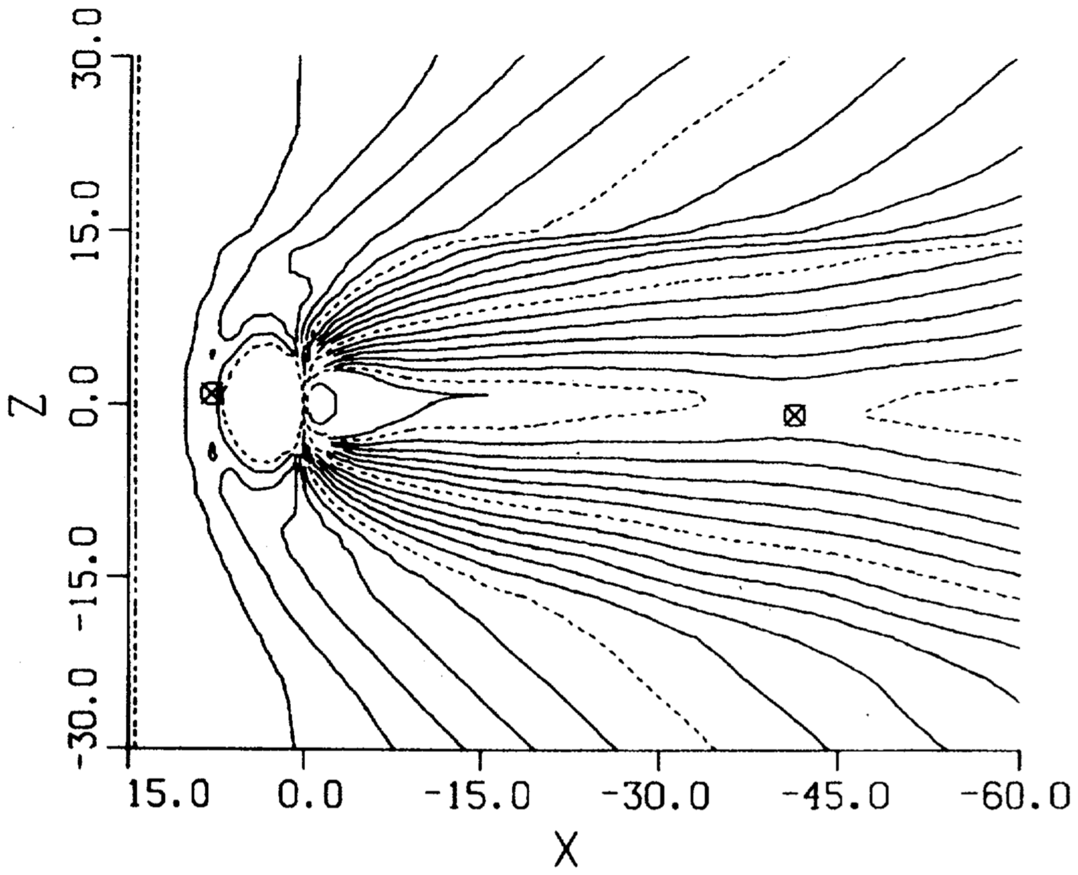
LFM history

- LFM — MHD code developed by J. Lyon, J. Fedder and C. Mobarry at NRL in the 80's
- MHD numerics by J. Lyon
- Heritage traced to pioneering work on Flux Corrected Transport (FCT) schemes in the same group (J. Boris, D. Book, S. Zalesak, K. Hain)
- One of the first FCT MHD codes in multiple dimensions
- Started with very high order fluid schemes (20th order, Lyon et al., PRL, 1981)
- Finite volume, arbitrary hexahedral mesh
- Constrained transport (Yee-mesh), Magnetic field divergence-less to round-off ($\nabla \cdot \mathbf{B} = \mathbf{0}$)

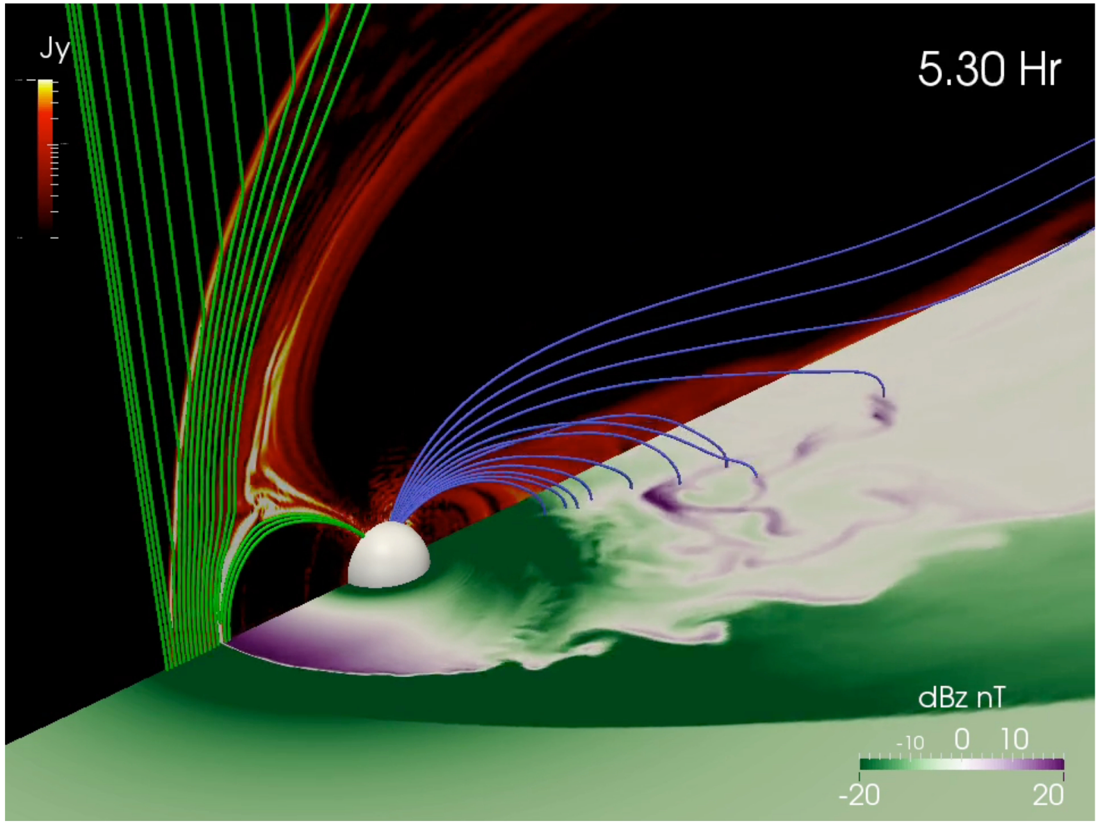
1980	MHD magnetosphere simulation (2-D)
1982	3-D magnetosphere
1985	Self-consistent ionosphere coupling
1992	CRRESS Barium release (Huba et al., JGR); Hall MHD
1995	Saturn, Neptune, Uranus simulations Higher resolution
1997	Acquired name (LFM)
1998	Venus simulation (Kallio et al., JGR)
1999	Outer heliosphere, neutrals, pickup ions (McNutt et al.)
2004	MPI parallelized Numerics paper written (Lyon et al., JASTP); done in 1987
2008-2010	Geospace coupling framework Operational at CCMC
2010	Multi-fluid extension
2011	Inner heliosphere, solar wind (Merkin et al., GRL)
2013	High-resolution magnetosphere KHI (Merkin et al., JGR)
2015	High-resolution magnetotail dipolarizations (Wiltberger et al., JGR)

…

Then and now



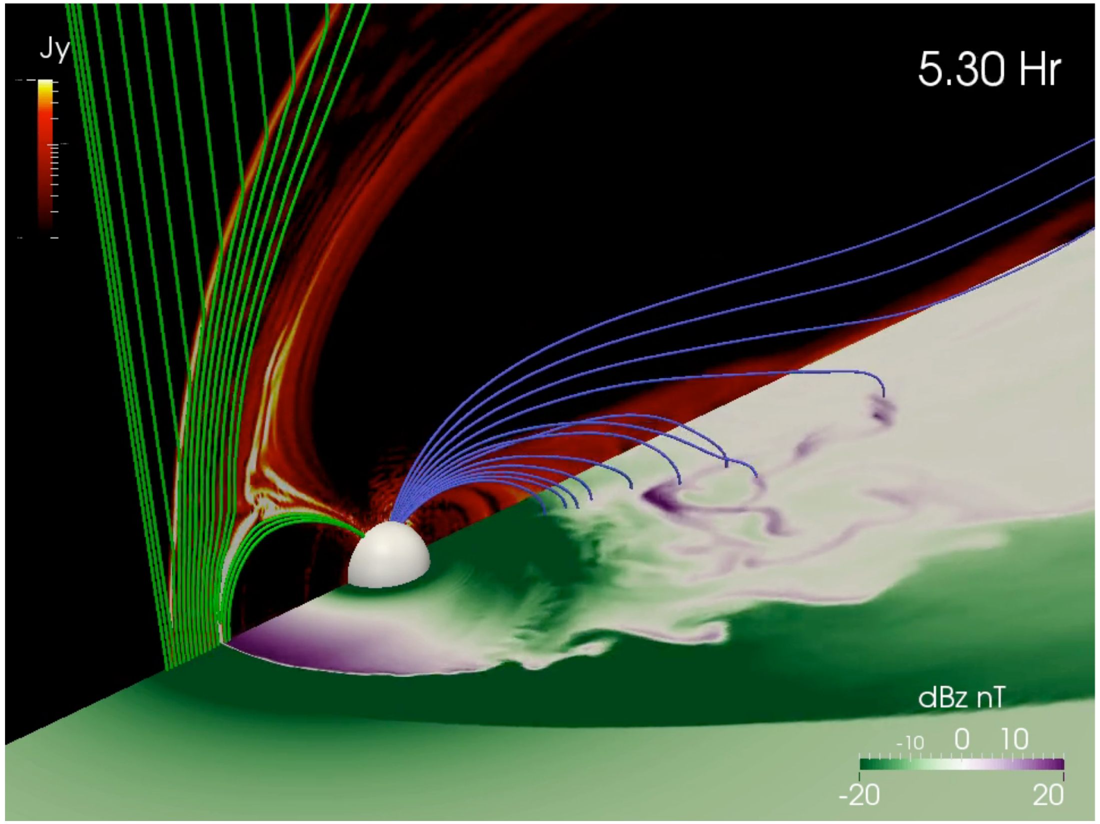
Lyon et al. [1981], 50x40



Wiltberger, Merkin&Lyon [2016], 212x196x256

Going forward

- LFM numerics are quite unique
  - Handles arbitrary, non-orthogonal (and singular!) grid
  - High-order spatial reconstruction
  - Can capture 3D dynamics with relatively few cells
  - Intrinsically div-free B updates (constrained transport)
- LFM underlying code was written ~30 years ago
- Optimized for architectures long retired
- The code is robust and performs well on existing architectures
- Speed and portability becoming an issue with time
- Needs a serious upgrade for next generation supercomputers



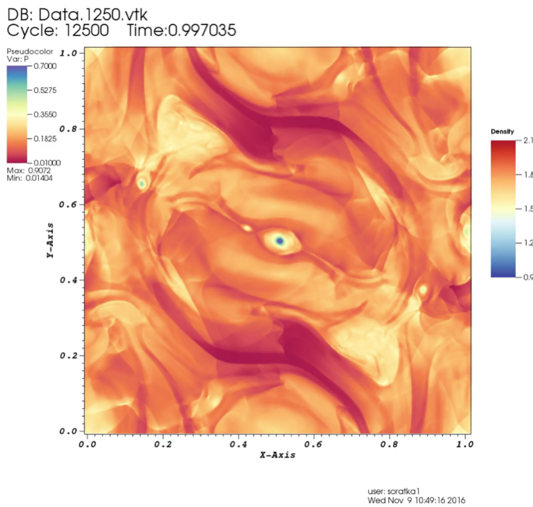
Wiltberger, Merkin&Lyon [2016], 212x196x256

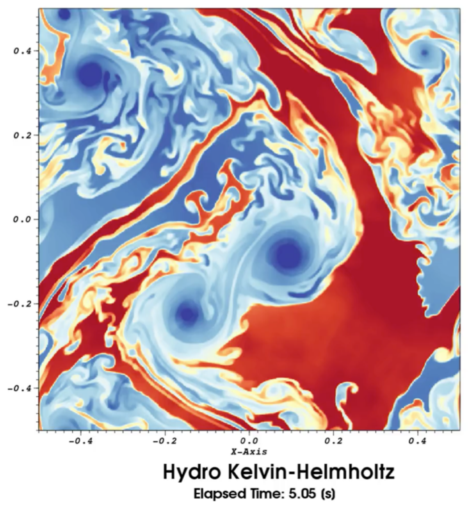
Meet Gamera

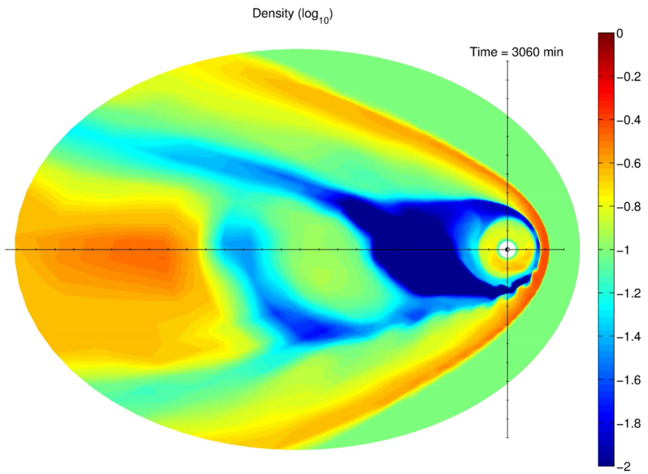
- Gamera is a reinvention of LFM
- Built to tackle modern challenges, but preserve the unique numerics of LFM
- Code written to expose multiple layers of heterogeneous parallelism (vectorization, OpenMP, MPI)
- Fortran 2003+, minimal external library dependence
- Portable, user-friendly, flexible
- Model coupling for inter-connected, multi-physics, multi-scale systems
- Standard tests to be published

GAMERA

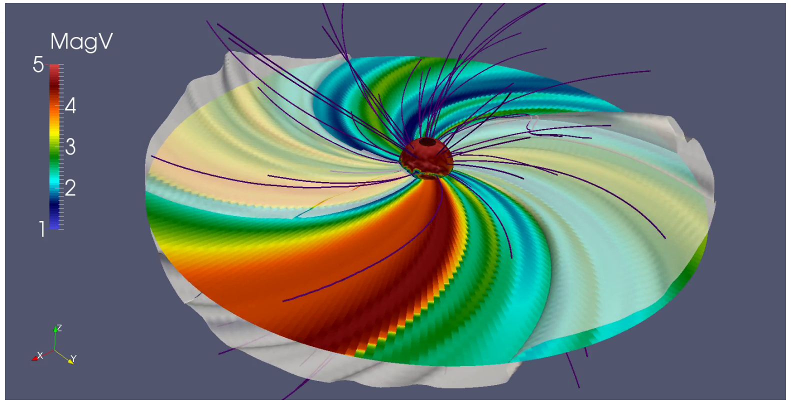
Grid Agnostic MHD for Extended Research Applications







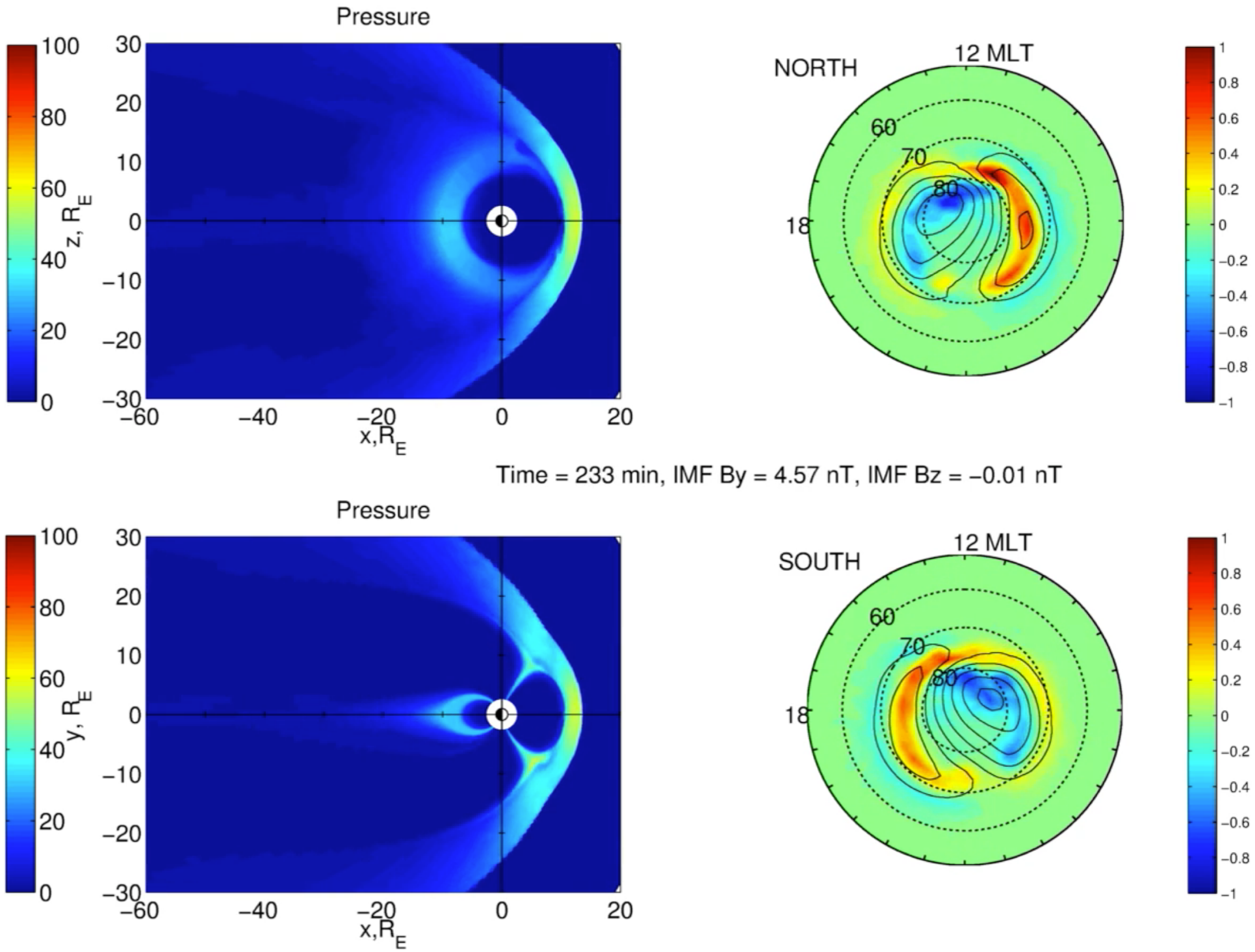
Saturn magnetosphere



Inner heliosphere

Gamera for space weather

Magnetosphere



- Ionospheric solver rewritten from scratch in Fortran 2003+ as well
- Fully incorporated
- Example: 96x96x128 resolution
- Comparable to LFM "quad"
- About real-time on 2 Cheyenne nodes
- Coupling infrastructure in progress; flexible, minimal lib dependency
- Ready for coupling with RCM and TIEGCM

Conclusions

- Diverse set of space weather simulation tools
- Primary applications:
  - Geospace
    - Magnetosphere-ionosphere-thermosphere coupling
    - Radiation belts
    - Ring current
  - Inner heliosphere
- Backbone is the global magnetosphere MHD code (LFM, and now Gamera)
- LFM has been in production for ~30 years
- Numerous applications to various plasma problems
- Very high quality MHD numerics but…
- Needs an upgrade for sustainable future
- Developed a general application, flexible, portable, and efficient MHD code = Gamera

- Gamera preserves (and improves upon) all the high heritage LFM numerics
- Also, building a robust and flexible coupling framework
- In particular, tools for model agnostic ring current coupling
- New test particle code incorporated with Gamera (ions and electrons)
- Minimal external library dependence
- Magnetosphere and heliosphere applications already operational and used for science-quality production runs
- Ready for coupling with RCM and TIEGCM
- Website: civspace.jhuapl.edu/gamera

GAMERA
Grid Agnostic MHD for Extended Research Applications

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