Magnetosphere Panel

Key questions:

- What observations/models are needed to fulfil user needs?
- What observations/models are needed to improve, test, and validate models?
- What is the key strategic space weather dataset needed to advance (a) research and (b) operations?
- What is the key strategic space weather model capability needed to advance (a) research and (b) operations?
- What current (or past) assets (observations or models) have proved to be ineffective? Why?
- Are there any other concerns/issues we're missing that you'd like to raise?

Moderator: Terry Onsager, Committee

Christine Gabrielse The Aerospace Corporation

Matina Gkioulidou Johns Hopkins University/Applied Physics Laboratory

Vania Jordanova Los Alamos National Laboratory

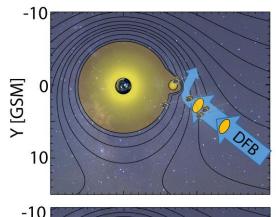
Larry Kepko NASA Goddard Space Flight Center

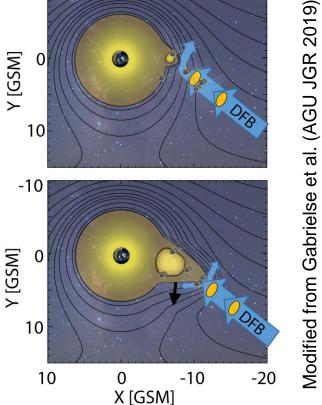
Space Weather Operations and Research Infrastructure Workshop: Phase II, Tuesday April 12, 2022, 1430 ET

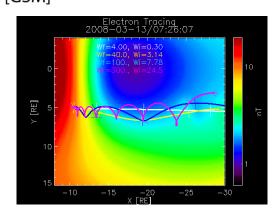


What is [a] key strategic space weather dataset/model needed to advance (a) research and (b) operations?



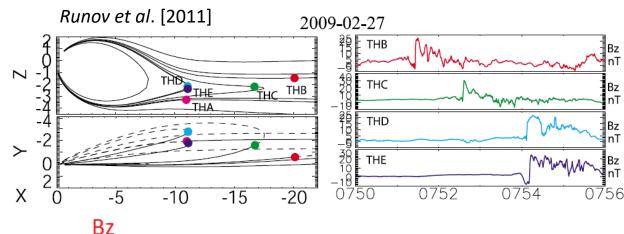


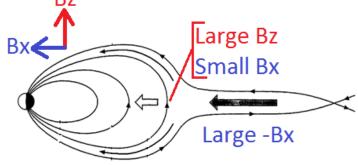




Earth's transition region: Lots of dynamics, energy conversion & transport

- Better resolution at mesoscales (~1-4 RE)
- Grid of satellites with magnetometers and particle detectors Imagers that can measure particle dynamics in 2D
- Ground-based
- Space-based

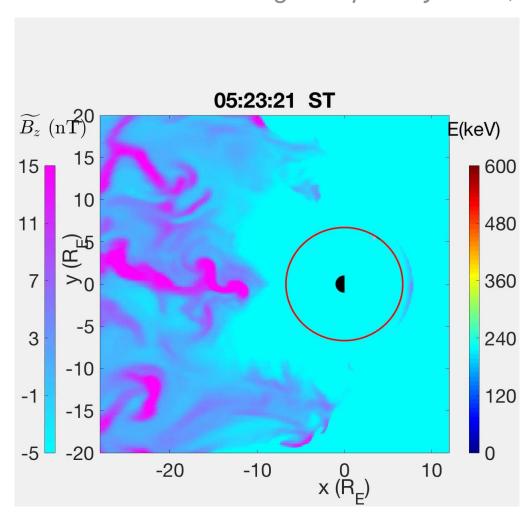




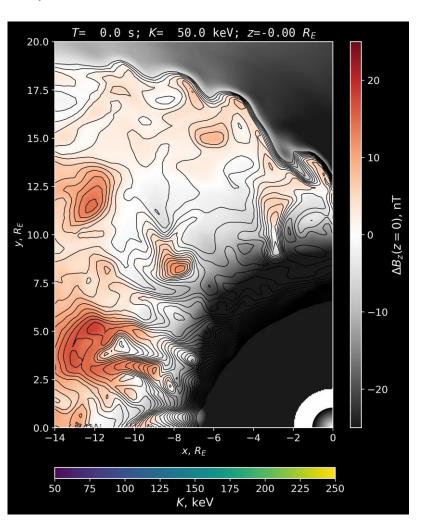
Gabrielse et al. (AGU JGR 2017)

Some Current Models Capturing Mesoscale Dynamics (MHD)

Future needs in modeling: Coupled systems, full dimensional, kinetic scales included



Eshetu et al. (AGU JGR 2019): Electrons in LFM MHD See also: Kim et al. (AGU JGR 2000) and Sorathia et al. (AGU JGR 2018) for electron trapping in MHD fields



Ukhorskiy et al. (AGU JGR 2019): Ions in MHD

User Motivation: Better Constrain Radiation Environment



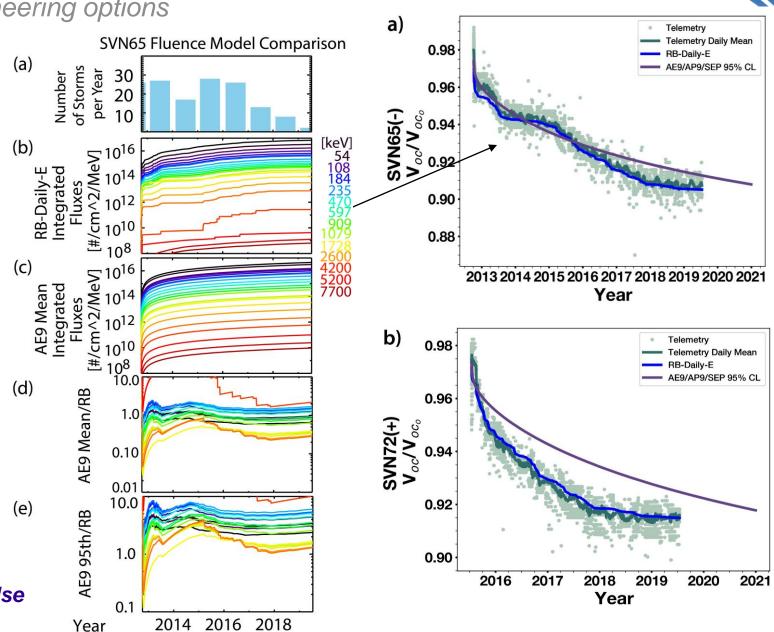
Could lead to more efficient engineering options

Modeling using 7 years of NASA's Van Allen Probe mission data demonstrated that

- 1. The radiation environment is the almost sole source of solar cell voltage degradation.
- The AE9/AP9 models are insufficient to predict fluences on short (few years) time scales.
- Important to maintain telemetry data to monitor solar cell output.

We did this with TWO radiation belt monitors—But with MORE satellites in GTO we could capture MLT dependence as well!

Figures and results from Gabrielse and Lee et al. (in prep)



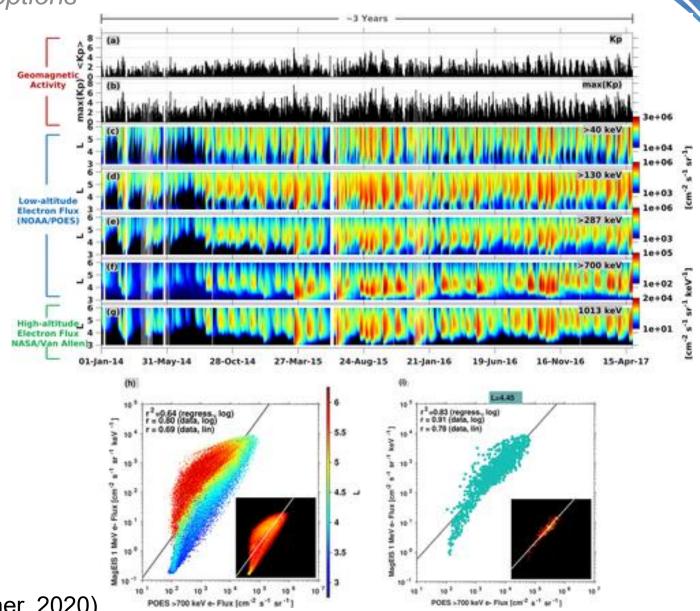
User Motivation: Better Constrain Radiation Environment

Could lead to more efficient engineering options

Al and neural networks could be useful!

Specifying High-Altitude Electrons Using Low-Altitude LEO Systems: The SHELLS Model Claudepierre and O'Brien (Space Weather, 2020)

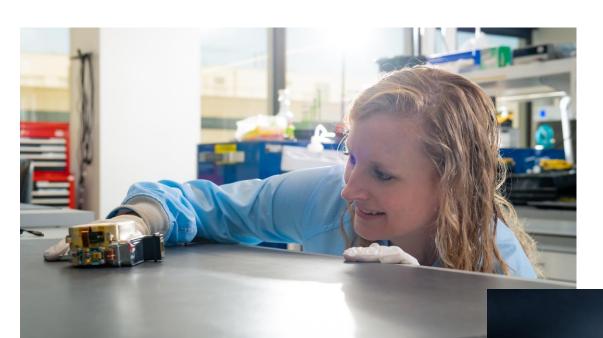
Artificial neural network model of the near-Earth space radiation environment. Kp index and LEO electron flux measurements from NOAA POES operational spacecraft are used as model training inputs.

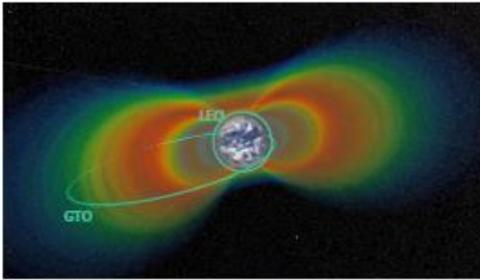


Claudepierre and O'Brien (Space Weather, 2020)

Build Smaller, More Affordable: Allows for More Numerous Satellites

SmallSats like GTOSat (PI: Lauren Blum)





The Relativistic Electron Magnetic Spectrometer (REMS) built at Aerospace has both an electron and proton detector. It only weighs ~1 kg.

Image courtesy of NASA and Lauren Blum.

Mesoscales in 2D



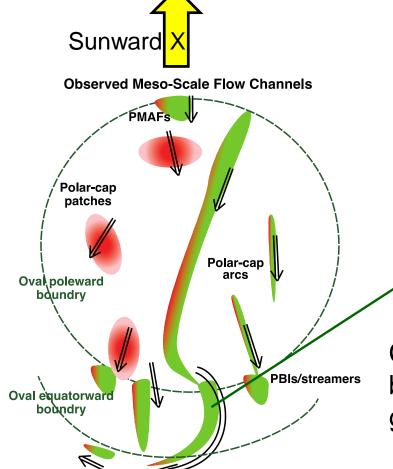
High

flow

speed Earthward

region

Magnetotail Flows and the lonosphere



Modified from Lyons al. [AGU JGR 2016]

Sergeev et al. [AGU GRL 2000]

Convection on mesoscales can be studied in the magnetosphere by satellites or in the ionosphere by low-earth orbiting satellites, ground-based radar, or imagers.

BBF

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m L}$ 80

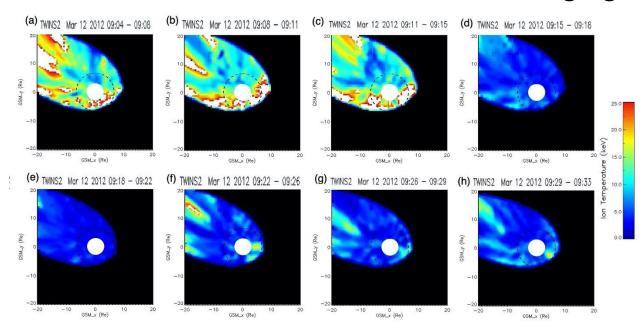
stream cr

Sunward

Difficulty with satellites alone: Mesoscales are only ~1-3 RE wide, hard to constrain actual size even with 3-4 satellites. Without a dense satellite grid, IMAGERS provide context in 2D.

Mesoscales in 2D: TWINS and ENA Imaging, Ground-based All-sky-imagers

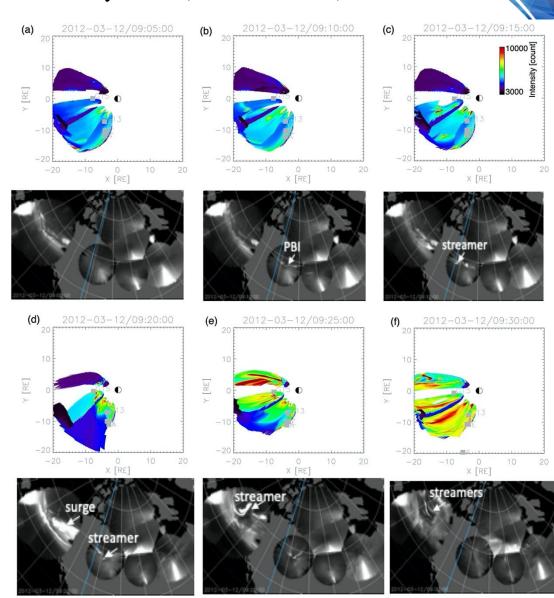




New techniques that use 2D datasets to study mesoscale plasma flows: TWINS ENA images and THEMIS ASIs.

- Flow channels come in from the magnetotail before the sudden storm commencement (SSC), indicating the importance of mesoscale injections to the inner magnetosphere at SSC.
- TWINS decommissioned last year.
- THEMIS ASIs only have a few years left.
- Canadian TREx ASI array being implemented.
- What about U.S. infrastructure?

Adewuyi et al. (2021, Frontiers)

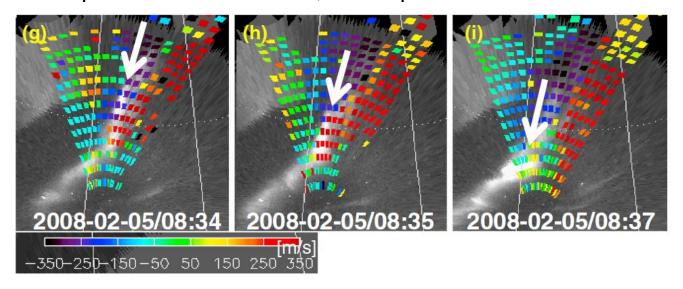


Mesoscales in 2D: Imaging

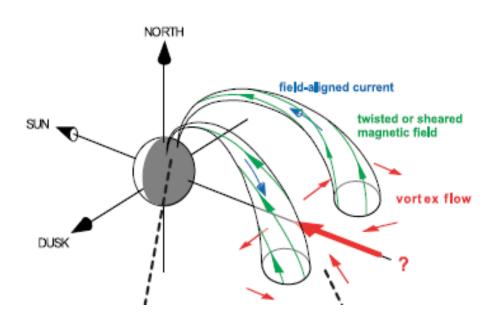
Magnetotail Flows and the lonosphere

Flow shear from vortex creates field-aligned current, accelerates electrons and creates equatorward-traveling auroral streamers.

Blue=poleward/tailward flow, red=equatorward/earthward flow



Gallardo-Lacourt et al. (AGU JGR, 2014)



Birn et al. (AGU JGR, 2004)

Read more!

Henderson et al., 1998; Sergeev et al., 1999, 2000; Lyons et al., 1999, 2002; Kauristie et al., 2000; Zesta et al., 2000; Zou et al., 2010, 2013.

2008 Jan 14 10 How is energy transferred from M'sphere to l'sphere? atitude SuperDARNTHEMIS ASI Energy flux mosaic from THEMIS Poleward **RANK eflux** atitude] ergs/cm²/s Streamer 100 80 2008-01-14/05:57 Total eflux [GW] 60 Total 500km 300km 100km ₂60 240 500km 300km 100km Mesoscales Important! hhmm 0540 0550 0600 0610 11

User Motivation: Energy Transport Important for Ionosphere Heating

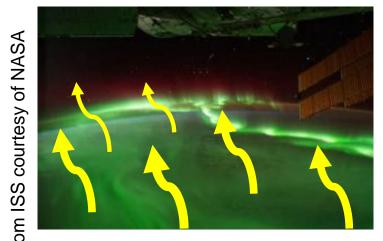


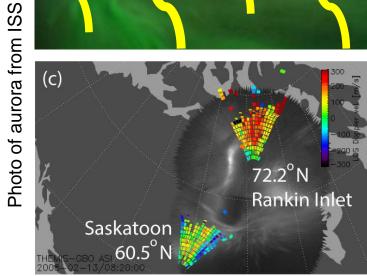
Flows, precipitation

- → Heating, upwelling
- →Effects on mesosphere/thermosphere

Existing models use solar wind parameters to drive the system

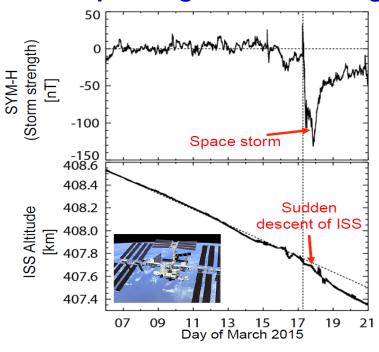
- →Capture large-scale global effects
- → Meso-scale phenomena are **poorly** characterized
- → Meso-scale phenomena are very dynamic!





Bottom: Gabrielse et al. (AGU JGR 2018)

Upwelling → **Satellite Drag**



Nishimura et al., AGU talk 2016

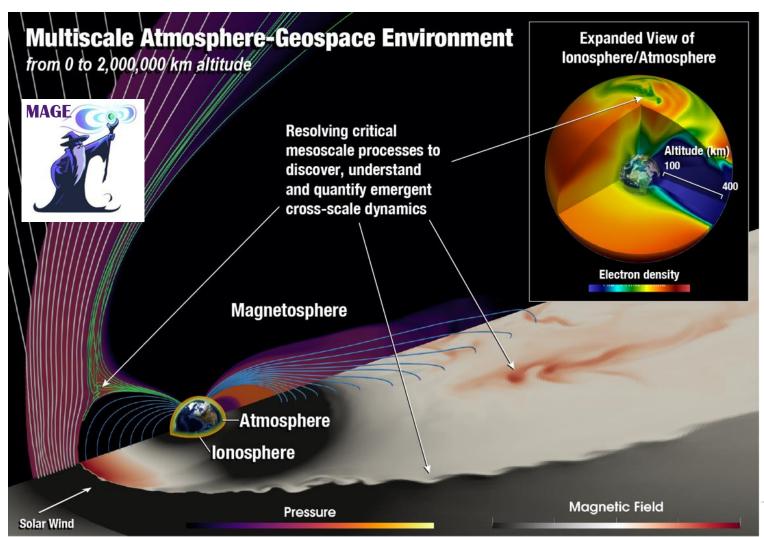


National Academies of Sciences
Space Weather Operations and Research
Infrastructure Workshop: Phase II

Session 3.3 – Observation and Model Needs – Magnetosphere

Matina Gkioulidou (matina.gkioulidou@jhuapl.edu)

What are the key strategic model capabilities needed to advance (a) research and (b) operations?



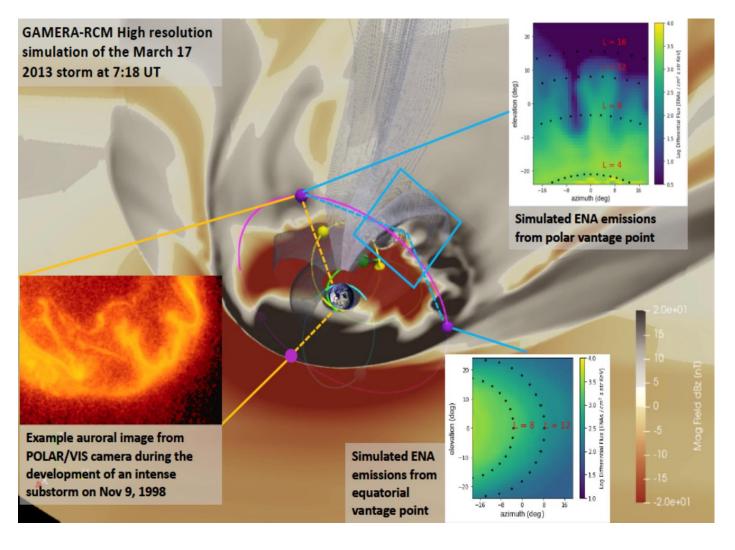
Geospace: System of Systems



We need models that connect those systems in the critical mesoscale resolution



What are the key strategic datasets needed to advance (a) research and (b) operations



- Over the years, missions have targeted either the local nature of geospace with in-situ probes, or the global nature of geospace with global imaging or multi-point, yet sparse in-situ measurements.
- In order to validate the models we also need to measure the global geospace in mesoscale resolution (1000 km to few R_E in the magnetotail, ~10s - 100s km in the ionosphere)



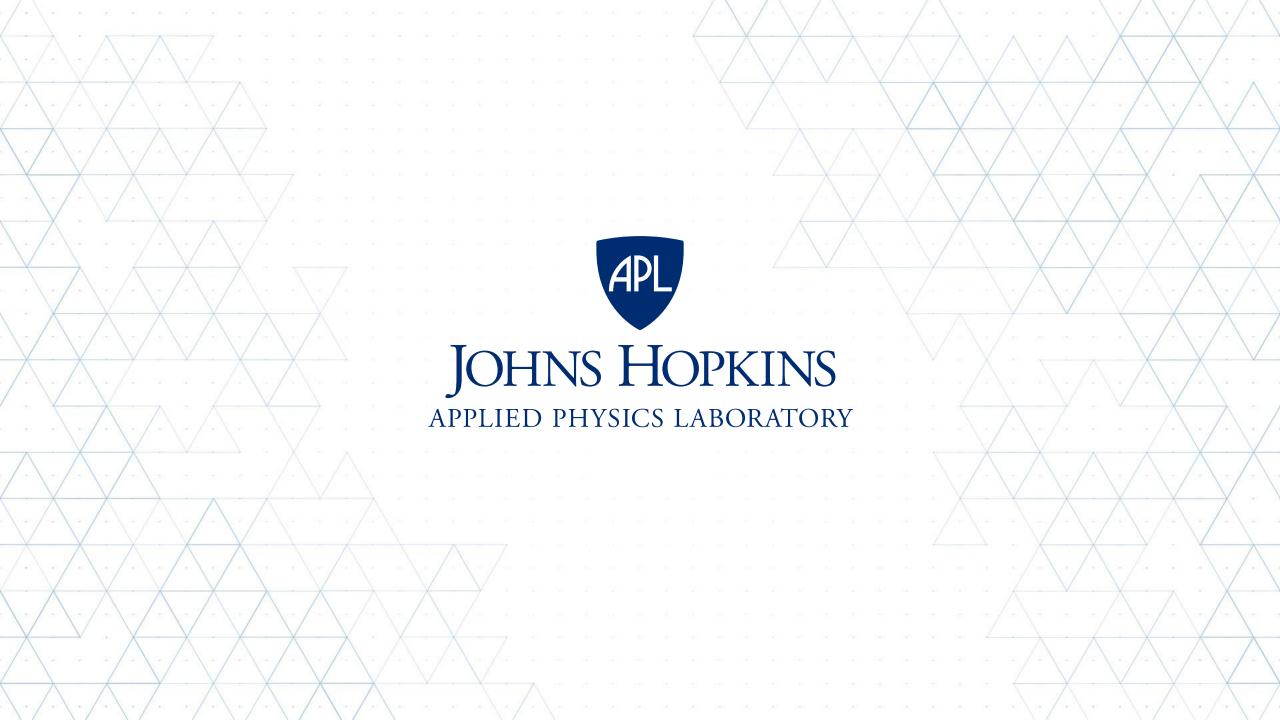
Coordination between constellations of in-situ measurements (plasma, energetic particles, magnetic field) and high temporal-spatial resolution imaging (ENA imaging of the plasma sheet and ring current, aurora, plasmasphere)

Are there any other concerns/issues we're missing that you'd like to raise?

• Yes, the issue of workforce development: Space Weather is a highly technological advanced field, of high societal importance. Yet, we seem to be lacking career opportunities that would attract people with the right expertise to enter **and stay** in the field.

Generally, what observations/models are needed to fulfill user needs?

• It depends i) on the users, ii) on how willing the users are to share their data with us, iii) on whether the users know that they are users ©







National Academies of Sciences Space Weather Operations and Research Infrastructure Workshop: Phase II

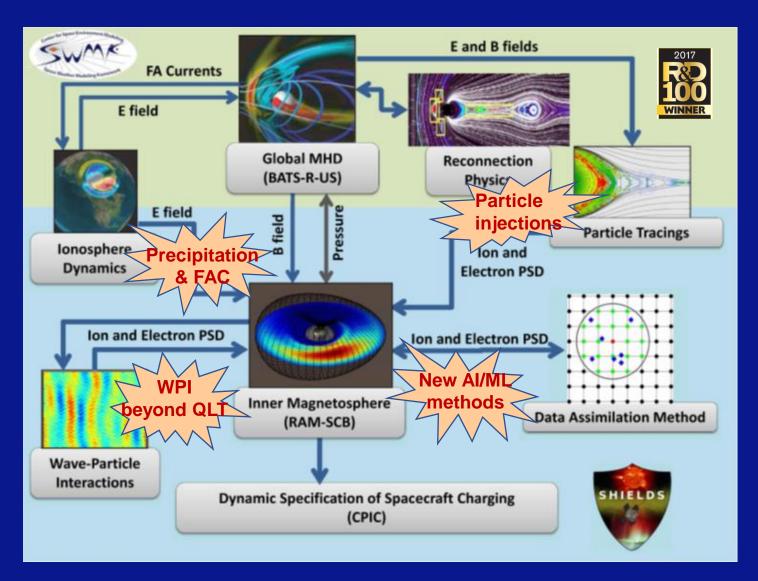
Session 3.3 – Observation and Model Needs – Magnetosphere

Vania K. Jordanova (vania@lanl.gov)

- What key modeling capabilities are needed to advance (a) research and (b) operations?
- What key observations are needed to improve, test, and validate models?

April 12, 2022

Need improved understanding/modeling of cross-regional and cross-scale coupling



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

- Rapid particle injection and acceleration during storms and substorms
- Plasma wave generation and feedback on the particles
- Particle precipitation and coupling with the ionosphere

Heliophysics 2050 White Papers:

- More powerful computing technologies will lead to new physics-based approaches: multifluid, hybrid, Vlasov, spectral and implicit kinetic solvers [Merkin et al., Active Geospace 2050 Vision for First-Principles Modeling]
- Larger amount of data from new missions will lead to novel combinations of physicsbased models with machine learning (ML), high performance deep learning, and "physics emulator" approaches [Dorelli et al., Deep Learning for Space Weather Prediction]
- Successful application of artificial intelligence (AI) methods for automatic event identification, feature detection and tracking, uncertainty quantification have already been demonstrated [ML-Helio 2022 Conference]



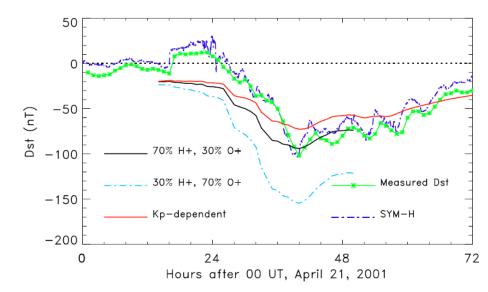
Need detailed knowledge of the near-Earth plasma ion composition

Ion composition measurements at GEO are needed for the set-up of model boundary conditions:

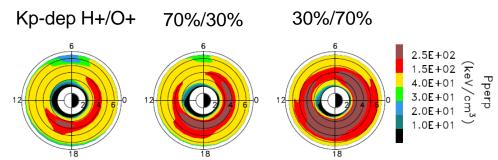
- Need ion composition measurements with good species (mass and charge) separation and high time and energy resolution
- Our knowledge of the composition of plasma in space mostly comes from decades-old measurements with mass spectrometers that outperformed many contemporary instruments
- This observation gap inhibits our ability to accurately predict and characterize hazardous space weather events in the near-Earth space environment

Heliophysics 2050 White Papers:

- Significant advances in technology enable more sophisticated mass spectrometers in smaller design packages than ever before [Fernandes et al., Heavy lons: Tracers and Drivers of SW-I-M Coupling]
- The presence of N+ ions plays a key role in the ionospheric outflow for all conditions [llie et al., The need for detailed ionic composition]



RAM pressure calculations at Dst minimum:



RAM test simulations assuming various ion density ratios at the outer model boundary at GEO:

- ⇒ The total ion energy density increases as O⁺ contribution to the ring current increases
- ⇒ Affects self-consistently calculated electric and magnetic fields, plasma wave generation
- ⇒ Affects the ring current asymmetry, dynamics of low(high)energy populations



Need detailed knowledge of cold plasma distribution and variability

Both physics and space weather predictions require the inclusion of dynamic plasmasphere modeling:

- ➤ The cold plasma distribution and variability affects many processes in the Earth's magnetosphere, like the properties of plasma waves controlling the behavior of radiation belt electrons and ring current ions
- The cold particle populations with energy <100 eV are difficult to measure and the least studied but often dominate the plasma density

Heliophysics 2050 White Papers:

- Our community must explore the cross-scale, critical phenomena of source and loss of core plasma [Goldstein et al., Core-Plasma Refilling and Erosion]
- ▶ Innovations are necessary (like the use of a plasma contactor, smart spacecraft material designs) for measuring the cold-particle populations in space [Delzanno et al., The Need to Understand the Cold-ion and Cold-electron Populations of the Earth's Magnetosphere]



Plasmasphere refilling and erosion processes [Goldstein et al., http://www.hou.usra.edu/meetings/helio2050/pdf/4063.pdf]

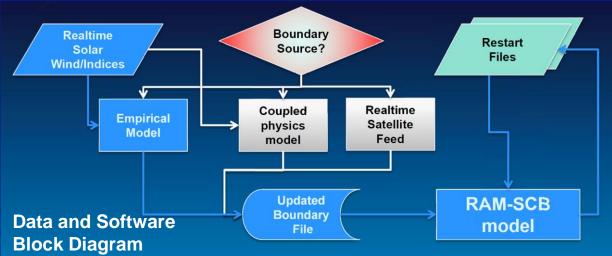
Plasma Imaging, LOcal measurement, and Tomographic experiment (PILOT): a mission concept for transformational multi-scale observations of mass and energy flow dynamics in Earth's magnetosphere [Malaspina et al., Frontiers Special Issue, 2022]



Need accurate measurements of the solar wind that hits the Earth

- Best RAM-SCB results obtained with boundary source provided by GEO satellite observations; not always available
- Developed simplified RAM-SCB model driven by solar wind conditions
- ➤ Given appropriate upstream solar wind measurements, the model provides a forecast with a ~1 hour lead time
- > Example shown for the Van Allen Probes:

Near Real-Time SHIELDS-RC Operation



[Jordanova et al., JASTP, 2018]

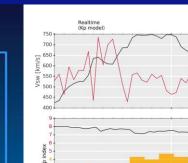
- Drivers (Vsw, Bz) and Kp & Dst indices as a function of time
- ❖ Electron energy spectra from ~1 to 350 keV
- ❖ Integrated electron flux at 10–50 keV as an indication of surface charging hazard

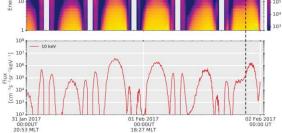
Heliophysics 2050 White Papers:

- Need to monitor upstream solar wind conditions [Nykyri et al., Improved Plasma Science Through Multi-Point, Multi-Scale Measurements in the Solar Wind]
- ➤ The observational gap between LEO and GEO must be filled with a constellation of radiation belt probes and the use of data-augmented physics-based models [Ukhorskiy et al., HWP #4092, 2021]

The solar wind that hits an L1 spacecraft can pass ~30 R_E duskward of the Earth:

[Borovsky, J. E. (2022). Noise, regression dilution bias, and solar-wind/magnetosphere coupling studies. Front. Astron. Space Sci. 9:867282]





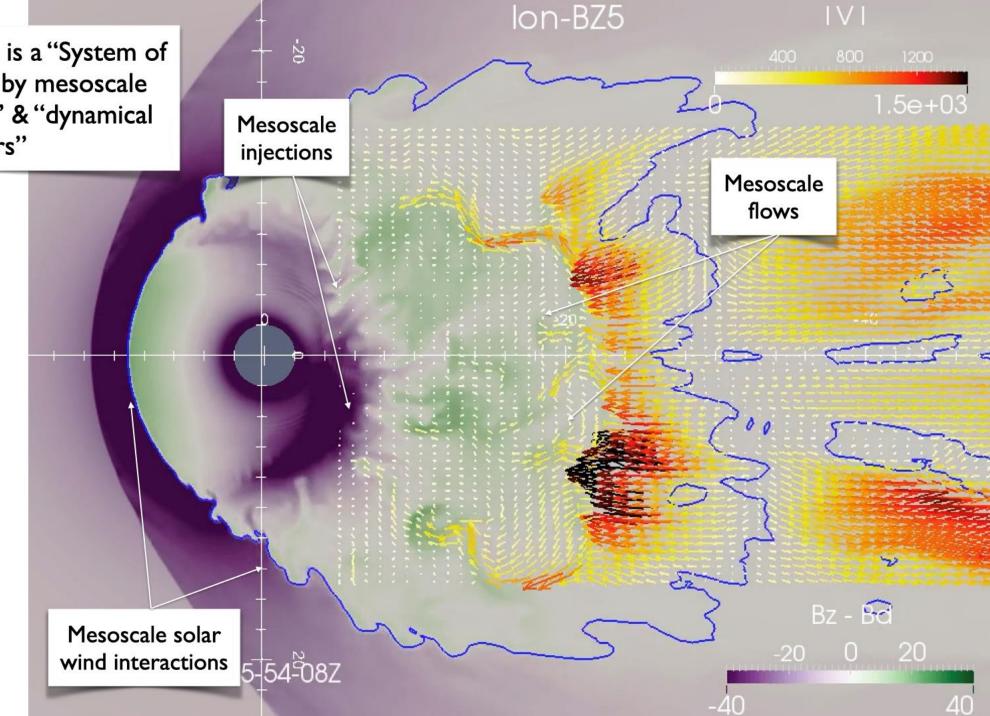
Sample Model Output:



Earth's Magnetosphere is a "System of Systems", connected by mesoscale "regional connectors" & "dynamical messengers"

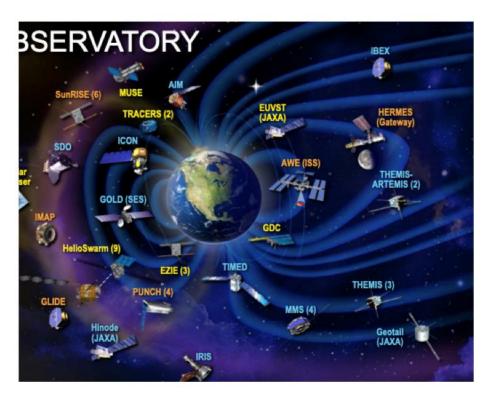
Mesoscales are fundamental units of transport, and carry mass, momentum, and energy throughout and across systems, and to and from micro and global.

Mesoscales also carry information about configuration changes.



HSO attempts coordination in pursuit of system science

But coordination is ad-hoc, often accidental, and inadequate for mesoscales.

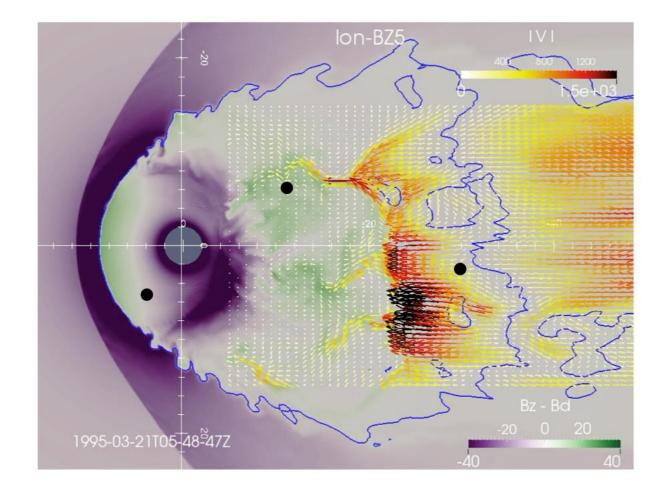


Earth's magnetosphere has an aging, inadequate fleet, with nothing in the queue.

Simulations are well beyond our ability to constrain or validate them.

We need a new approach.

Sparse measurements, even if coordinated, are inadequate to fully capture the mesoscales.



We need a (likely international) program to measure key points in the System of Systems, at mesoscale resolution, and state variables

Geospace mesoscale system science objectives

- Resolve mesoscale dynamics (flow bursts, magnetopause FTEs etc.)
 - Magnetospheric constellation
 - Soft x-ray imaging (SMILE)
- Resolve mesoscales in the inner magnetosphere & tail coupling
 - Inner magnetospheric remote sensing (Plasmasphere/ring current) ENA/EUV
 - In situ ground truth
- Determine the cold plasma distribution & variability
- Resolve ionospheric/auroral mesoscales, magnetospheric coupling, auroral acceleration region
 - GDC <- linchpin mission
 - Auroral imager (e.g. SMILE)
 - Alfvén (ESA M Competition)
 - DYNAMIC (joint with GDC?)
 - ENLoTIS (ESA-E & NASA)
 - FACTORS (JAXA)
- Quantify ion outflow & effect on magnetosphere
- Resolve kinetic <-> mesoscale coupling
 - insert small constellation into mesoscale backbone, with high temporal resolution measurements, e.g. Plasma Observatory (ESA M Competition)

Geospace state variables (LWS/ESA/NOAA/HSO)

- LI
- Auroral imagery
 - Space-based 24/7 and ground-based high resolution
- Cross polar cap potential
 - DMSP
- State of radiation belts
 - (e.g., SAMPEX type measurements). COSPARTGCSS & SGRB
- Amount of open flux in the polar cap
- Solar irradiance/ionizing radiation spectrometer (better than F10.7)
- Cold plasma density
 - FLRs, in situ direct & in situ plasma line
- Geosynchronous measurements
 - GOES and LANL
- AMPERE FACs
- Convection maps (radars)
- Geomagnetic indices Dst, AE, Kp
- TEC maps

We need more than just measurements

With the revelation that mesoscale dynamics (~I-3 RE in scale) are both ubiquitous and central to magnetospheric dynamics, the science questions are dictating that we need a large undertaking to answer these questions. The ad hoc has approach is, and will continue to be, insufficient. Any initiative must resolve the mesoscales.

We need both a new coordination mechanism & a new worldwide effort that contains:

- Intentional, forward-thinking coordination of new & planned missions, not after the fact
- A mesoscale/fluid backbone to stitch the system together ← key missing element = multiple constellations of spacecraft in key regions at the mesoscales (MagCon, inner magnetosphere petals)
- Remote imaging measurements simultaneous with in situ
- Measurement of the state variables
- Coordinated & easily accessible ground-based measurements
- Advanced numerical modeling including data assimilation
- Big data coordination

All activities and initiatives are coordinated and working in concert to study Geospace holistically, as a system, at the scale sizes that we now know are driving the overall dynamics.

The magnetosphere is big; this would be a large effort. Needs to be international (think "mesoscale ISTP")