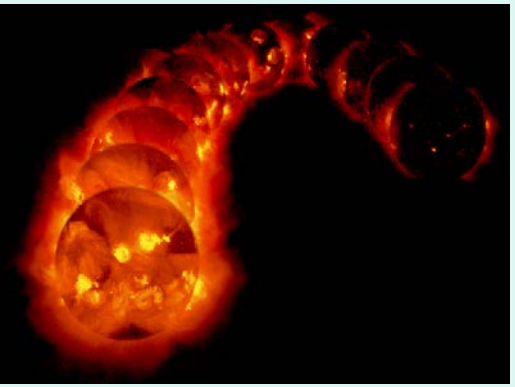
The LANL SHIELDS Project

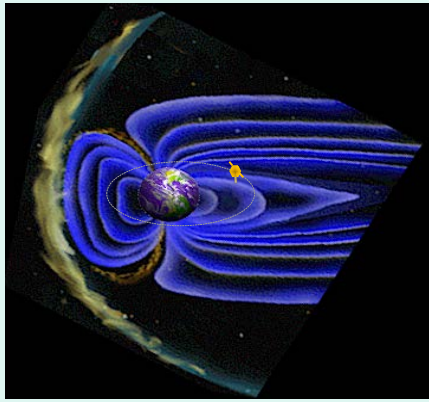
Space Hazards Induced near Earth by Large, Dynamic Storms: Understanding, Modeling, Predicting

V. K. Jordanova, Space Science and Applications, LANL



Project Goals & Scientific Impact:

- **Develop a new modeling capability of the complex near-Earth environment for space assets protection and Space Situational Awareness (SSA):**
  - **Transformational: from correlative to causal understanding of a complex system, exciting new physics addressing interactions across multiple scales/plasma regimes**
  - **Application: mitigate spacecraft charging effects, assist spacecraft designers, forensic analysis of space system failures**



SHIELDS Team

Funded by the U. S. Department of Energy through the Los Alamos National Laboratory (LANL) Laboratory Directed Research and Development (LDRD) program, the SHIELDS framework is being developed by a cross-disciplinary team of scientists in the fields of space science and computational plasma physics:

- **V. Jordanova (PI), M. Henderson, C. Jeffery, J. Woodroffe, T. Brito, C. Harris, ISR, LANL**
- **G.L. Delzanno (Co-PI), J. D. Moulton, H. Godinez, C. Meierbachtol, D. Svyatsky, T, LANL**
- **B. Bergen, E. Lawrence, L. Vernon, CCS, LANL**
- **G. Tóth, D. Welling, Y. Chen, J. Haiducek, University of Michigan**

Collaborators:

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Space Weather Hazards

Our society is more and more dependent on satellite based technologies:

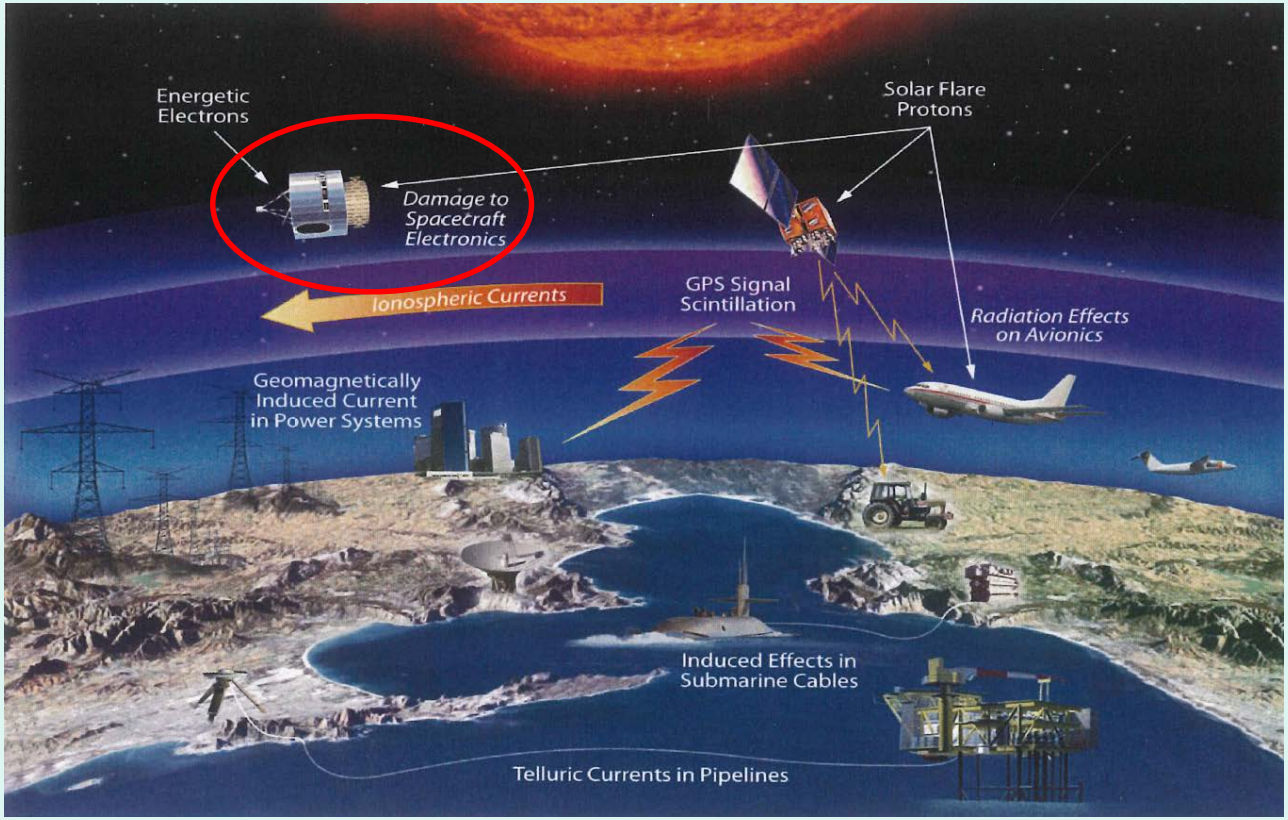
- **broadcast TV/Radio**
- **cell phones, GPS, internet**
- **military/national security assets**

Space weather endangers:

- **humans in space (more and longer manned missions)**
- **ground based technologies (power grids, pipelines, etc.)**

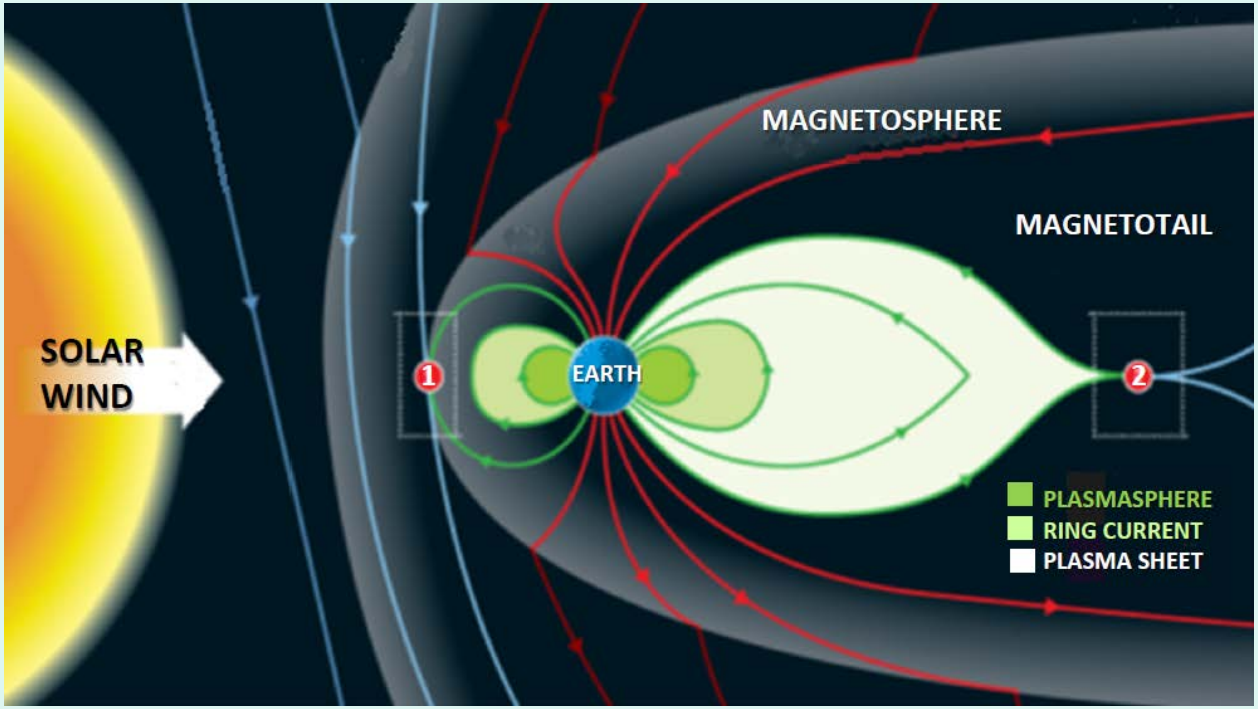
Severe geomagnetic storms:

- **1 to 2 trillion dollars economic damage**
- **recovery times of 4 to 10 years [*NRC report*, 2008]**



The National Science and Technology Council released the National Space Weather Action Plan (NSWAP) in October 2015!

Science Goals & Outcomes



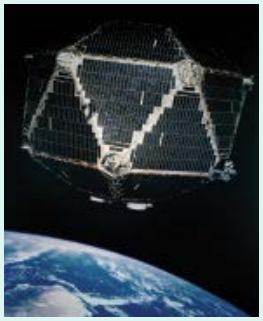
Outstanding science questions related to storm/substorm dynamics we will answer:

- **What determines where and when hot plasma is injected into the inner magnetosphere?**
- **How are the injected particles transported, and how does the magnetosphere respond?**
- **What waves do the injected particles excite and how do these waves feed back on the acceleration and loss of the particles?**

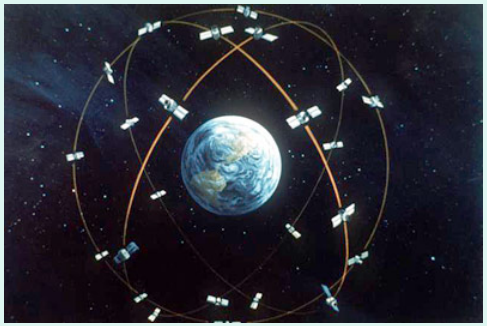
Observations are inadequate to address these questions globally, modeling is the only way!

LANL Capabilities

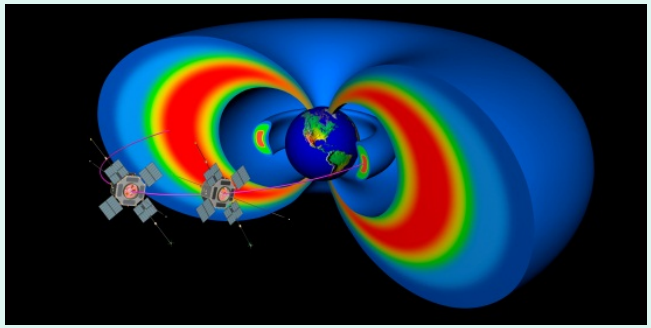
- The crucial national security need to maximize the safety of civilian and military satellites requires the ability to distinguish between various modes of failure
- Building on more than 50 years of space science heritage at the Laboratory
- Challenging problem ideally suited for LANL; the Laboratory has:
  - Unique scientific expertise in data analysis and physics-based modeling
  - Exceptional computational models and capabilities (RAM-SCB, PIC, substorm injection model) at the forefront of space plasma physics
  - Unique data to constrain and validate the models (GEO satellite data, RBSP)



Vela Satellite Program (1963-1984) for monitoring nuclear explosions



Global Positioning System (GPS) constellation (1978- to present), geosynchronous (GEO) satellites

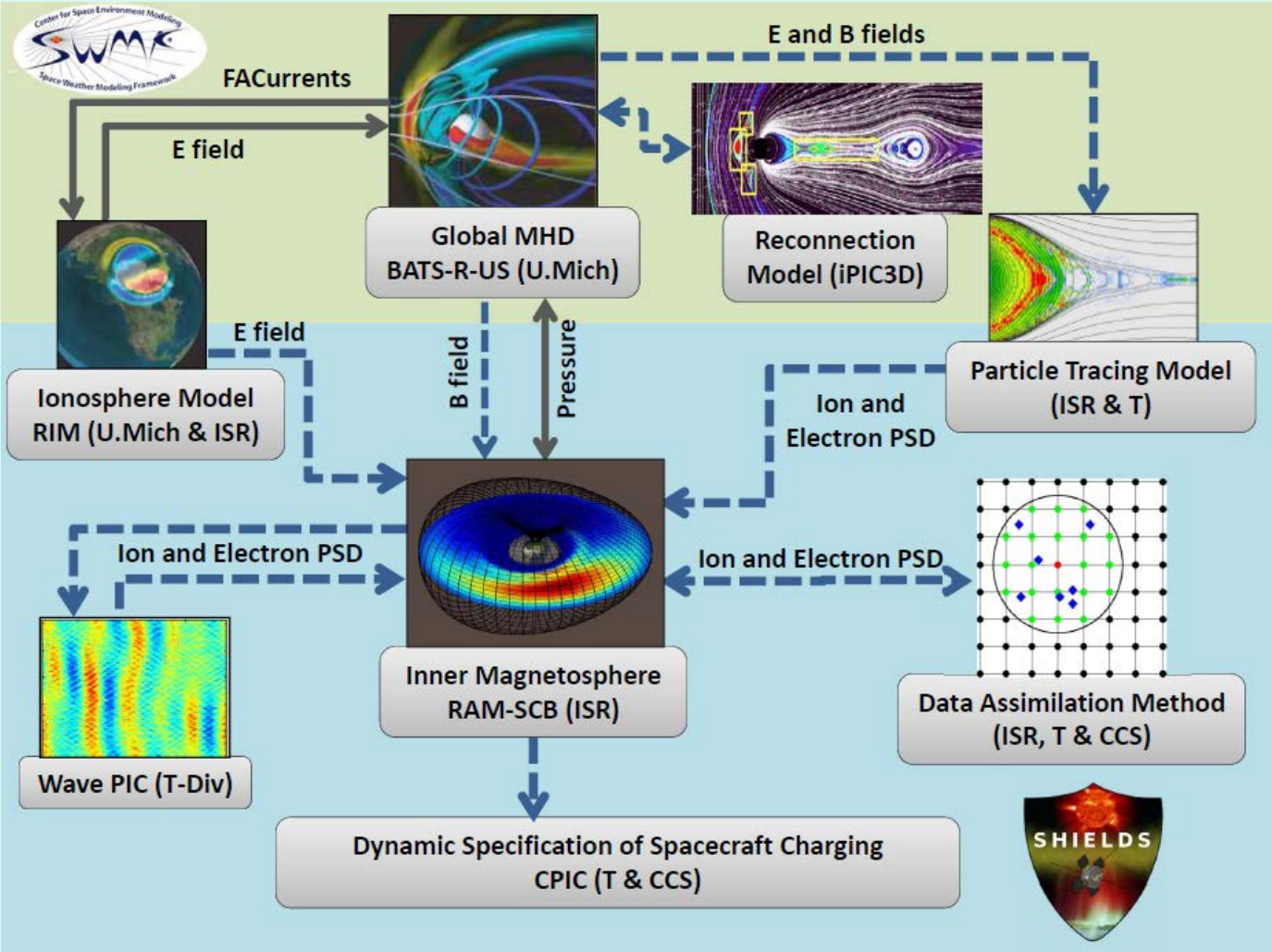


Radiation Belt Storm Probes (RBSP) (2012-) exploring the extremes of space weather, now renamed as Van Allen Probes

Links in the SHIELDS Framework

Bridging macro- and micro-scale models, combined with data assimilation tools:

- **Capture rapid particle injection and acceleration during substorms**
- **Include plasma wave generation and their feedback on the particles**



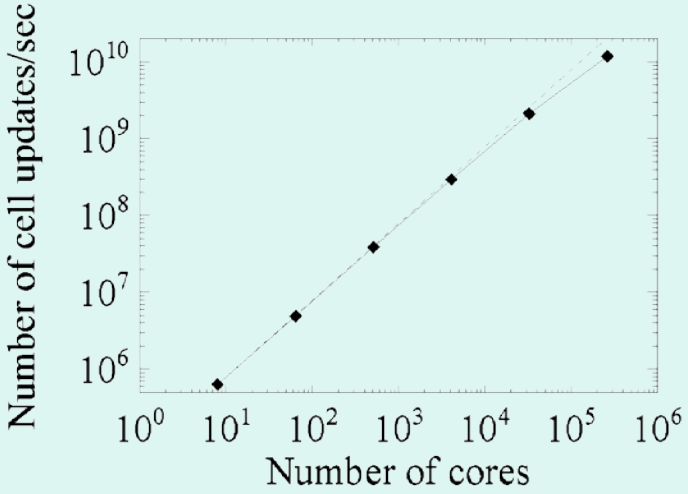
Solid arrows: existing coupling at start of project; Dashed arrows: new coupling

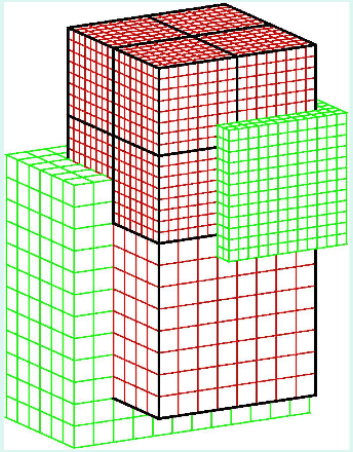
BATS-R-US

Block Adaptive Tree Solar-wind Roe Upwind Scheme

- Physics
  - Classical, semi-relativistic and Hall MHD
  - Multi-species, multi-fluid, anisotropic pressure
  - Radiation hydrodynamics multigroup diffusion
  - Multi-material, non-ideal equation of state
  - Solar wind turbulence, Alfven wave heating
- Numerics
  - Conservative finite-volume discretization
  - Parallel Block-Adaptive Tree Library (BATL)
  - Cartesian and generalized coordinates
  - Splitting the magnetic field into $B_0 + B_1$
  - Divergence B control: 8-wave, CT, projection, parabolic/hyperbolic
  - Numerical fluxes: Rusanov, AW, HLLE, HLLD, Roe
  - Explicit, point-implicit, semi-implicit, fully implicit time stepping
  - Up to 4th order accurate in time and 5th order in space
- Applications
  - Heliosphere, sun, planets, moons, comets, HEDP experiments
- 100,000+ lines of Fortran 90 code with MPI parallelization

Parallel scaling from 8 to 262,144 cores on Cray Jaguar. 40,960 grid cells per core.





RAM-SCB

Ring current - Atmosphere interactions Model with Self-Consistent magnetic (B) field

» **Ring current-atmosphere interactions model (RAM)**
[Jordanova et al., 1994, 2006; 2012]

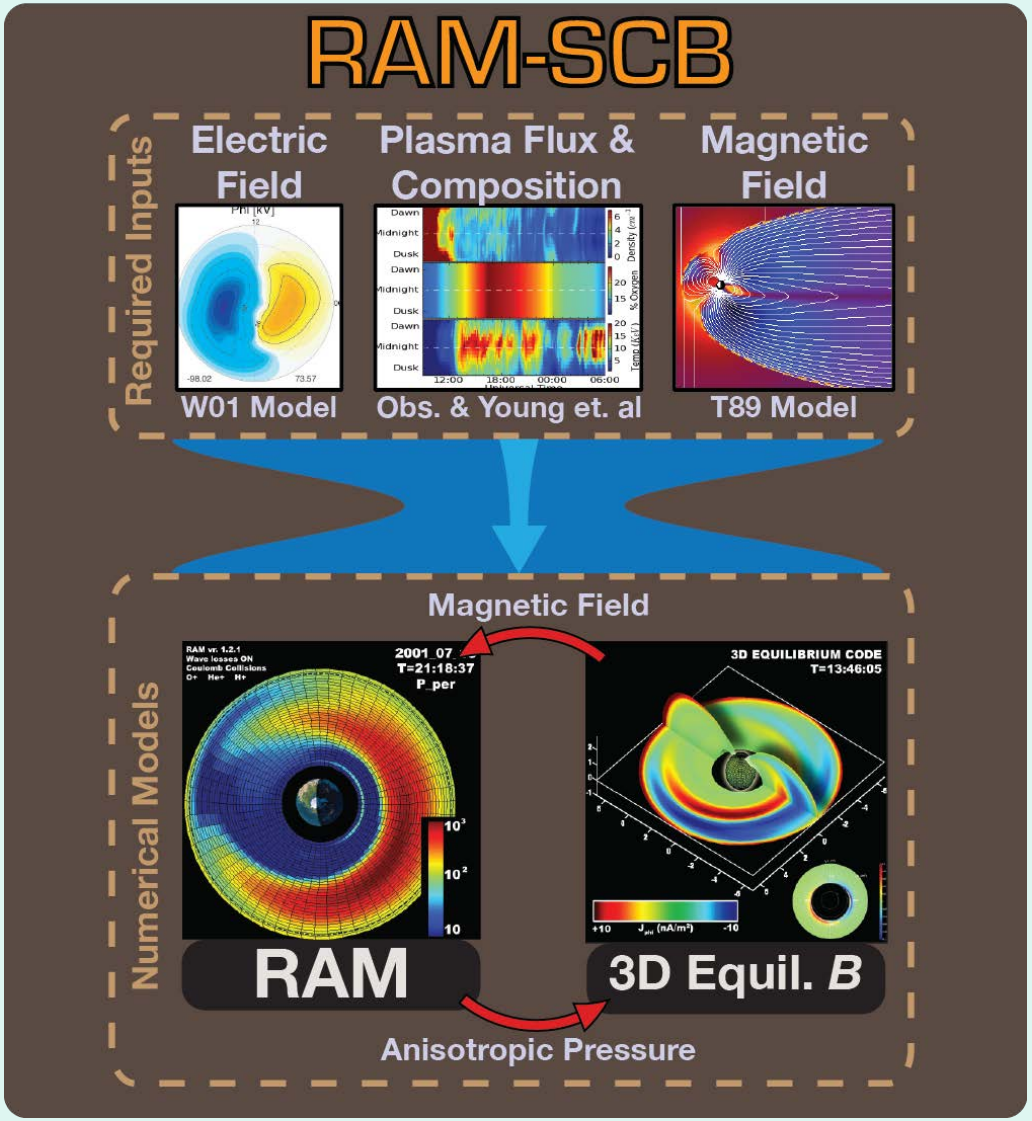
- **Kinetic equation for H^+, O^+, and He^+ ions and electrons**
- **Including all major loss processes**
- **Convection and corotation E field**
- **Updated to general B field**

» **3D equilibrium code**
[Cheng, 1995; Zaharia et al., 2004; 2010]

- **Force-balanced equation**

$$\mathbf{J} \times \mathbf{B} - \nabla \cdot \mathbf{P} = 0$$

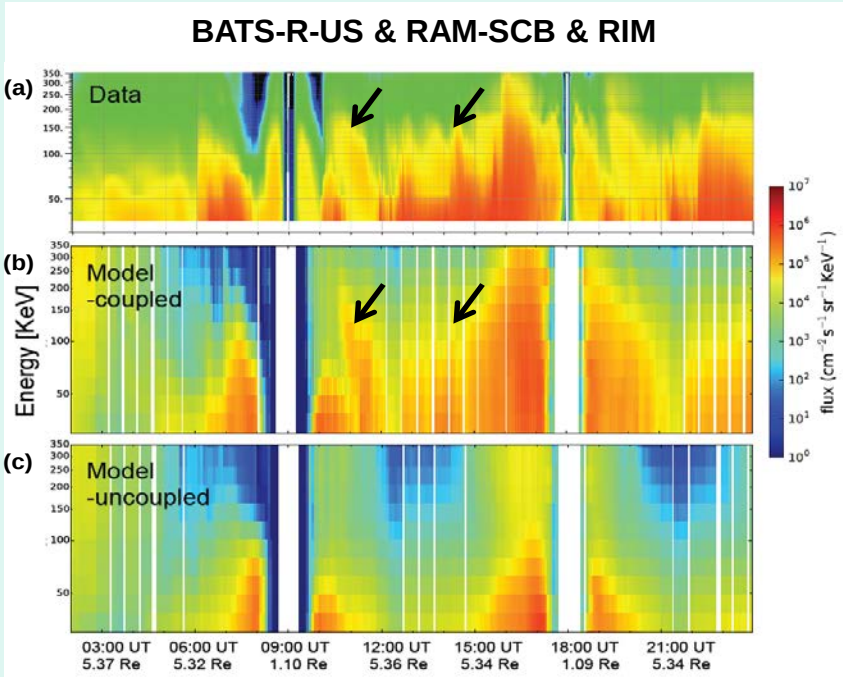
- **Euler potentials (flux coordinates)**



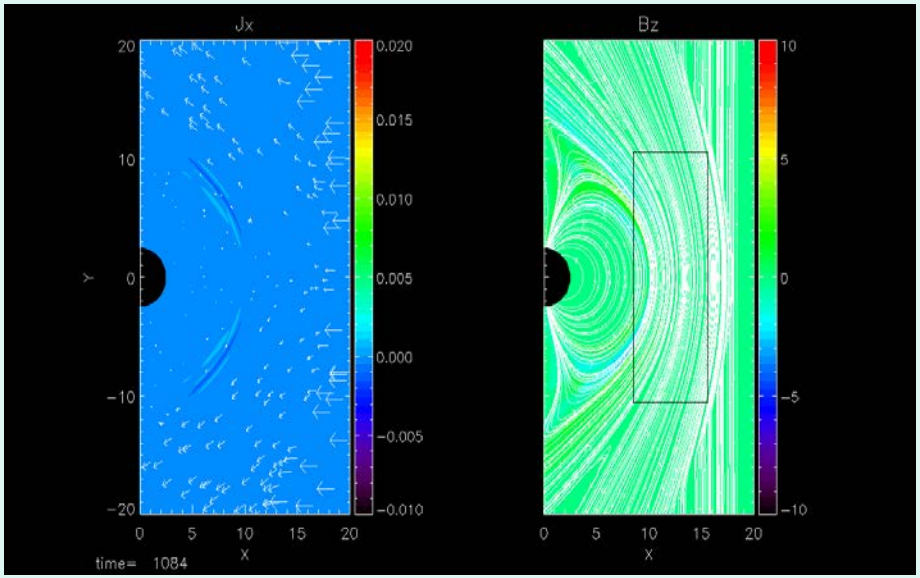
SHIELDS Project Studies

I. Achieved a fully self-consistent "two-way" coupled **BATS-R-US & RAM-SCB & RIM** simulation, applied to study substorm dipolarization and electron transport

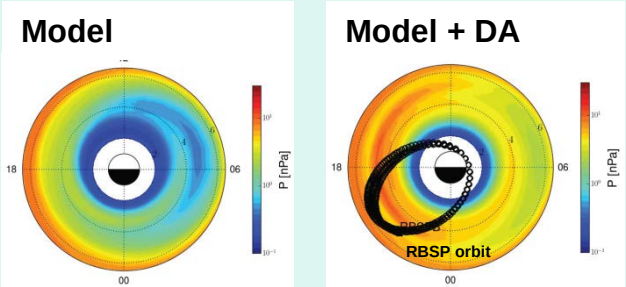
⇒ Demonstrated that substorms enhance significantly the electron fluxes inside GEO [Yu et al., Geophys. Res. Lett., 2014]



II. Achieved a fully "two-way" coupling of global MHD model **BATS-R-US** with an implicit Particle-in-Cell model **iPIC3D** [Daldorff et al., J. Comp. Phys., 2014]



III. Successful **data assimilation study** using RBSP data confirms the capability of producing more accurate ring current dynamics (submitted to Geophys. Res. Lett.)

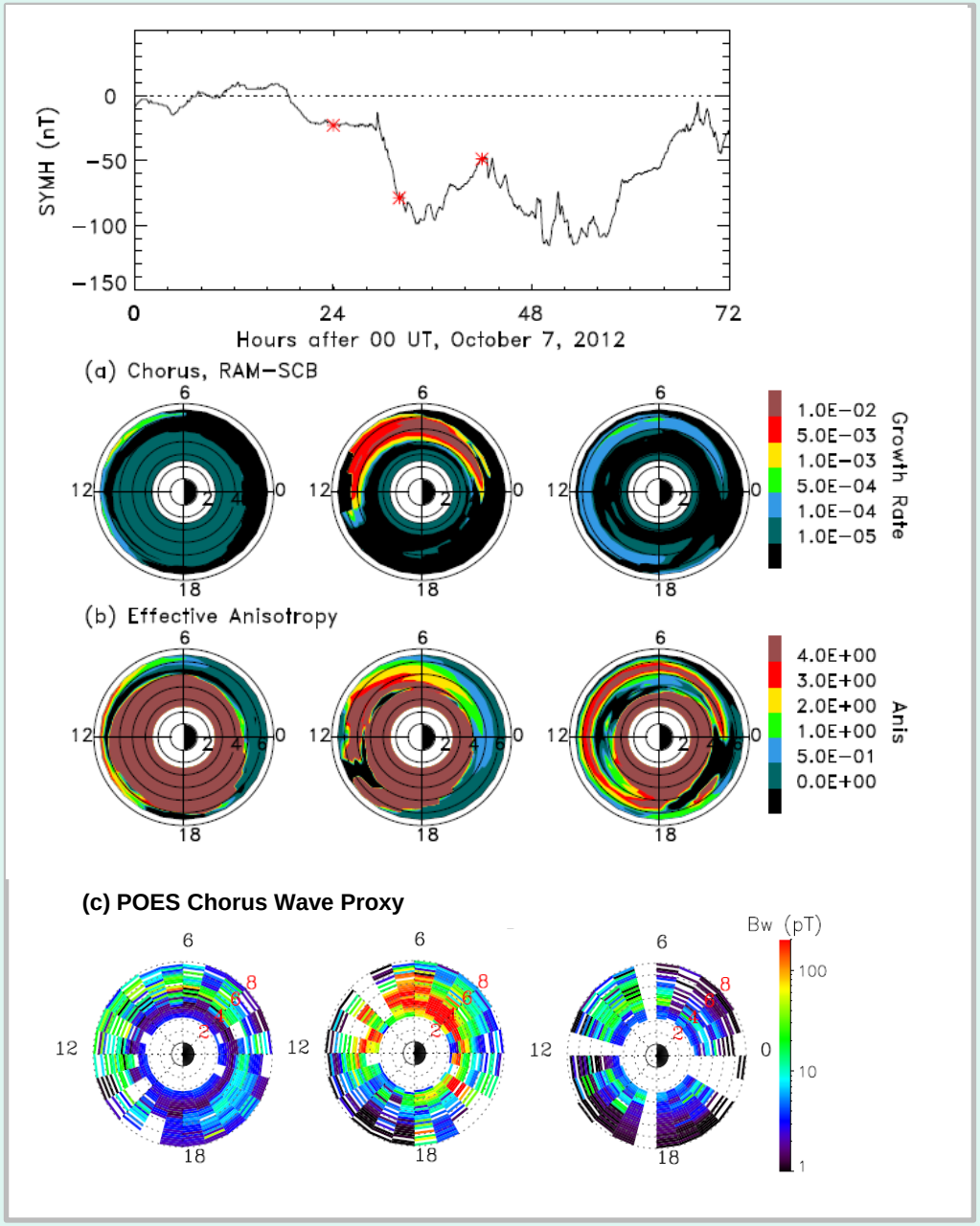


Wave-Particle Interactions

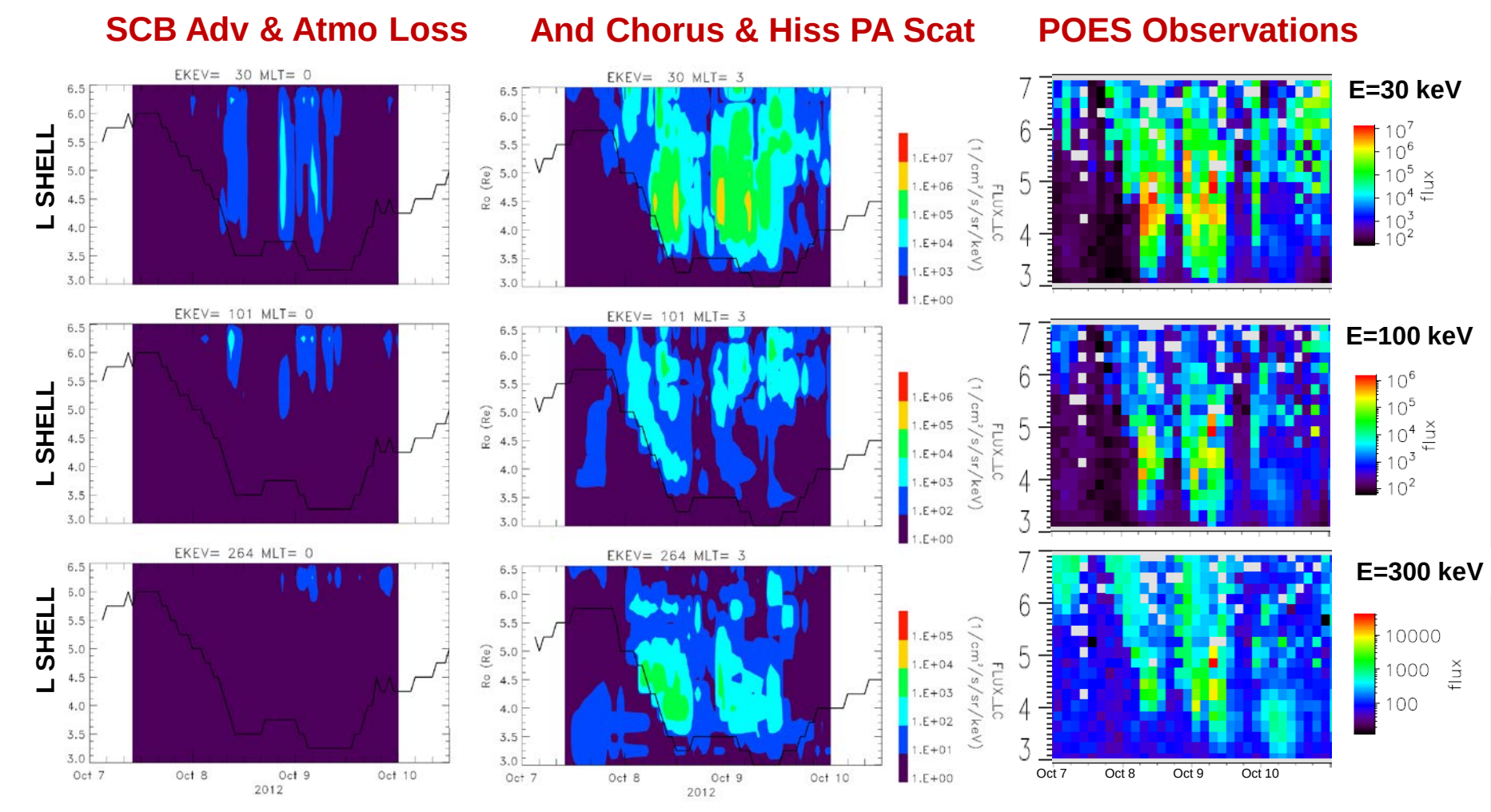
We simulated ring current dynamics with RAM-SCB during the 7-9 October 2012 storm:

- RAM-SCB predicted significant chorus wave growth due to the large electron anisotropy developed near minimum Dst
- Comparison with the global wave proxy derived from precipitating 30-100 keV electrons measured by the NOAA POES satellites during the storm [Chen et al., 2014]

⇒ Good agreement regarding the spatial and temporal evolution of the chorus wave instability during the storm main phase



RAM-SCB Simulations & NOAA Data: Precipitating Flux



- RAM-SCB electron simulations considering advection & atmospheric loss, and adding pitch angle scattering by chorus and hiss (MLT=3)
- POES electron data (binned by three hours) in predawn (MLT 00-06) sector
- Precipitating electron flux increases significantly in agreement with observations when plasma wave scattering is included

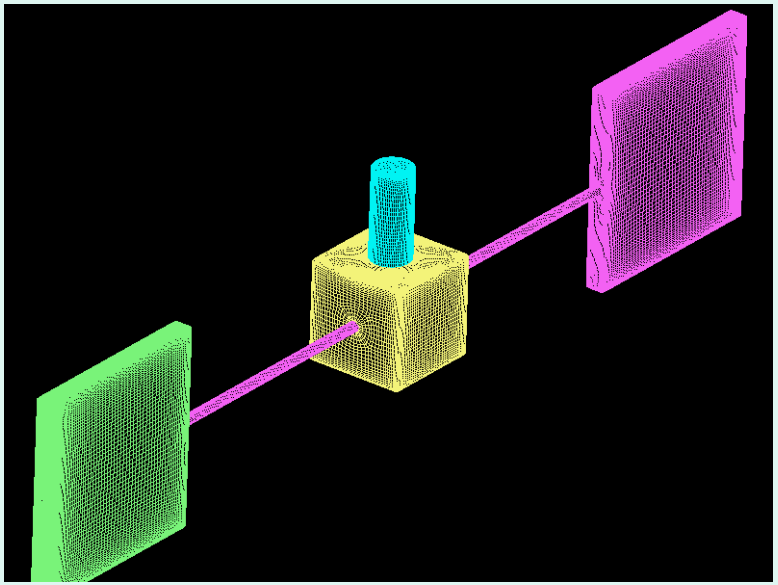
SHIELDS Application & Future Use

- **Spacecraft surface charging: interaction of a plasma with material objects, additional scales due to the object: 'more' multiscale!**
- **Spacecraft charging is platform dependent**
- **LANL state-of-the-art Curvilinear PIC (3-D, parallelized, multigrid) will be used to perform simulations of spacecraft charging for the specific geometry & material properties of Van Allen Probes**

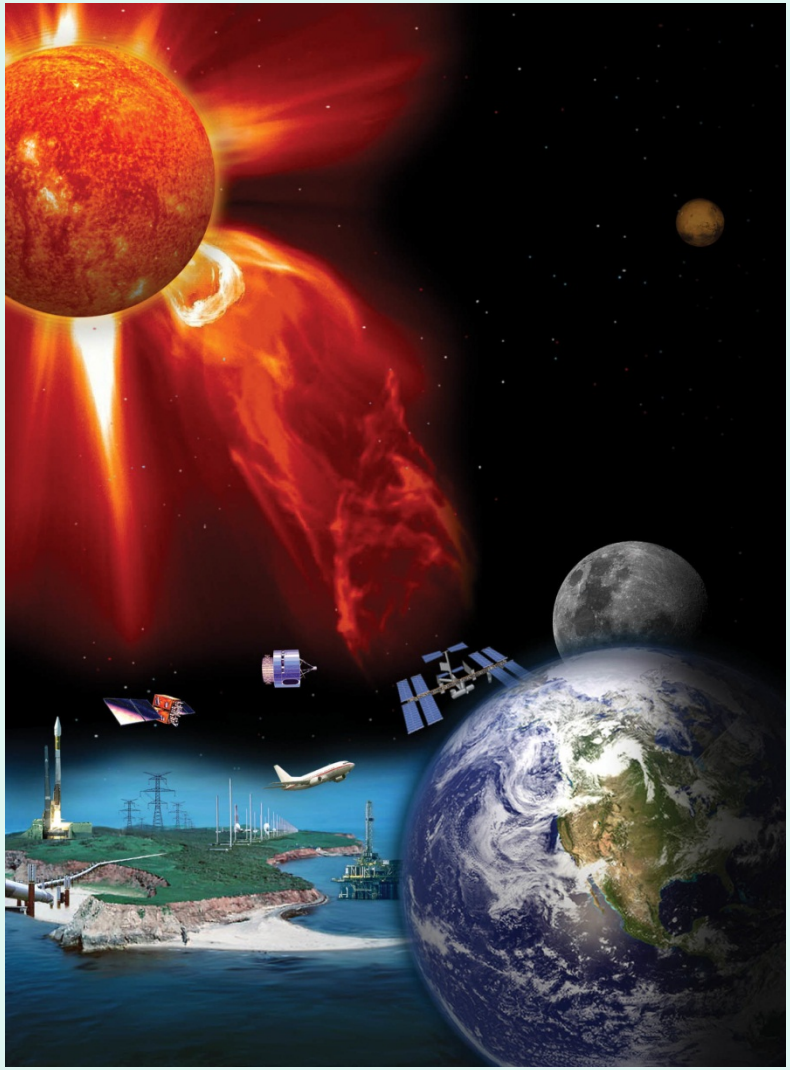
Example: geosynchronous spacecraft
- Spacecraft size ~1-10 m
- Debye length ~300 m
- Electron gyroradius ~ 800 m
- Ion gyroradius ~ 30 km

A uniform grid would require at least 10^5 cells in each spatial direction UNFEASIBLE!

Spacecraft grid generated with GridPro



SHIELDS Impact

- Unique space weather model will position LANL as a leader in Space Situational Awareness and forensic analysis of space system failures
- Science-based understanding needed for the analysis and interpretation of LANL data from past and current missions (GEO, RBSP)
- Advances LANL design capabilities for space-based instrumentation for national security missions
- Space weather – growth area; building strategic partnerships with other agencies (DOD, NOAA, NASA, NSF, FAA), institutions (Aerospace, universities), and commercial customers (satellite operators, etc.)

SHIELDS 2017 Challenge