OpenGGCM New Developments

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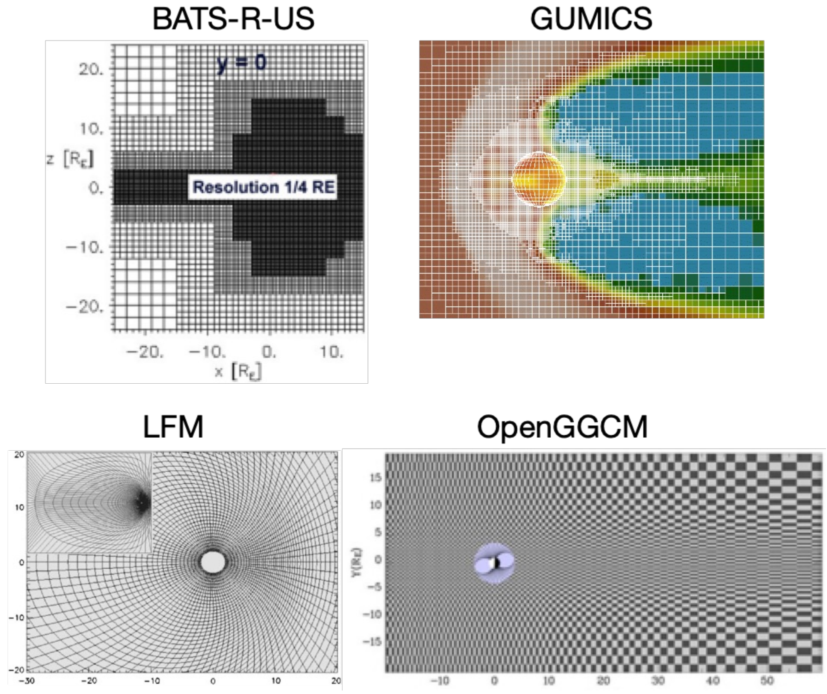
OpenGGCM

Global Magnetosphere Models

Open Geospace General Circulation Model

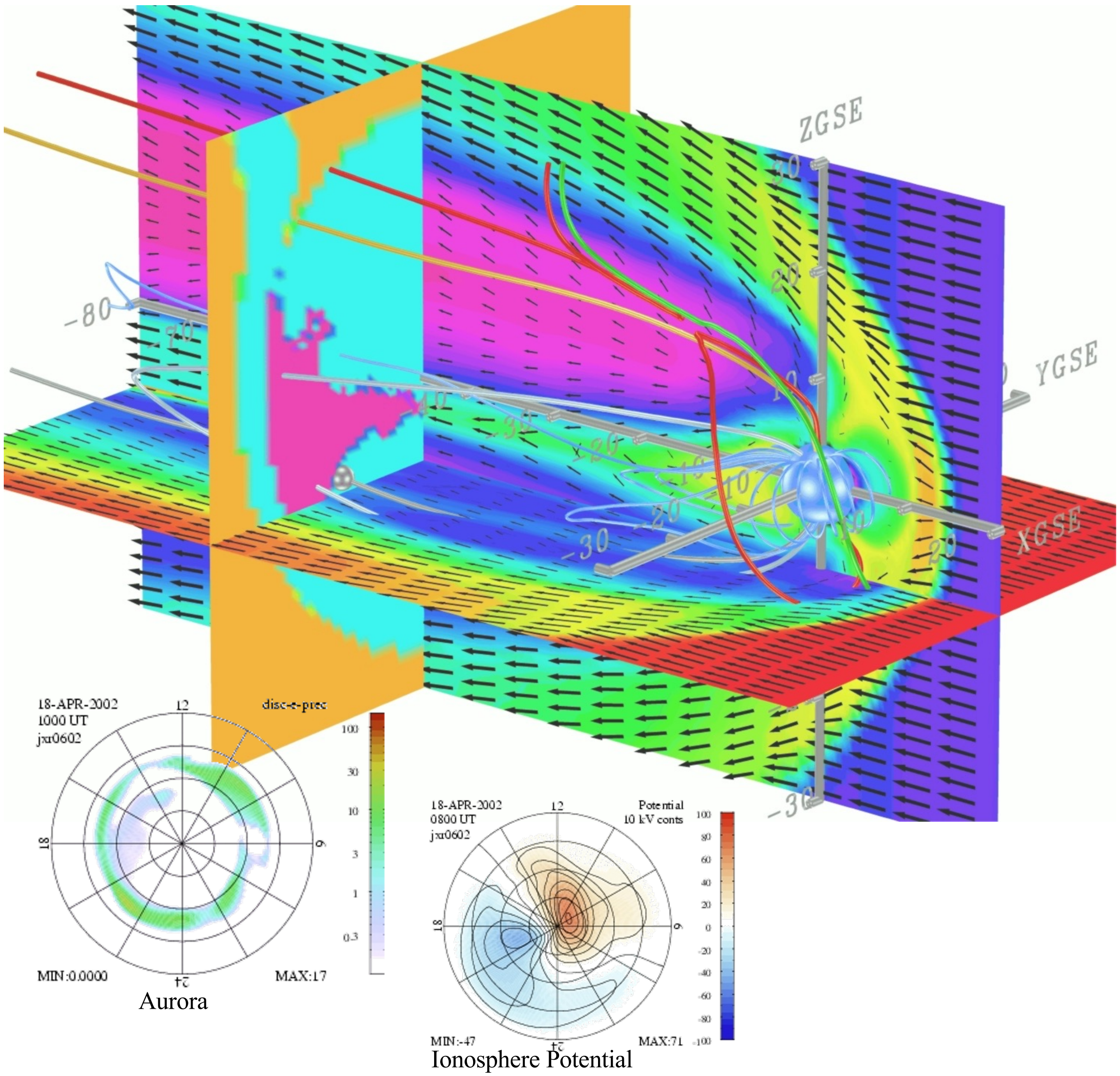
- One of a few global magnetosphere models
- All MHD, but different numerics, grid, etc.
- Two-way coupled with ionosphere-thermosphere (CTIM, IPE-in development) and inner magnetosphere models (RCM, CRCM)



	BATS-R-US	GUMICS-4	LFM	OpenGGCM
MHD equations	ideal, conservative, $B_0 + B_1$	ideal, conservative, $B_0 + B_1$	ideal, semi-conservative, $B_0 + B_1$	semi-conservative with resistivity
Solver notes	eight-wave approximate Riemann	mostly Roe, subcycling, $\nabla \cdot B$ cleaning	total variation diminishing (TVD), constrained transport (CT)	TVD, CT
Order of MHD discretization: spatial / temporal	2 / 2	1 / 1	8 / 2	4 / 2
MHD grid	Cartesian, static, block-refined	Cartesian, dynamic, cell-refined	distorted spherical, static, not refined	stretched Cartesian, static, not refined
Dipole tilt updated with time	yes	no	yes[a]	no
Coordinate system of magnetosphere	GSM	GSE	SM	GSE

[a]The dipole orientation is fixed in SM coordinates, but solar wind and solar EUV conditions are adjusted with time.

OpenGGCM



- NASA/THEMIS mission support
- Mission planning
- Kelvin- Helmholz instabilities (*Kavosi et al., 2018*)
- Reconnection rates (*Connor et al., 2014, 2015; Jensen et al., 2017*)
- Storms (*Raeder et al., 2001; Cramer et al., 2017*)
- Substorms (*Raeder et al., 1998; Raeder et al., 2008; Ge et al., 2011*)
- Ionosphere (*Ferdousi & Raeder, 2016; Gilson et al., 2012; Raeder, Zhu, et al., 2013*)
- Shocks (*Connor et al., 2014; Oliveira and Raeder, 2015; Shi et al., 2017*)
- Magnetosphere X-ray imaging (*Connor and Carter, 2019*).
- Funding from NASA/LWS, NASA/TR&T, NSF/GEM, NSF/ITR, NSF/PetaApps, AFOSR programs.

OpenGGCM Development Team

University Of New Hampshire

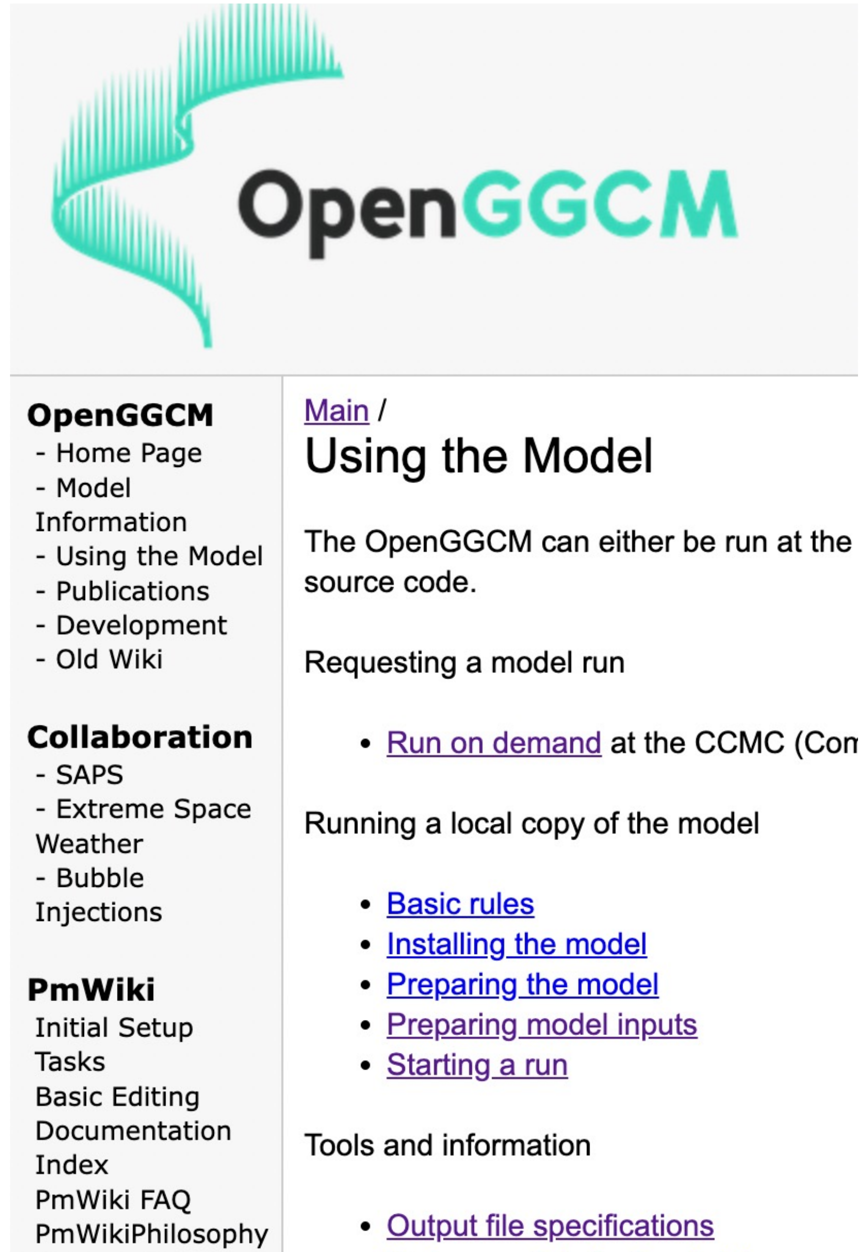
- Jimmy Raeder – main contact, general development
- Doug Cramer – RCM, CRCM, general development
- Kai Germaschewski - general development

Non-UNH Collaborators

- Bashi Ferdousi – ionosphere models
- Tim Fuller-Rowell – CTIM
- Naomi Maruyama – IPE
- Frank Toffoletto, Sina Sadeghzadeh – RCM
- Mei-Ching Fok – CRCM

Model Info/ Access

- CCMC (v4 and v5)
- GitHub repository (github.com/unh-hpc/openggcm)
- Wiki (openggcm.sr.unh.edu)



Model Info/Use

Collaborative Projects

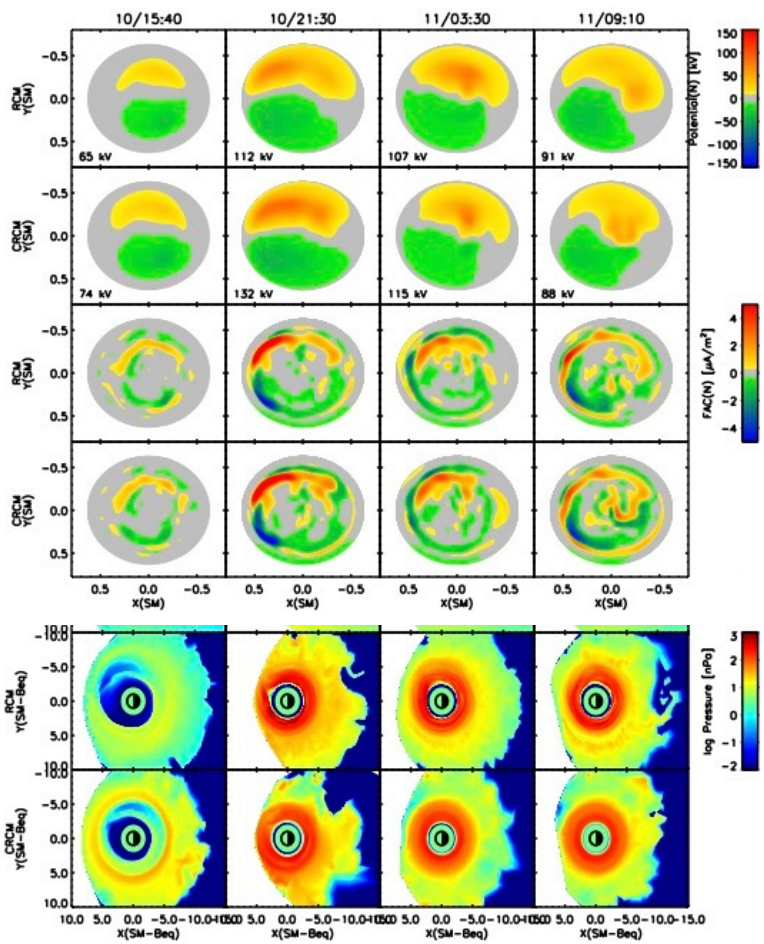
Developments

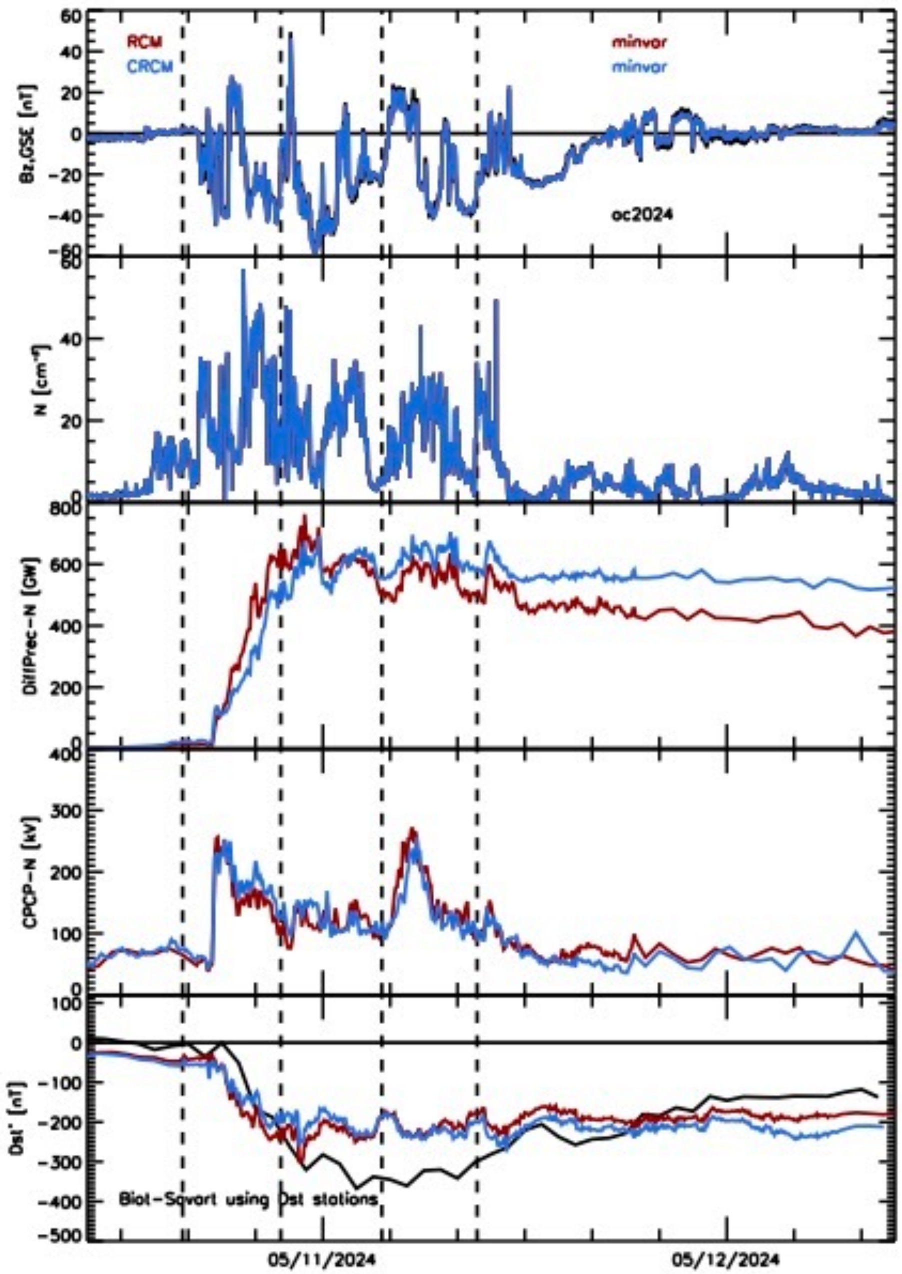
- Version 5 has been hosted at CCMC since 2022
- CRCM coupling – not available at CCMC yet
- OpenGGCM Conference March 11-13, 2024 at UNM/AFRL with ~30 participants.
- Bashi Ferdousi and Shiva Kavosi recently took permanent positions at AFRL and will continue to work with OpenGGCM on various topics: GIC, SAPS, KH waves, etc.
- Also continued strong collaboration with GSFC, in particular Hyunju Connor and post-docs on MI coupling, particle tracing, exosphere, and x-ray emissions, and David Sibeck (with graduate student Neha Srivastava, TD – bow shock interactions), Nithin Sevadas (SW propagation effects), Mei-Ching Fok (CRCM).
- New collaborations with Vince Eccles (AFRL, ionosphere ARATHRON model) and Jay Albert (AFRL, radiation belts).

CRCM 2-way Coupling

RCM/CRCM differences

- RC domain (RCM 10/12/13 ellipse vs CRCM rb=12), also affects boundary conditions
- Energy ranges not identical (Energy invariant vs Energy)





Research in last ~2 years

- Space Weather
  - Maharana, A., W. D. Cramer, E. Samara, C. Scolini, J. Raeder, and S. Poedts (2024), **Employing the coupled EUHFORIA-OpenGGCM model to predict CME geoeffectiveness**, *Space Weather*, doi:10.48550/arXiv.2403.19873.
  - Tulegenov, B., J. Raeder, W. D. Cramer, B. Ferdousi, T. J. Fuller-Rowell, N. Maruyama, and R. J. Strangeway (2023), **Storm time polar cap expansion: interplanetary magnetic field clock angle dependence**, *Ann. Geophys.*, 41(1), 39–54, doi:10.5194/angeo-41-39-2023.
  - Gowtam, V. Sai, Hyunju Connor, Bharat S. R. Kunduri, Joachim Raeder, Karl M. Laundal, S. Tulasi Ram, Dogacan S. Ozturk, Donald Hampton, Shibaji Chakraborty, Charles Owolabi, Amy Keesee (2024), **Calculating the High-Latitude Ionospheric Electrodynamics Using a Machine Learning-Based Field-Aligned Current Model**, *Space Weather*, 22.
- Ionosphere
  - Jung, J., Connor, H. K., Carter, J.A., Koutroumpa, D., Pagani, C., and Kuntz, K.D. (2022), **Solar Minimum Exospheric Neutral Density Near the Subsolar Magnetopause Estimated From the XMM Soft X-Ray Observations on 12 November 2008**, *JGR*, e29676. doi:10.1029/2021JA02967610.1002/essoar.10507377.1.
  - Ferdousi, B., J. Raeder, E. Zesta, W. Cramer, and K. Murphy (2021), **Association of Auroral Streamers and Bursty Bulk Flows During Different States of the Magnetotail: A Case Study**. JGR, 126(9), doi:10.1029/2021JA029329.
- Machine Learning
  - Millas, D., M.-E. Innocenti, B. Laperre, J. Raeder, S. Poedts, and G. Lapenta (2020), **Domain of Influence analysis: implications for Data Assimilation in space weather forecasting**, *Frontiers*, 1-34, 2020, doi:arXiv:2009.04211.
- Various other topics
  - Liu, T Zixu, V Angelopoulos, H Zhang, A Vu, J Raeder (2024), **Magnetosheath ion field-aligned anisotropy and implications for ion leakage to the foreshock**, arXiv: 2402.01978
  - Innocenti, M.E., J. Amaya, J. Raeder, R. Dupuis, B. Ferdousi,and G. Lapenta (2021), **Unsupervised classification of simulated magnetospheric regions**, https://doi.org/10.5194/angeo-39-861-2021.

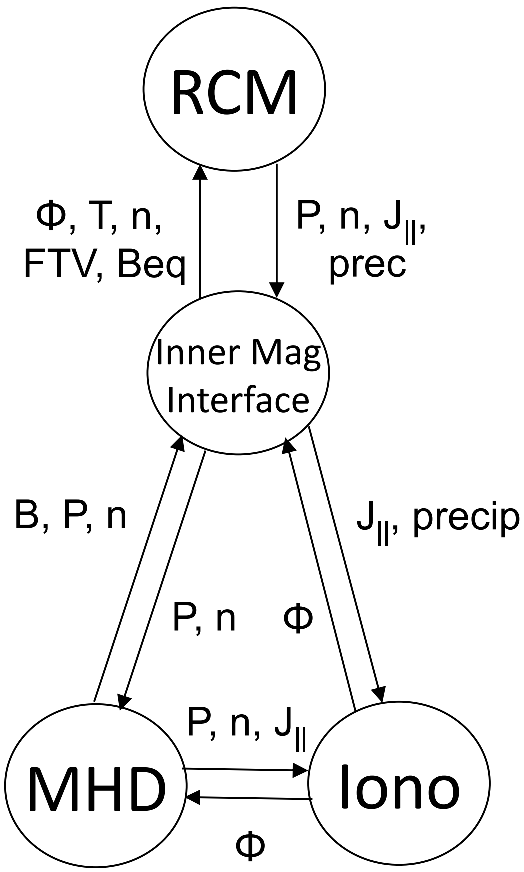
Under Development

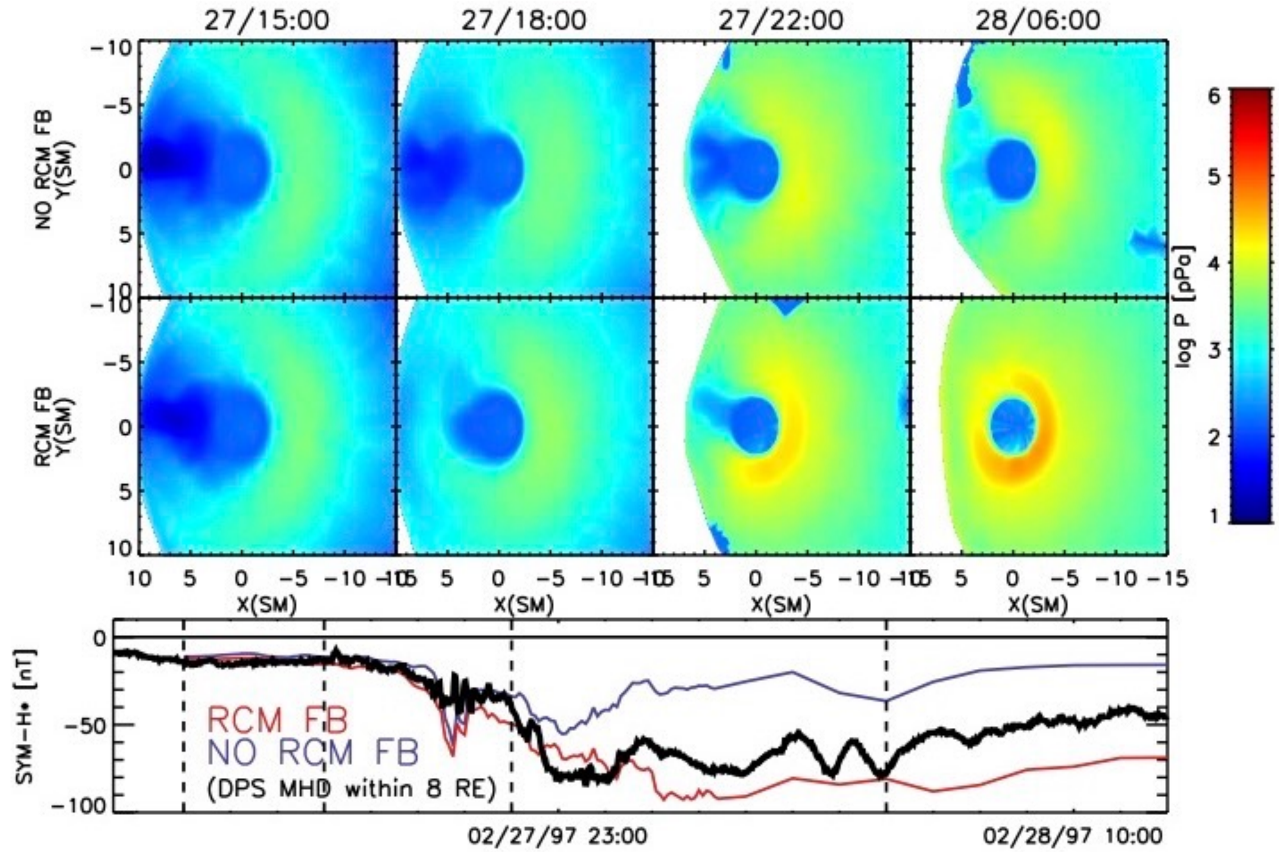
- CRCM coupling
- IPE integration
- Dipole rotation
- New visualization tools
- Static mesh refinement
- New MHD / Hall-MHD solvers
- Coupling with gkeyll to provide multi-fluid capabilities
- Flexibility to simulate systems other than Earth

Extra Slides

RCM two-way coupling

Improved representation of pressure, magnetic field, region 2 currents



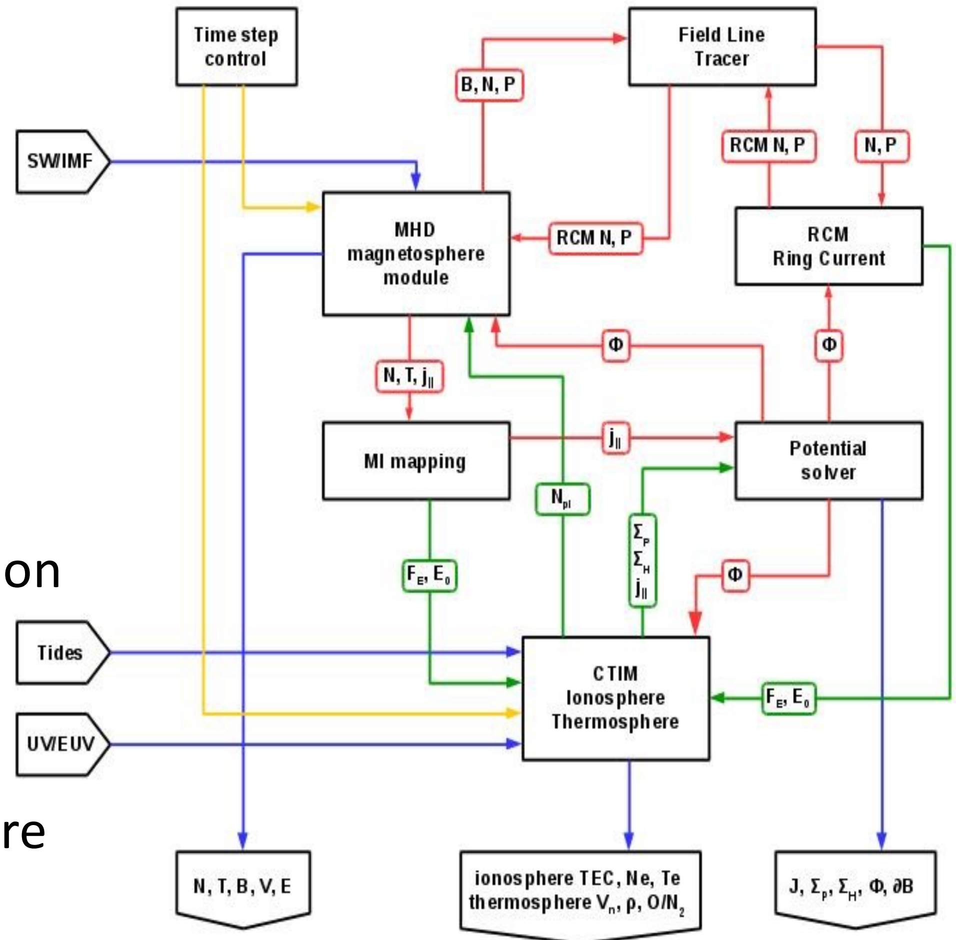


Model Components

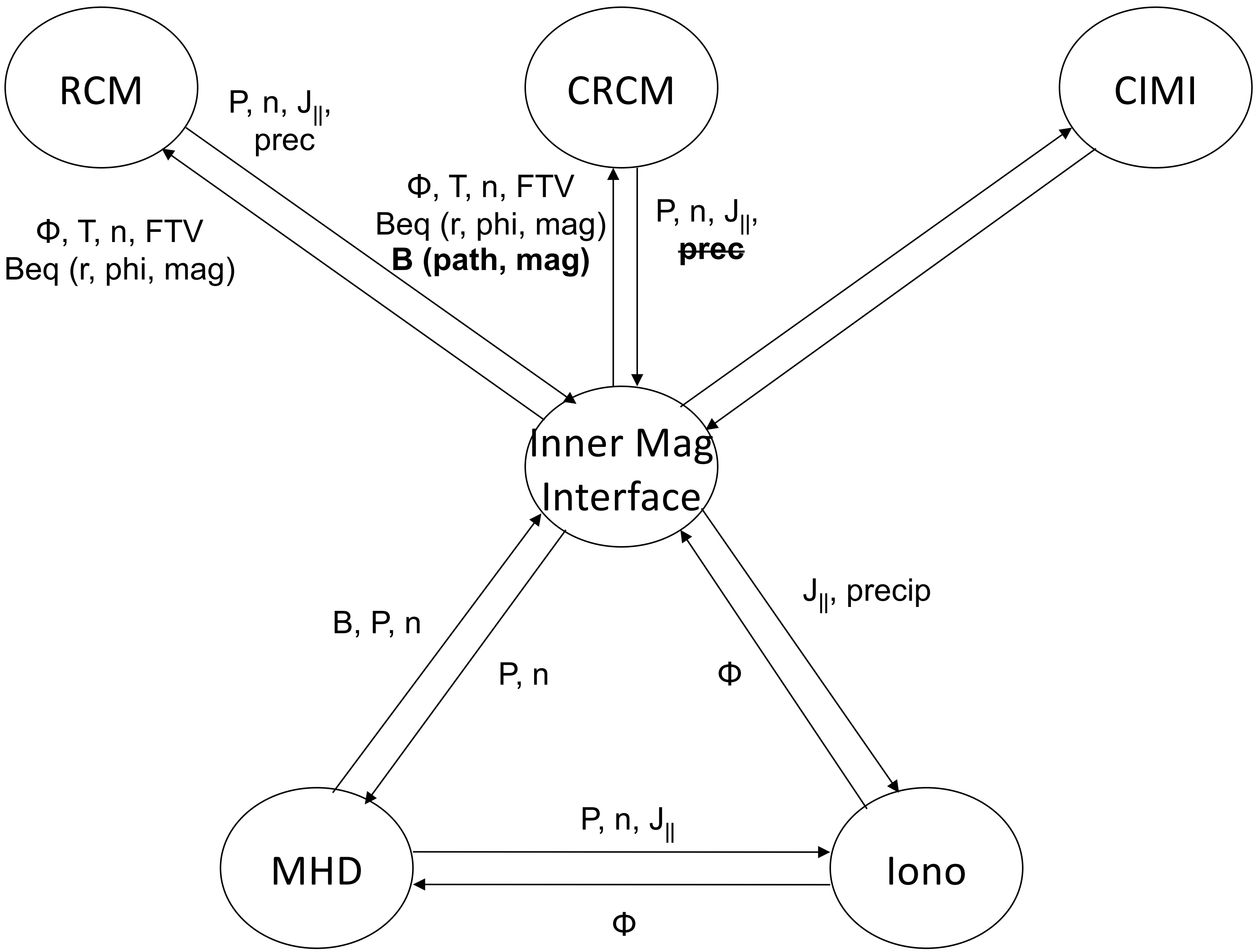
- OpenGGCM
  - 3-D stretched cartesian grid
  - Solves semi-conservative MHD equations for single fluid (plasma energy conserved)
  - Solves ionosphere potential on 2-D spherical grid using conductances, field-aligned currents
  - Two-way coupling interface for ring current models (RCM, CRCM)
  - Main inputs: solar wind plasma parameters, interplanetary magnetic field
- CTIM (Coupled Thermosphere-Ionosphere Model)
  - Models chemical and photo-chemical reactions
  - Determines conductances
  - Main inputs: FACs, auroral precipitation, solar EUV
- Ring Current Models
  - RCM (Rice Convection Model)
    - 2-D ionosphere grid representing footpoints of flux tubes
    - Solves motion of flux tubes due to potential, magnetic induction and drift
  - CRCM (Comprehensive Ring Current Model)
    - Solves bounce-averaged Boltzmann equation
  - Main inputs: outer boundary conditions, ionosphere potential

Model Coupling Methodology

- OpenGGCM -> Ionosphere
  - Sends MHD density, pressure, auroral precipitation, FAC
  - Receives Ionosphere Potential
- RCM -> Ionosphere
  - Receives Ionosphere Potential
  - Sends RCM FACs, auroral precipitation
    - Blends with MHD values
- RCM -> OpenGGCM
  - Convert flux tube content to pressure and density (and vice-versa)
  - Receives MHD pressure, density at boundary
    - Flux tube volume-weighted averages along field line
  - Sends RCM pressure, density
    - Nudge MHD P, n values (RCM influence greater in inner region)
    - RCM feedback slowly ramped up after MHD initialization period



Coupling Interface Diagram



Extra Slides