OpenGGCM New Developments

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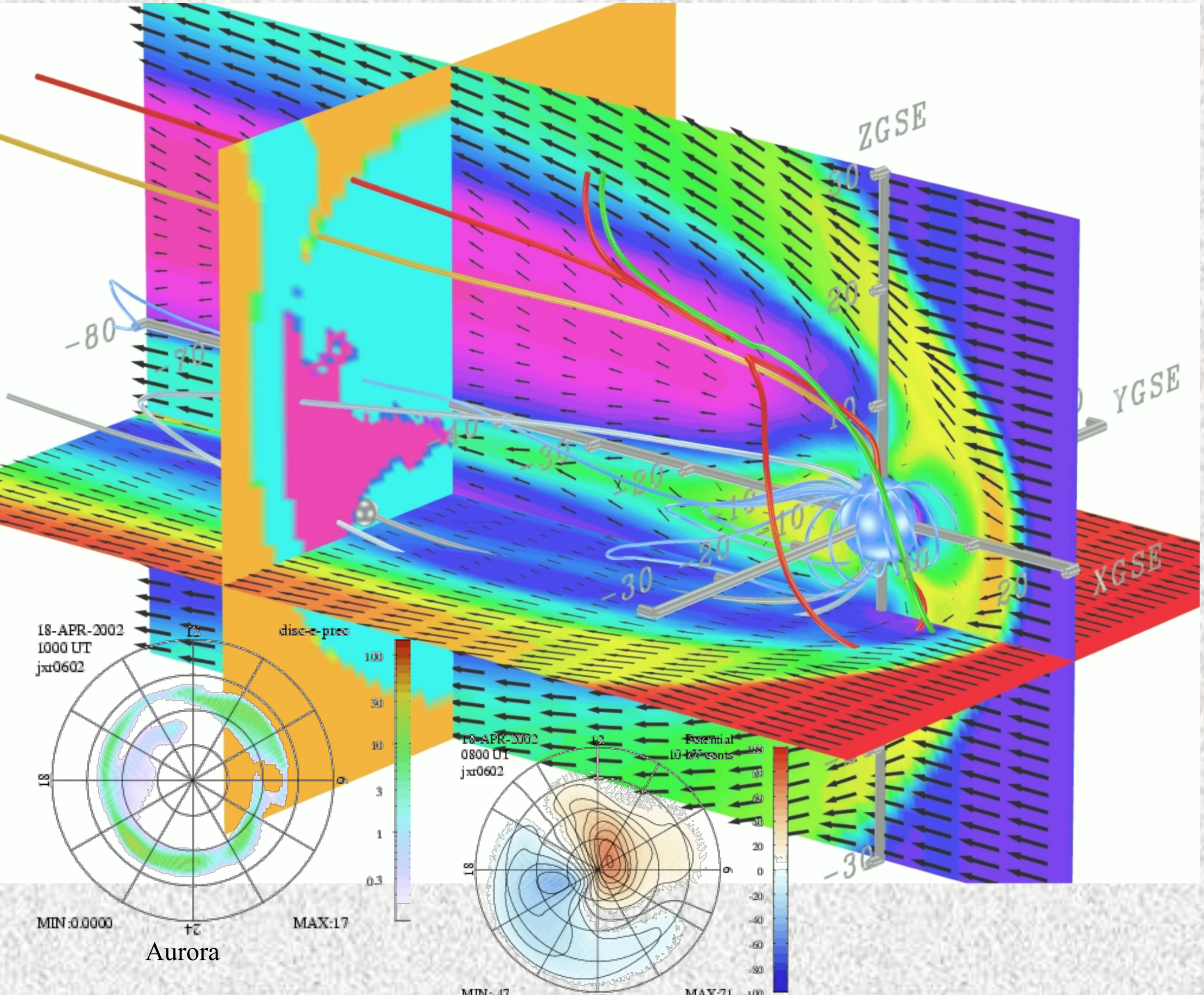
OpenGGCM: Global Magnetosphere Modeling



Aurora

Ionosphere Potential

The Open Geospace General Circulation Model:

- Coupled global magnetosphere - ionosphere - thermosphere model.
- 3d Magnetohydrodynamic magnetosphere model.
- Coupled with NOAA/SEC 3d dynamic/chemistry ionosphere - thermosphere model (CTIM).
- Coupled with inner magnetosphere / ring current models: Rice U. RCM, NASA/GSFC CRCM.
- Model runs on demand (>500 so far) provided at the Community Coordinated Modeling Center (CCMC at NASA/GSFC). http://ccmc.gsfc.nasa.gov/
- Fully parallelized code, real-time capable. Runs on IBM/datastar, IA32/I64 based clusters, PS3 clusters, and other hardware.
- Used for basic research, numerical experiments, hypothesis testing, data analysis support, NASA/THEMIS mission support, mission planning, space weather studies, and Numerical Space Weather Forecasting in the future.
- Funding from NASA/LWS, NASA/TR&T, NSF/GEM, NSF/ITR, NSF/PetaApps, AFOSR programs.

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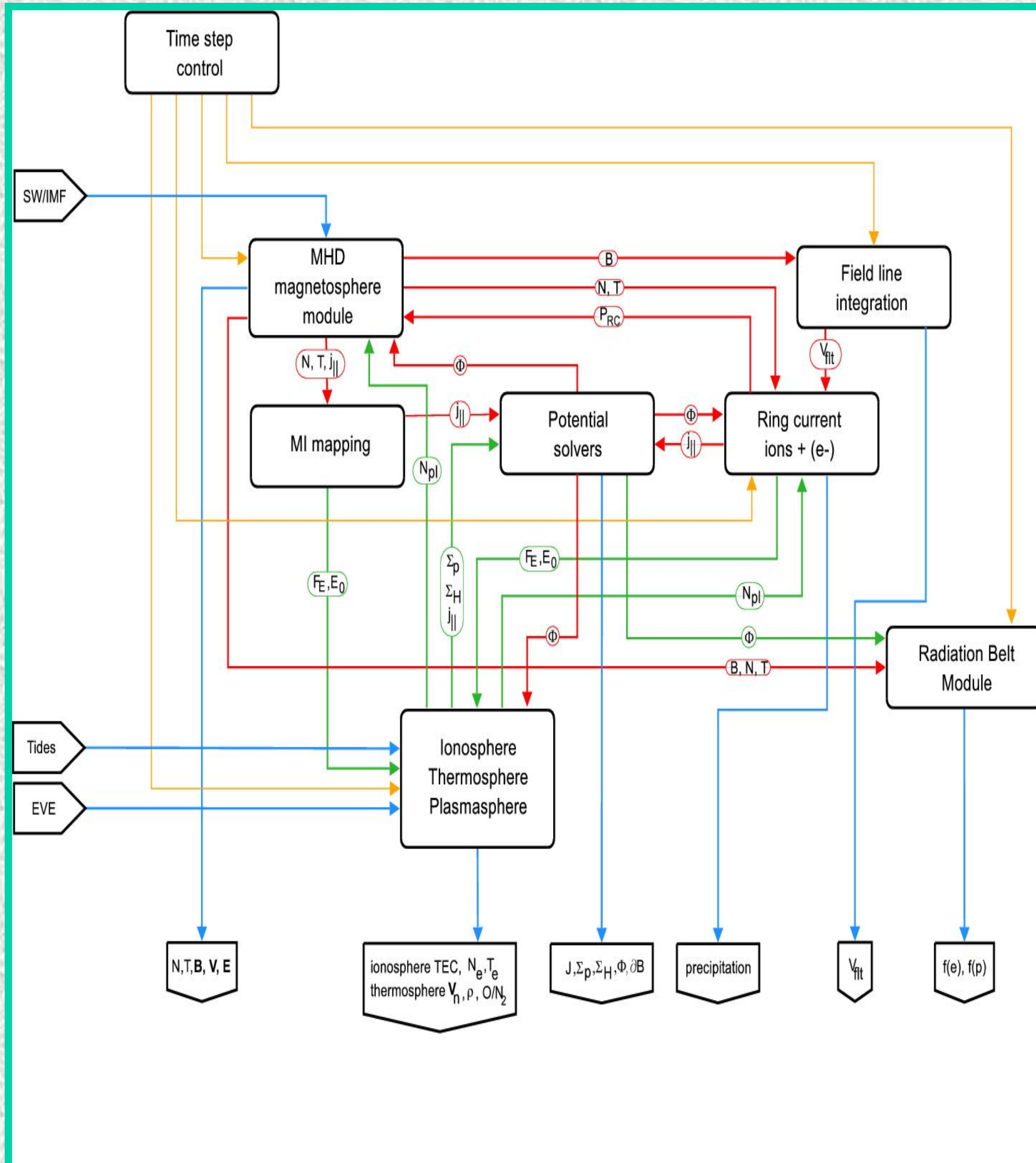
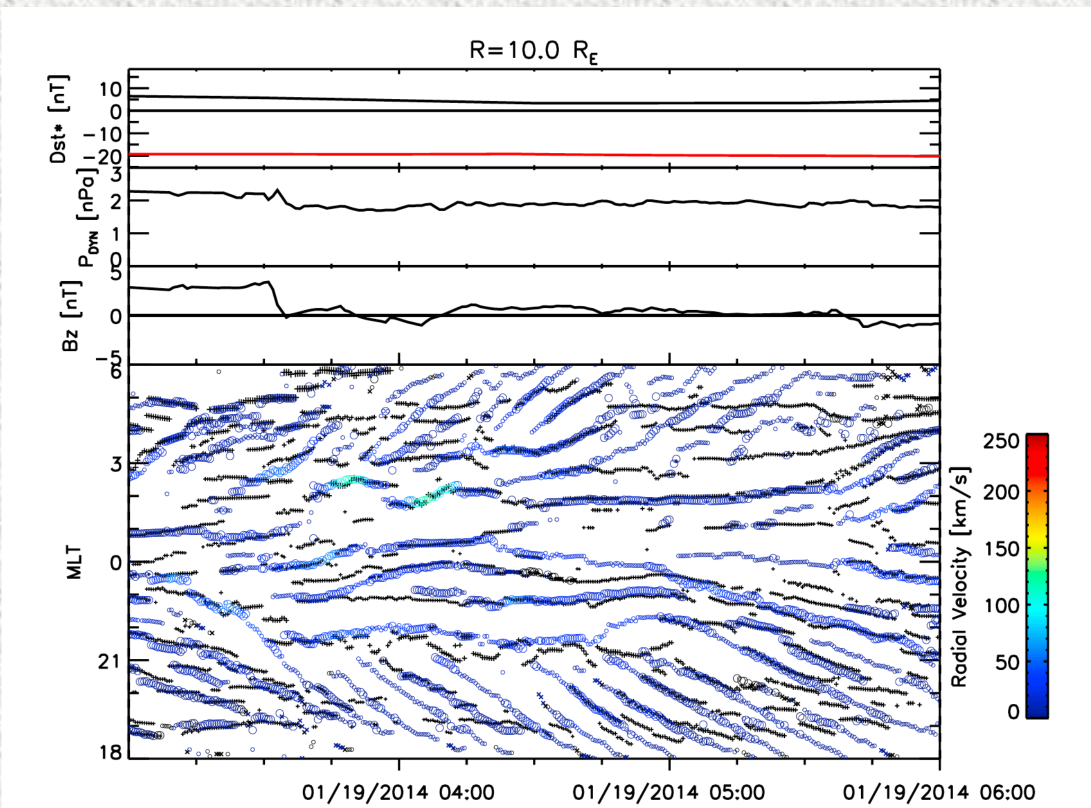
OpenGGCM-RCM-CTIM Model Data Flow

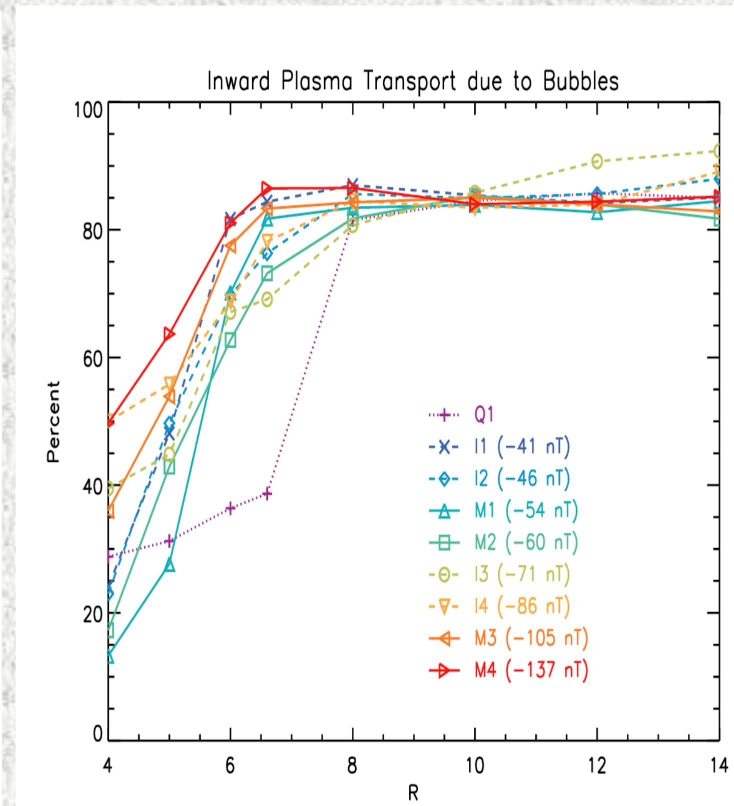
- Solving the outer magnetosphere driver → convection E-field, precipitation, R1 FAC.
- Proper solution of the inner magnetosphere → ring current, partial ring current, precipitation, R2 currents.
- Proper IT modeling → e-densities, conductances, neutrals, recombination, etc.
- All coupled with the appropriate feedbacks.



Coupling With RCM

- 10+ years in the making.
- Metric of success: paper published: Cramer, W. D., J. Raeder, F. R. Toffoletto, M. Gilson, and B. Hu, Plasma sheet injections into the inner magnetosphere: Two-way coupled OpenGGCM-RCM model results, *J. Geophys. Res.* , 122, 5077-5091, 2017. (DOI: 10.1002/2017JA024104).
- Key points: BBF ← → Bubbles, transport due to bubbles.





A New Word: GKEYLL

- Developed at Princeton PPPL (A. Hakim, L. Wang et al.)
- Goal: beyond MHD → multi-fluid (w/e-), higher order moments, Vlasov, …
- Comparable to full particle kinetic codes.

- A computational framework for **Continuum Fluid and Kinetic** Simulations
  - Models: Multi-Fluid, Gyrokinetics, Vlasov-Maxwell
  - Schemes: Finite-Volume (robust and fast); Discontinuous-Galerkin (higher than 2nd order accuracy)
- Easy deployment and flexible user interface
- Coupled into OpenGGCM to provide the Multi-Fluid solver
- On track to deliver to CCMC, including a built-in ionosphere
- Post-processing: built-in Python library + native support by community tools like ParaView and VisIT
- Online user portal: `http://gkyl.readthedocs.io`

Examples of published applications of Gkeyll

- Multi-Fluid:
  - Local collisionless reconnection
  - Global 3d magnetospheric dynamics of Ganymede and Mercury
  - Reconnection of partially ionized solar plasmas
- Gyrokinetic
  - Parallel plasma transport in the scrape-off layer of JET tokamak
- Vlasov
  - Solar wind turbulence
  - Ion acceleration in electrostatic shocks
  - Nonlinear saturation of the Weibel instability

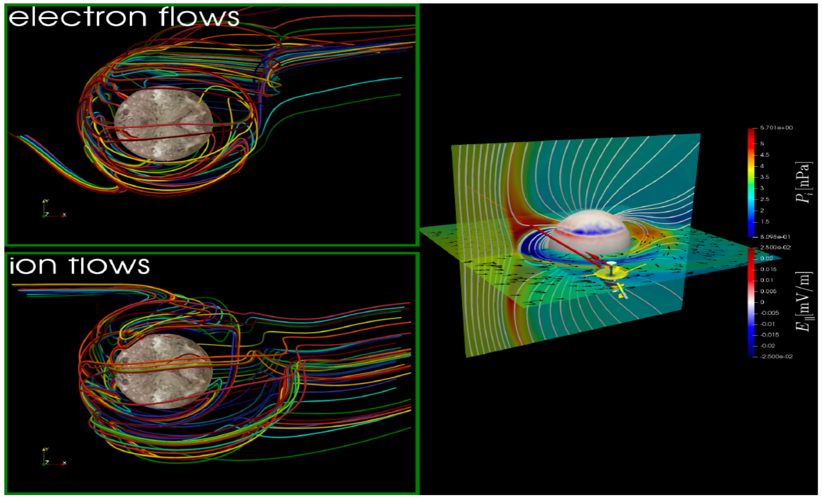


Figure: Global structure of the magnetosphere of Ganymede (right) and electron and ion bulk flow patterns (left).

- Comparison of multi-fluid moment models with particle-in-cell simulations of collisionless magnetic reconnection, L Wang, AH Hakim, A Bhattacharjee, K Germaschewsk, Physics of Plasmas 22 (1), 012108, 2015.
- Electron Physics in 3D Two-Fluid Ten-Moment Modeling of Ganymede's Magnetosphere, Liang Wang, Kai Germaschewski, Ammar Hakim, Chuanfei Dong, Joachim Raeder, Amitava Bhattacharjee, JGR, accepted, 2018.

3D multi-fluid simulations of Ganymede

- Ganymede's dipole interacting with southward Jovian magnetic field
- Uses realistic ion mass but artificial electron mass and speed of light
- Correctly captures Alfven wings due to sub-sonic sub-Alfvenic inflow boundary condition
- Demonstrates roles of electrons in both local reconnection physics and global convection

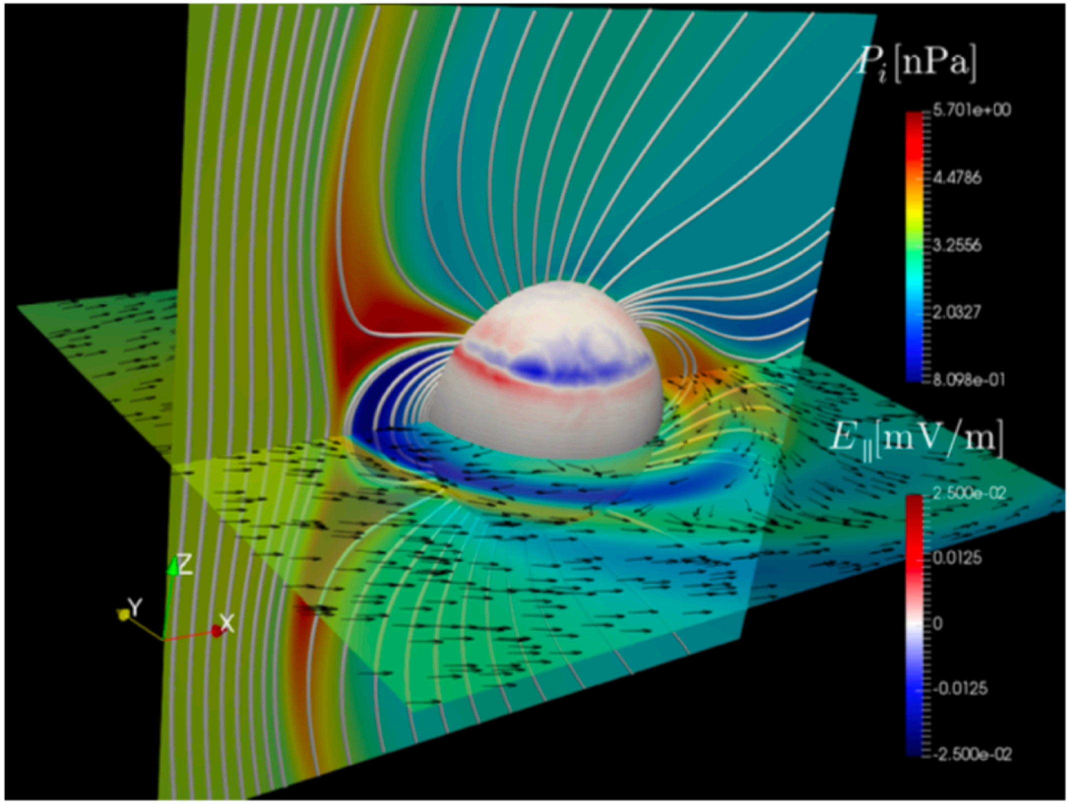


Figure: Snapshot near the Ganymede later in the simulation showing slices of ion pressure, surface parallel electric field, magnetic field lines and ion flow patterns.

Initial and boundary conditions

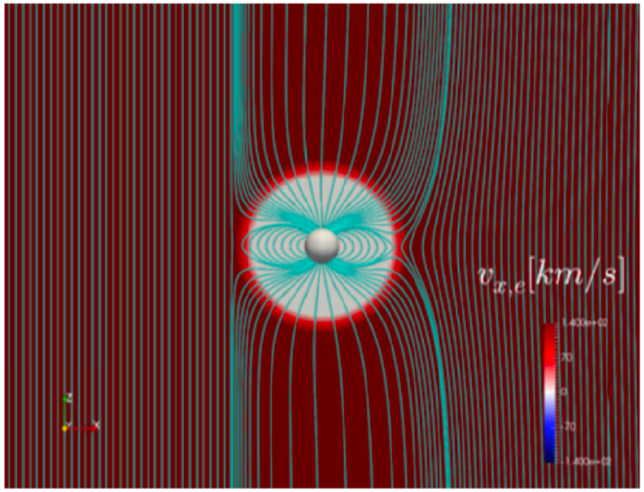
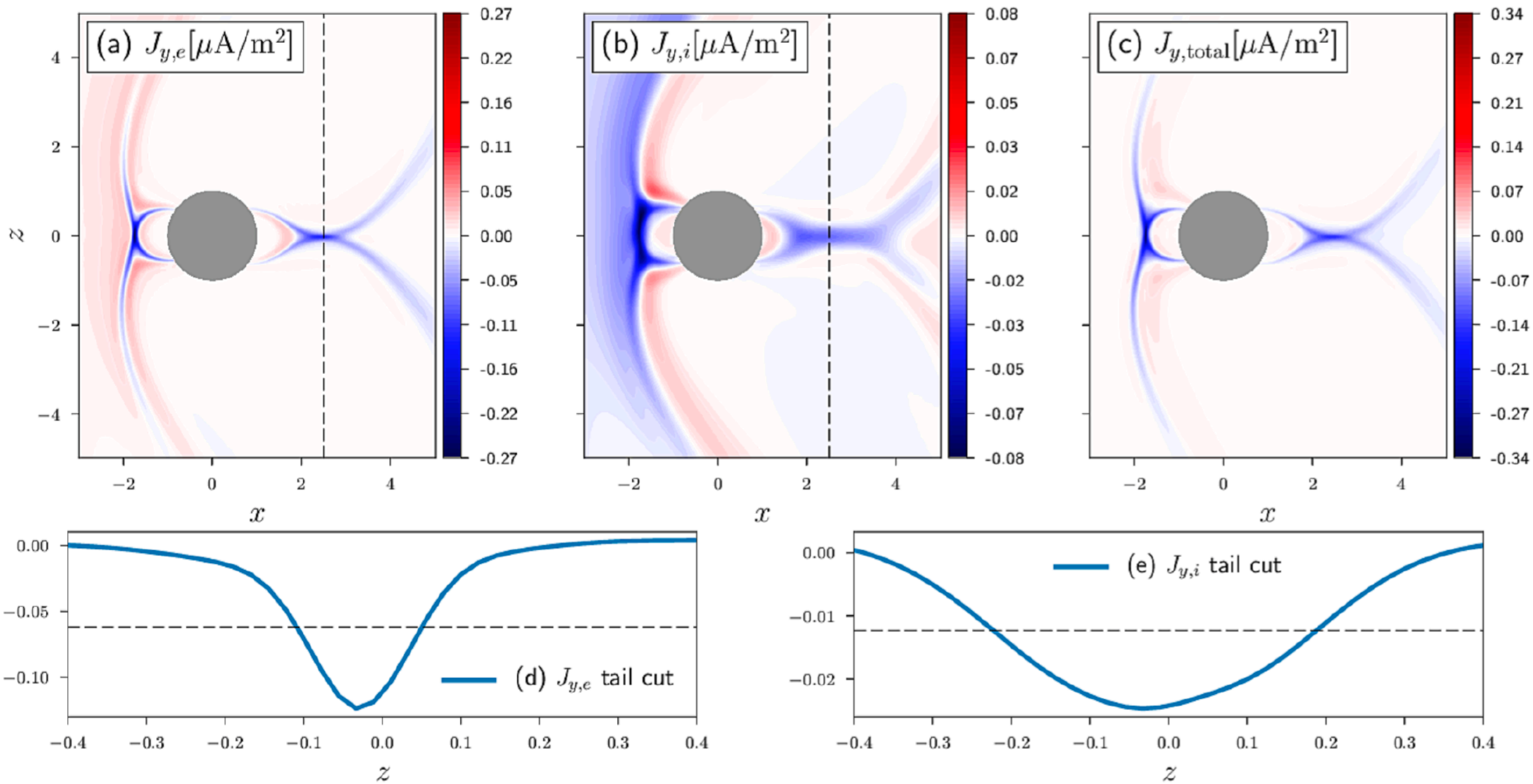


Figure: Initial flow velocity along $+x$ over magnetic field lines in the meridional plane.

- physical domain $[-64, 64]^3$ in unit of R, numerical grid $528 \times 512 \times 512$
- Ganymede is at origin, Jovian plasmas flow in from $-x$
- inflow Jovian: $B \sim (0, -6, -77)\,\mathrm{nT}$, $\rho \sim 56\mathrm{amu/cm}^3$, $p \sim 3.8\mathrm{nPa}$, $v_x \sim 140\mathrm{km/s} \Rightarrow M_s \sim 0.56$, $M_A \sim 0.62$
- Ganymede: $R \sim 2634.1\mathrm{km}$, surface dipole field $B_0 \sim (-18, 51.8, -716.8)\,\mathrm{nT}$

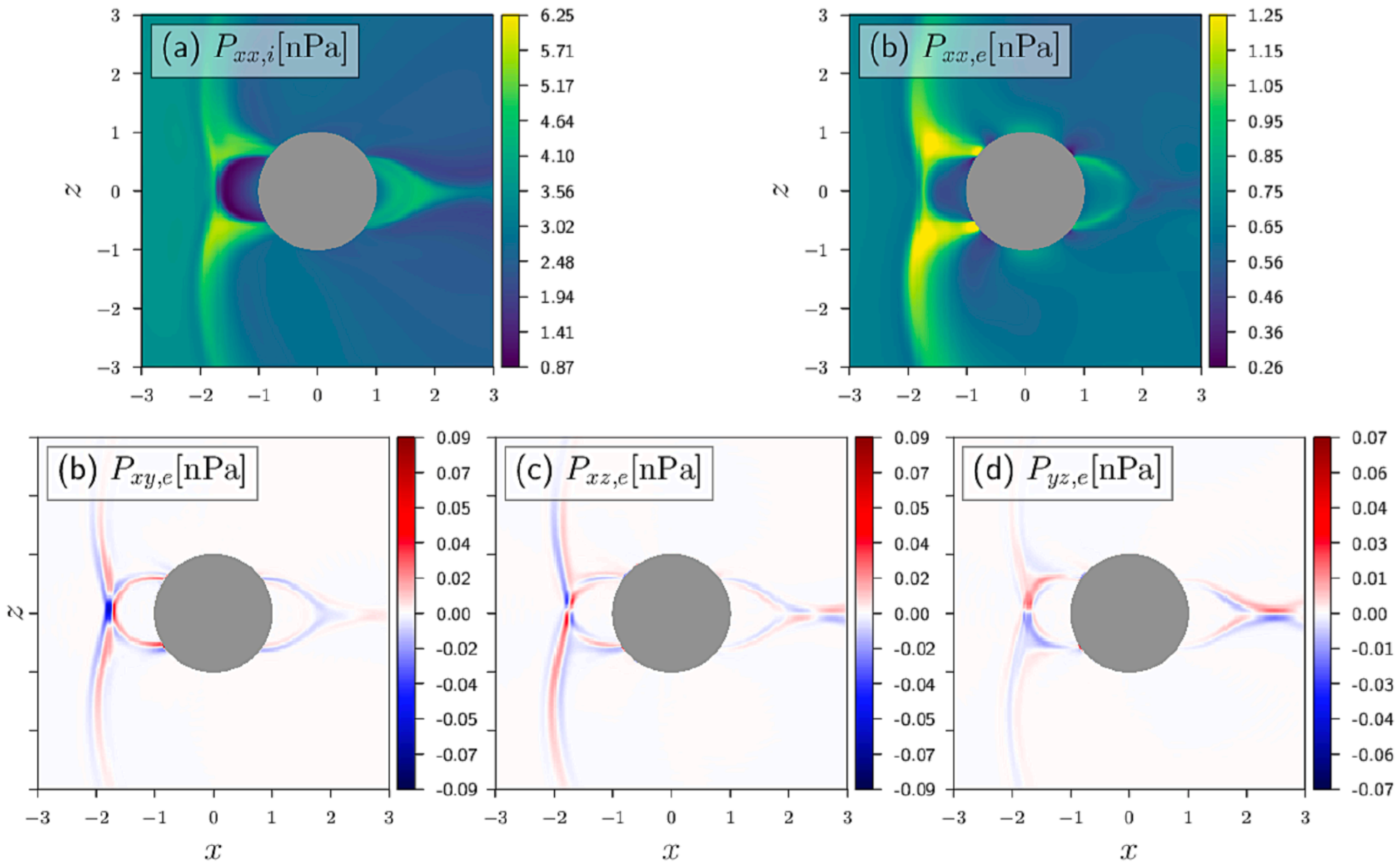
- $d_{i,\mathrm{Jovian}} \sim 0.2R$, $m_i/m_e = 25$, $p_i/p_e = 5$, $c = 6000\mathrm{km/s}$, $\Delta x_{\min} \sim d_i/10 \sim d_e/2$
- 10-moment closure, $k_e = 1/d_e$, $k_i = 1/d_i$ updated locally every time step
- fixed values at $-x$; floated values at $+x$, $\pm y$, and $\pm z$
- at radius $= R$, ghost cell values are constant ρ and p, $\rho\mathbf{v}$ radially reversed, $\mathbf{B_1}$ radially reversed, $\mathbf{E} = 0$
  - no induction layer

Reconnection physics 1: ion / electron scales



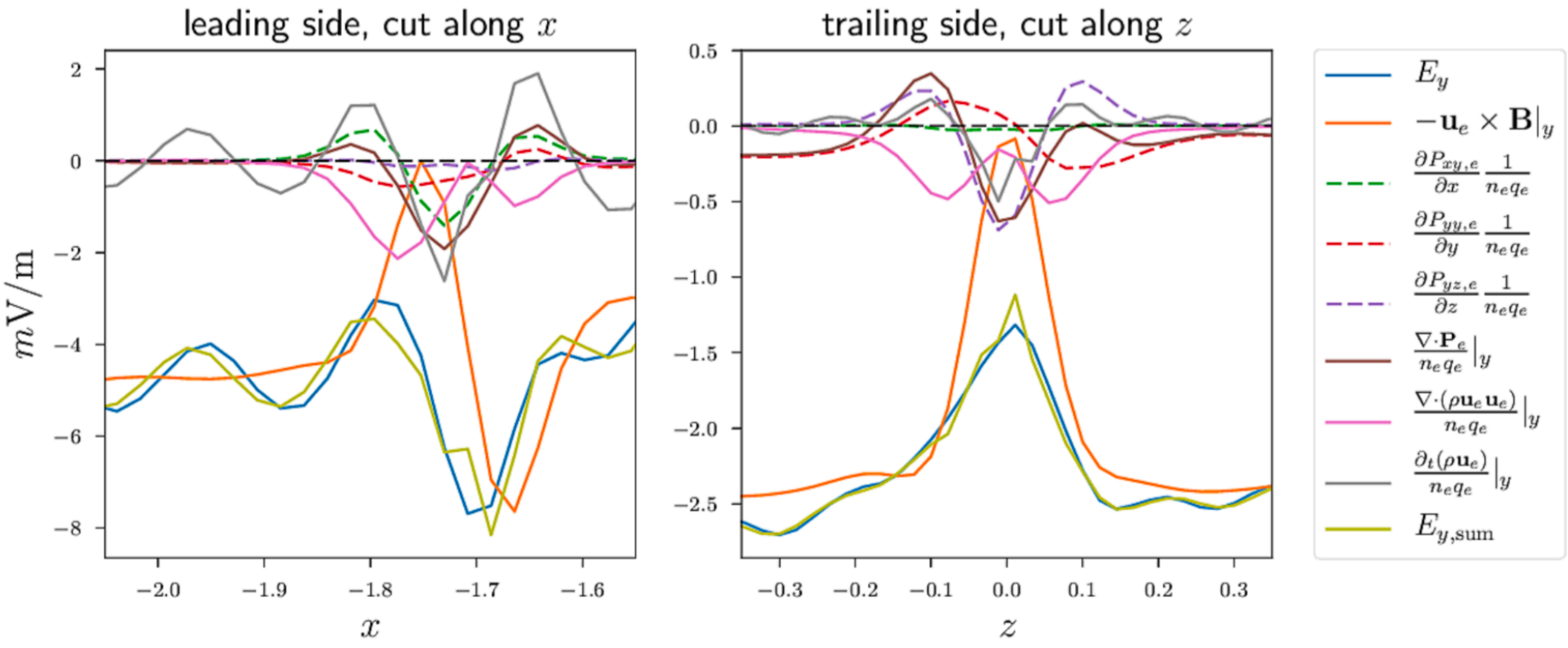
- currents carried mainly by electrons
- $J_{y,e}$ half-thickness $2d_e$; $J_{y,e}$ half-thickness $1d_i$;

Reconnection physics 2: pressure tensor

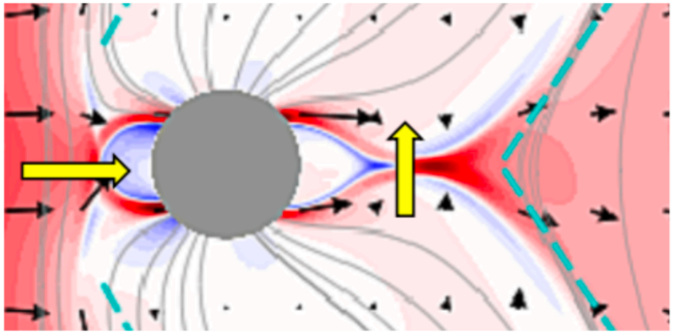


- $P_{xx,e}$concentration near foot-points
- $\mathbf{P}_{off,e}$ is small in magnitude but highly structured
- $\mathbf{P}_{off,e}$polarities agree with local 2D PIC/Vlasov studies

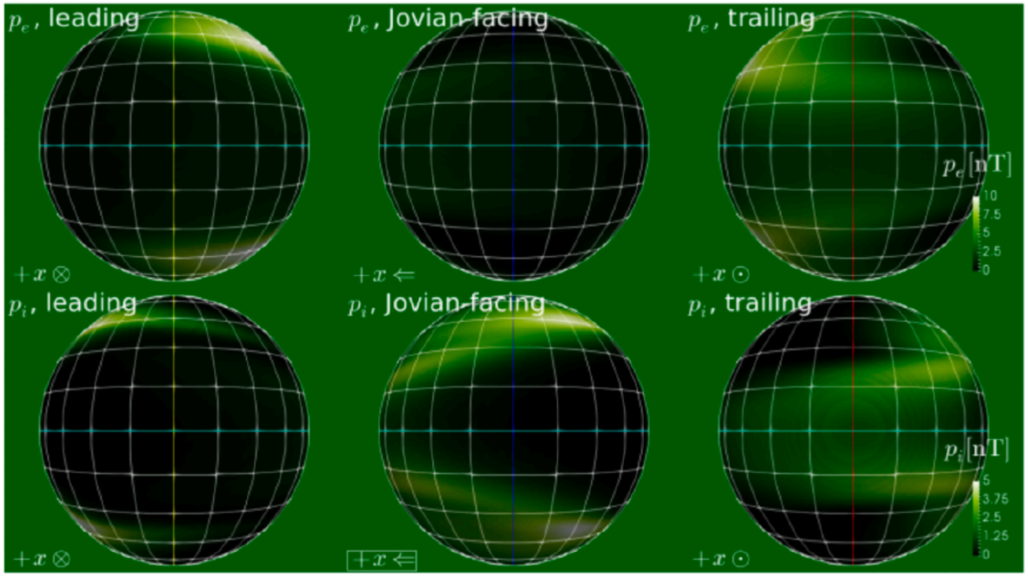
Reconnection physics 4: Ohm's Law decomposition



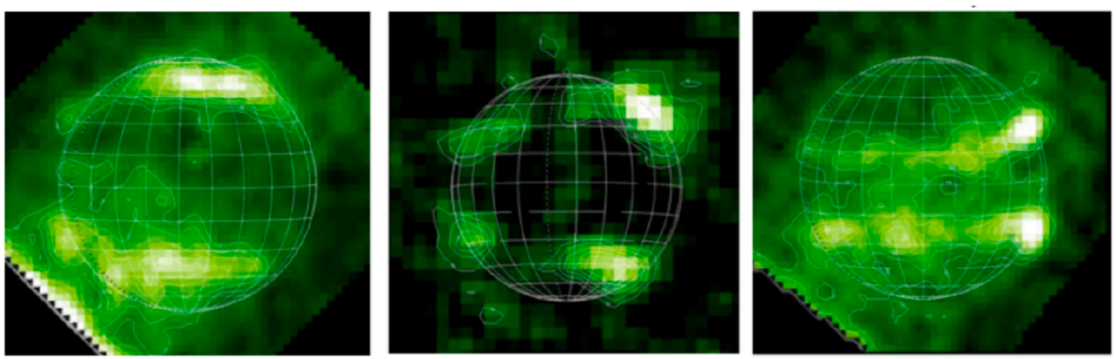
- $\nabla \cdot \mathbf{P}_e$ important on both reconnection sites
  - leading side, $\partial P_{xy}/\partial x$, $\partial P_{yy}/\partial y$
  - trailing side, $\partial P_{yz}/\partial z$, $\partial P_{yy}/\partial y$
- inertia terms also significant



Surface brighness



↑ simulation, pressures ↓oxygen emission from HST (McGrath2013)



- "brightness" represented by surface pressure, not from rigorous semi-empirical models
- captures some key features of observations
- p_e and p_i show different polarities

Multi-fluid simulations of Earth

- First simulations with Earth parameters and coupled ionosphere look reasonable.

Issues

- Resolution requirements: need to resolve d_i, d_e to give trustworthy results and avoid instability (as opposed to Hall-MHD, which gracefully degrades to MHD). 300 x 100 x 100 R_E box with .01 R_E resolution: 30000 x 10000 x 10000 grid points...
- Boundary conditions are really only defined in terms of MHD quantities (solar wind, ionosphere potential -> $E \times B$ velocity, while gkeyll wants rho, v, p per species, E, B)

$\Longrightarrow$ **multi-physics simulation**

Blending multi-fluid and MHD

Finding multi-fluid (electron + ion) quantities from single-fluid MHD:

- **E** directly from MHD
- **E** from Ohm's Law
- $\mathbf{v_s}$ from MHD momentum and current density
- ρ_s from ρ_{MHD} and assumptions (e.g., quasi-neutrality, $\rho_c = \nabla \cdot \mathbf{E}$)
- p_s from p_{MHD} and assumptions (e.g., fixed temperature ratio; preserve temperature ratio)

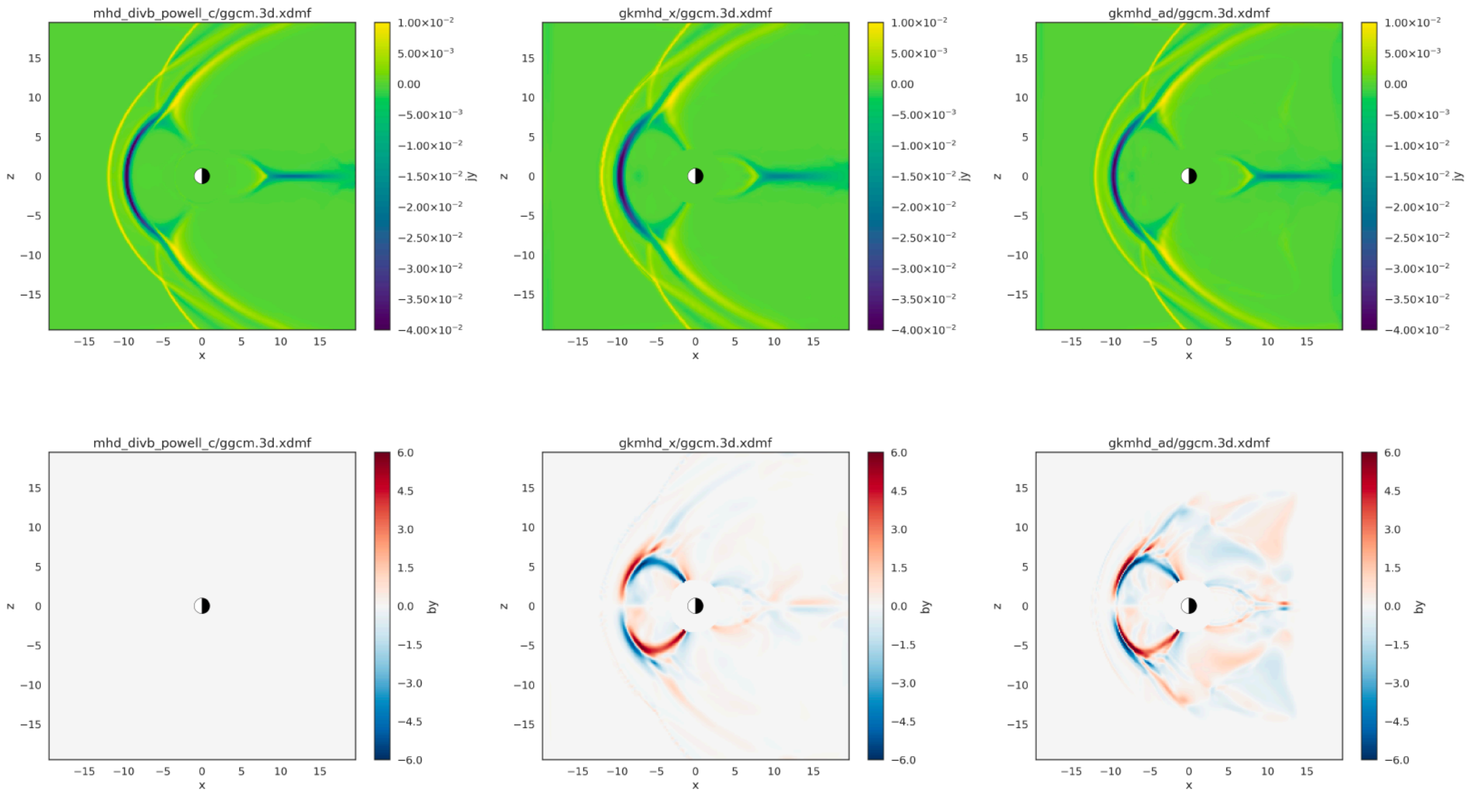
This all builds on transitioning to MHD in regions where gradients are smooth enough that multi-fluid mostly behaves like MHD already.

Blending OpenGGCM

MHD | multi-fluid | blended

j_y

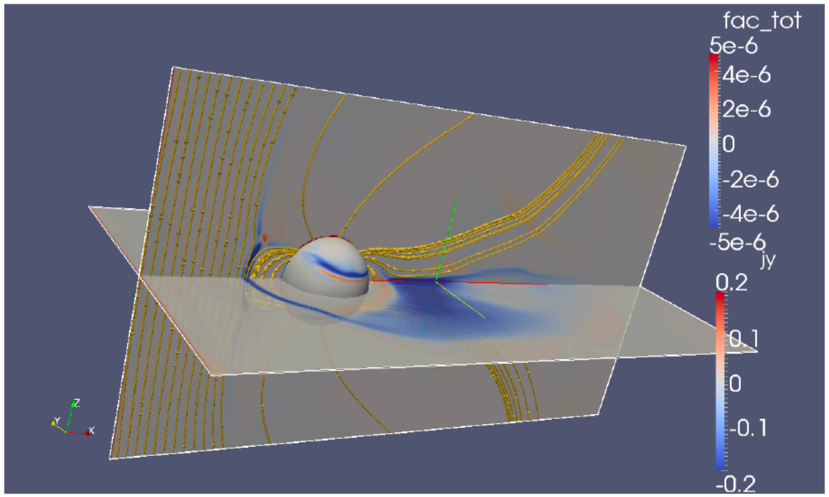
B_y



Blended: gkeyll for $r < 13R_E$, MHD otherwise

Our deliverable

Next generation OpenGGCM



- Options for fluid plasma models (MHD, Hall-MHD, multi-fluid, pressure tensor closures)
- Adaptive mesh refinement
- Implicit time integration
- Coupled to CTIM (done), IPE (in progress), RCM (done).

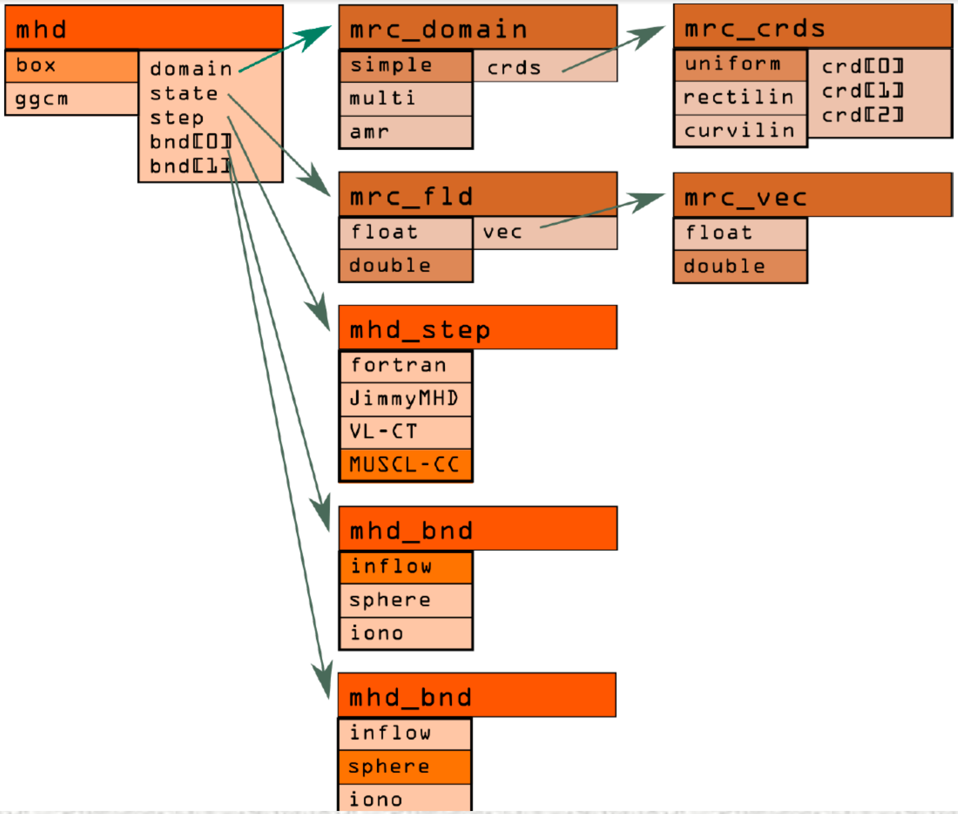
New components available as open source (LGPL), whole model to be delivered to CCMC.

solar wind b.c.	ionosphere b.c.	CTIM	RCM		openggcm
reconstruct	Riemann	divB	MHD	gkeyll	libmrc/mhd
multi-d fields	domain decomp	mesh refinement	I/O		libmrc/base

Modular OpenGGCM

LIBMRC

LIBMRC started out as a collection of commonly used code for solving domain-decomposed PDEs. It forms the basis of three complex codes: MRCV3, PSC and OPENGGCM.



Plasma fluid models in OpenGGCM

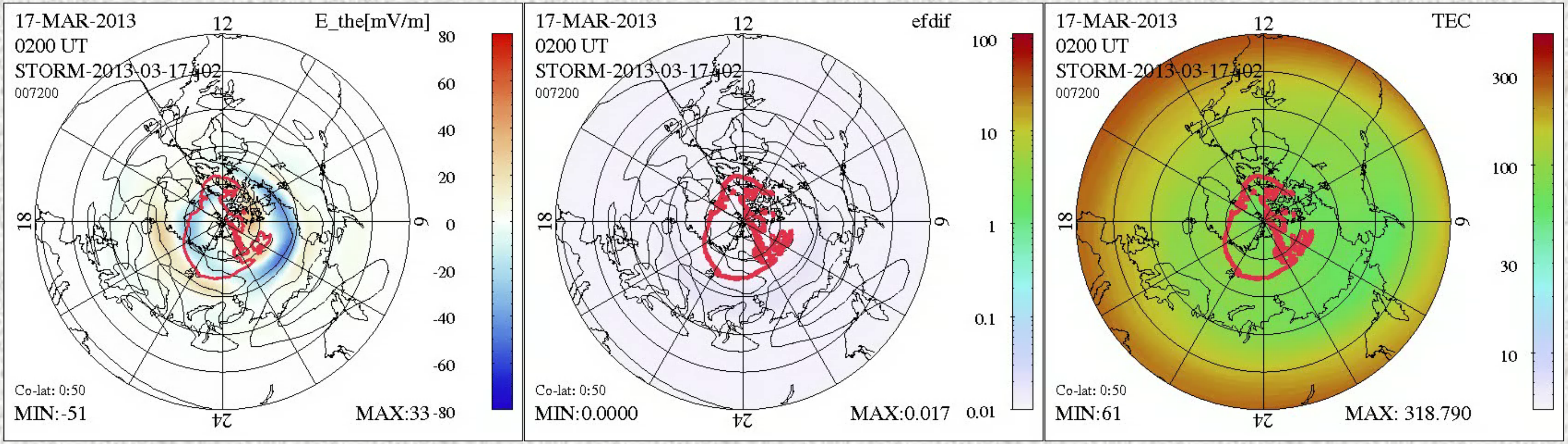
It is now possible to replace the existing MHD solver in OpenGGCM with various options:

- Jimmy-MHD + Hall
- CWENO + CT (Ziegler, 2004)
- VL + CT (Stone & Gardiner, 2009)
- direct coupling to ATHENA
- MUSCL-type cell-centered schemes with hyperbolic/parabolic divB cleaning
- coupling to GKEYLL multi-fluid moment code

LIBMRC: staggered AMR

- LIBMRC supports 2D/3D AMR on staggered grids, as required for FDTD / constrained transport.
- Standard schemes translate straight-forwardly: work as usual one patch at a time, LIBMRC takes care of flux correction and constrained transport.
- At coarse-fine boundaries, face-averaged fluxes from fine grid are used to correct coarse grid.
- Coarse-grid E-fields are corrected by line-averaged fine-grid E-fields.
- $\nabla \cdot B$ preserving restriction / prolongation based on Toth et al., 2004
- parallelization using space-filling Hilbert-Peano curve
- filling ghost-cells, flux correction, E-field correction are expressed as (parallelized) sparse-matrix computatons.

North-South E field, Precipitation, and TEC

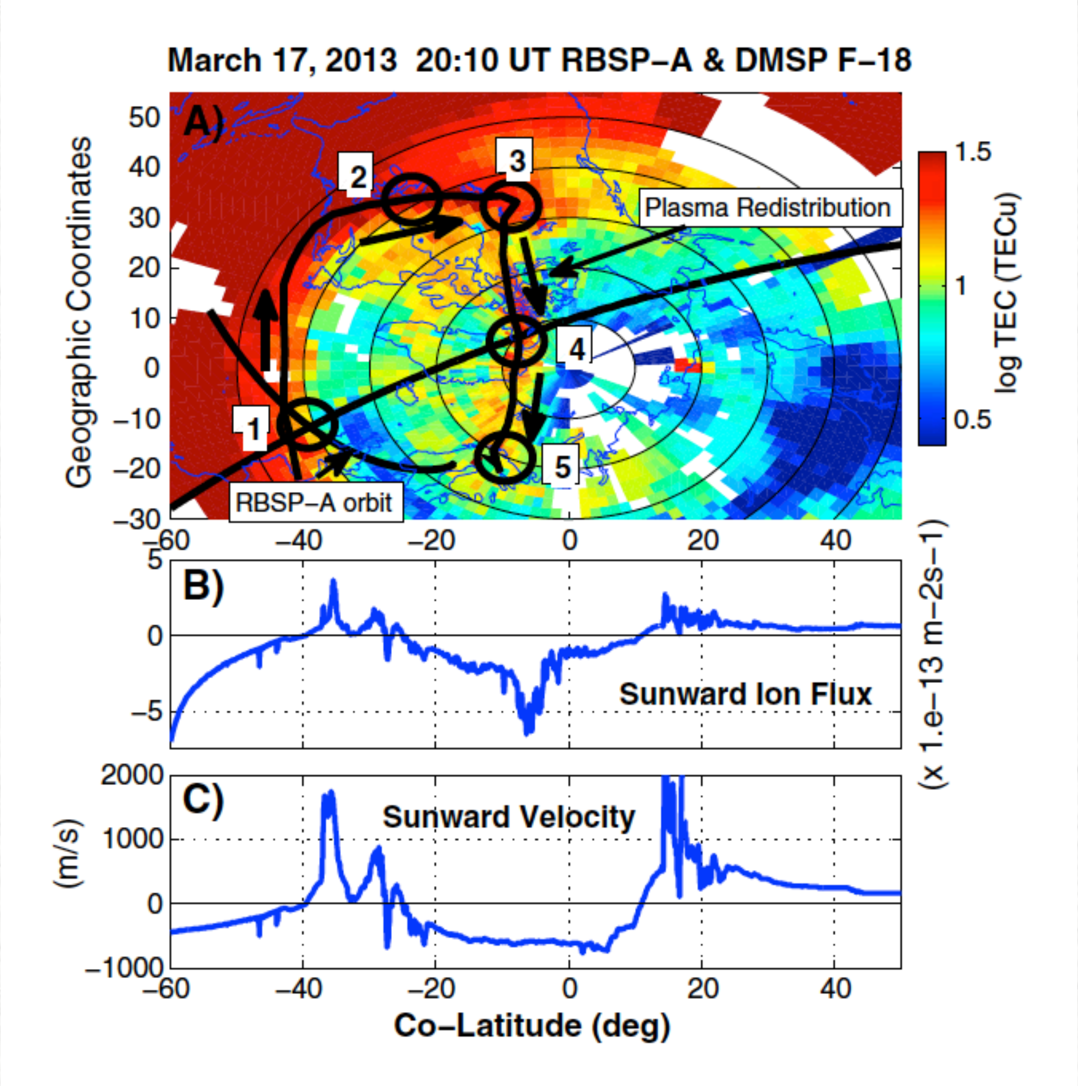


- The red line shows the polar cap boundary.
- Thin contours are FAC.
- PC expands quickly as IMF turns southward.
- Strong northward electric field develops well equatorward of PCB, and **just** equatorward of of precipitation (current continuity and Ohm’s law).
- TEC trough is co-located with electric field, but takes some time to develop.
- → LWS funding now

Storm Enhanced Density (SED)
Tongue of Ionization (TOI)

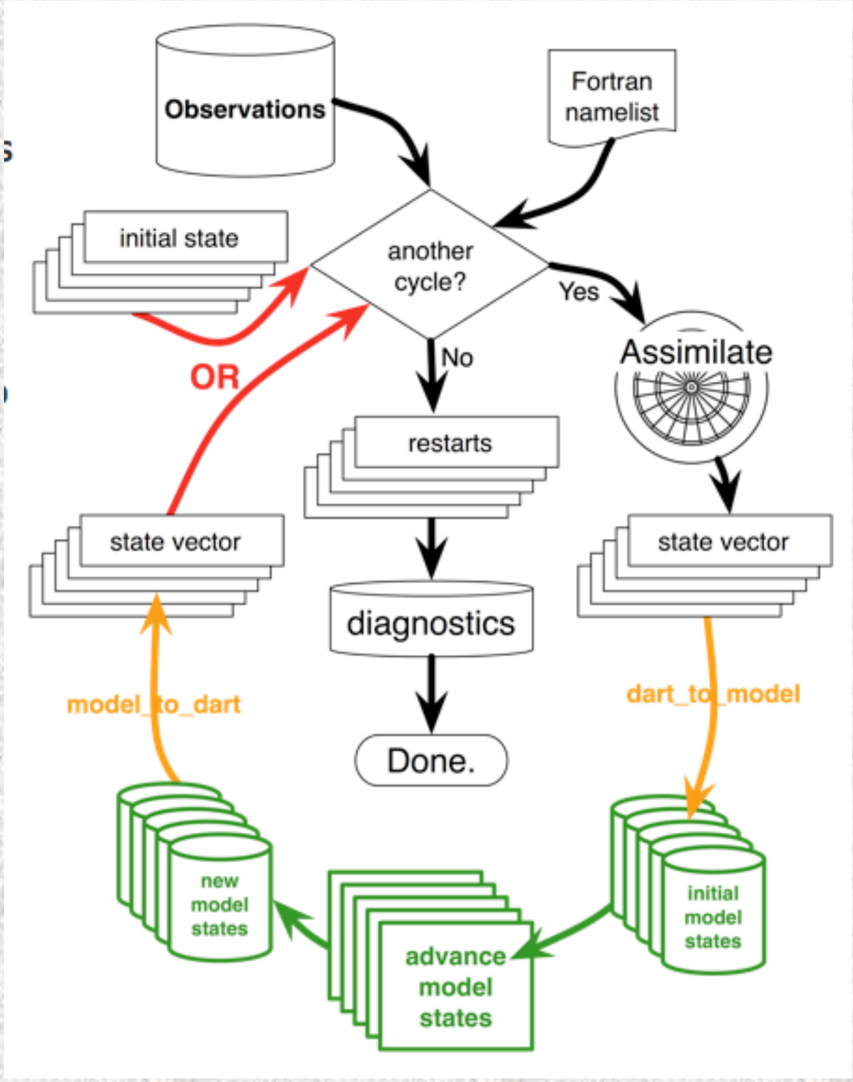
- The sunward convection associated with SAPS drives plasma into the dayside (1).
- High solar UV/EUV flux increases ionization and e- density (2), forming a region of storm enhanced density.
- When the flow turns tailward again (3), it is driven to higher altitude due to field line inclination (4). This forms the Tongue Of Ionization (4,5).
- We have yet to find this in the simulations. There are some issues with CTIM vertical transport, which should get resolved with IPE.

Foster et al., GRL, 2014 →



OpenGGCM – DART Data Assimilation

- DART: Data Assimilation Research Testbed. Ensemble Kalman Filter (EnKF) environment developed at NCAR.
- Determined the relevant prognostic and diagnostic variables.
- Grids and coordinates (a bit different than atmosphere and ocean.)
- Programmed data exchange (netcdf requirement).
- Prepared COSMIC data.
- Determined necessary control code requirements, no restarts by model pauses.
- AFOSR funded.



Upcoming CCMC additions

- GKEYLL. Details (dimensions, closures, B.C. etc.) TBD.
- OpenGGCM v5.0: w/RCM & numerous other improvements.

Space Weather with a Cell Phone

- December 30/31, 2015 storm.
- $10 cellphone in my backyard.
- Noise ~50 nT for 1 minute averages.
- My expensive cell phone is ~5 times better: 100 samples/s, ~10 nT noise when averaged to 1 minute.
- There are >5B cell phones in the world.
- Data are useless most of the time because phones move.
- But when they don't move they can catch something interesting.
- The magnetometers in cell phones cost <$1!!