CGS | CENTER FOR GEOSPACE STORMS

Mesoscale processes during geomagnetic storms:

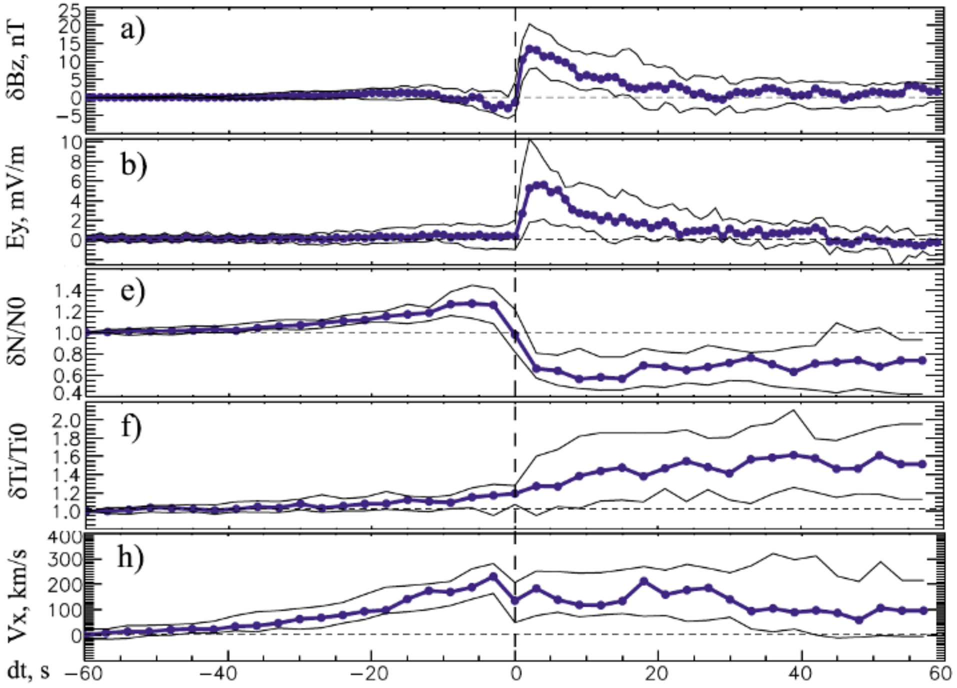
The future of *observing* *the global geospace in mesoscale resolution*

Matina Gkioulidou

Johns Hopkins Applied Physics Laboratory (APL)

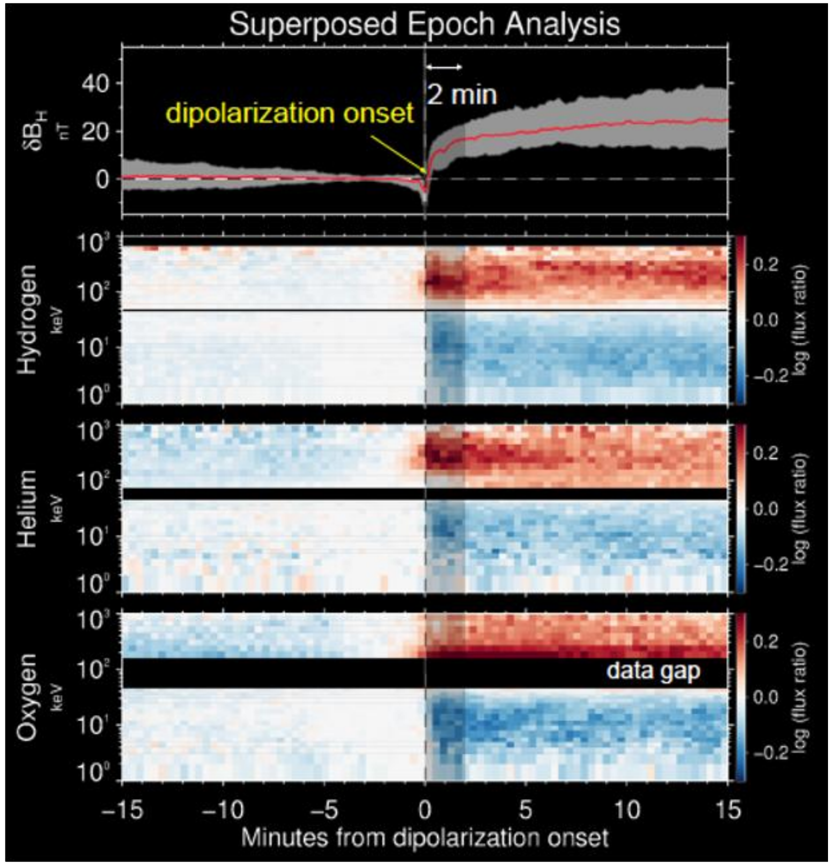
matina.gkioulidou@jhuapl.edu

What We Know: In-Situ Observations of Mesoscale Transport In the Plasma Sheet And Inner Magnetosphere



Runov et al., 2011 [JGR]: Superposed epoch analysis of dipolarization fronts and the associated particle and BBF signatures *in the plasma sheet*, based on THEMIS data

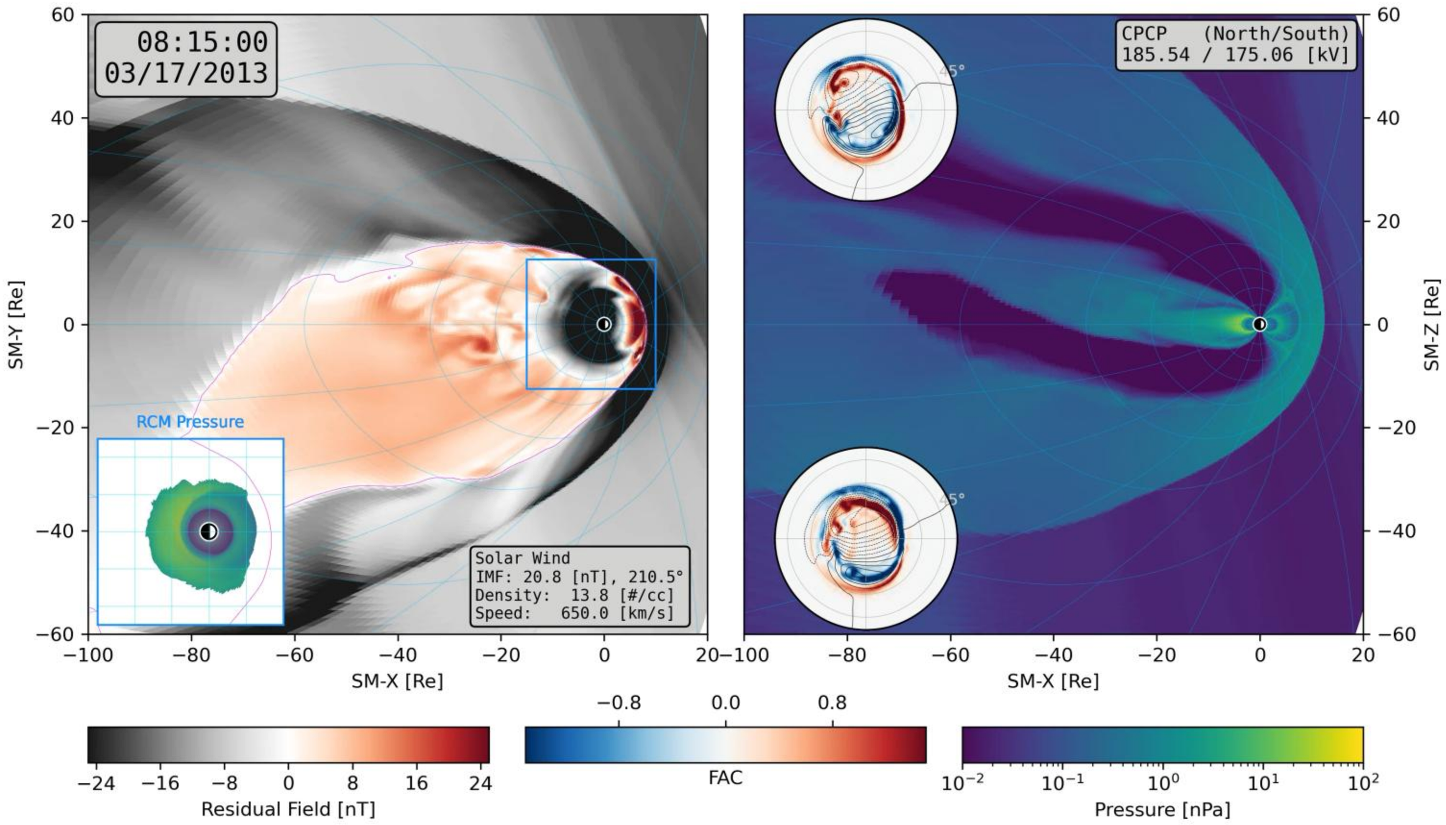
- *Plasma Sheet (~10-20 R_E from Earth):*
  - Bursty Bulk Flows (BBFs),
  - Dipolarization Fronts (DFs),
- *Inner Magnetosphere (inside GEO):*
  - Energetic ion injections



Motoba et al., 2018 [JGR]: Superposed epoch analysis of dipolarization fronts *inside geosynchronous orbit* based on Van Allen Probes data

What We Know: What Models Predict

Coupled GAMERA - RCM simulation of the March 13 2017 geomagnetic storm

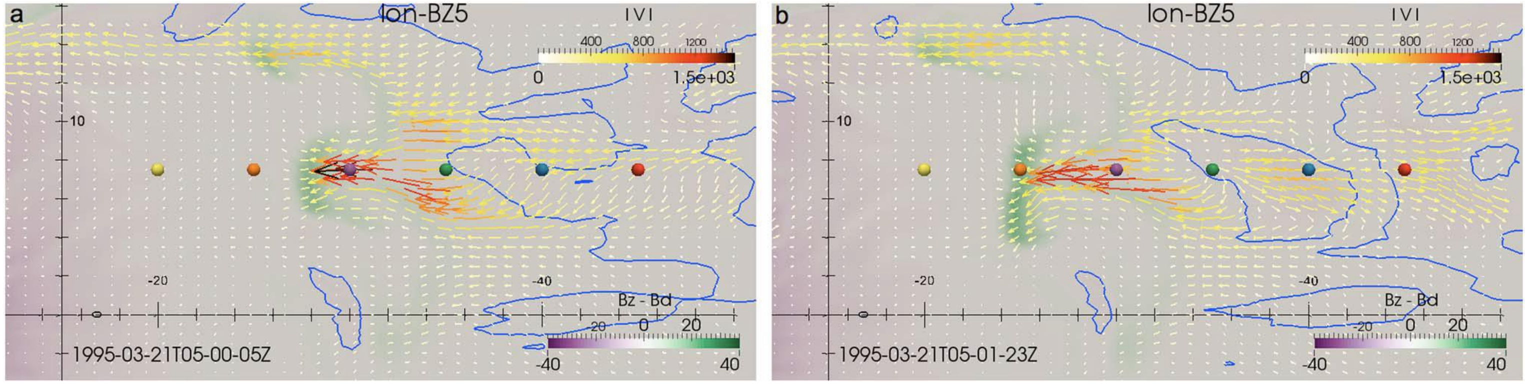


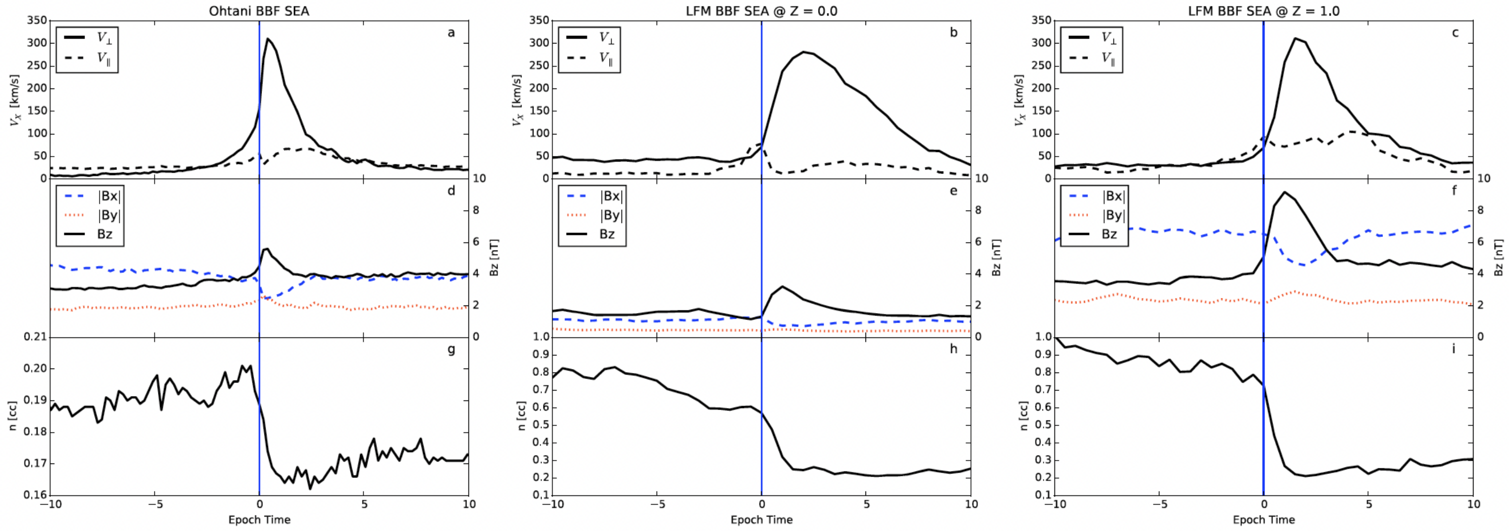
Simulations provide strong evidence that the plasma sheet mesoscale structures (BBFs/DFs) lead to energetic ion injections and contribute to the buildup of the storm-time ring current.

- *Yang et al., 2015 [JGR]* (RCM-E: inner magnetosphere self-consistent model)
- *Yu et al. 2014 [GRL]* (RAM-SCB coupled with BATS-R-US: inner magnetosphere model coupled with an MHD code)
- *Cramer et al., 2017 [JGR]* (RCM coupled with OpenGGCM: inner magnetosphere model coupled with an MHD code)
- *Ukhorskiy et al., 2018 [JGR]; Sorathia et al. 2021 [Frontiers]; Sciola et al. 2023 [JGR]* (GAMERA coupled with CHIMP and GAMERA coupled with RCM: MHD code coupled with particle tracing code and with an inner magnetosphere model)

Comparing models to statistical studies of in-situ observations

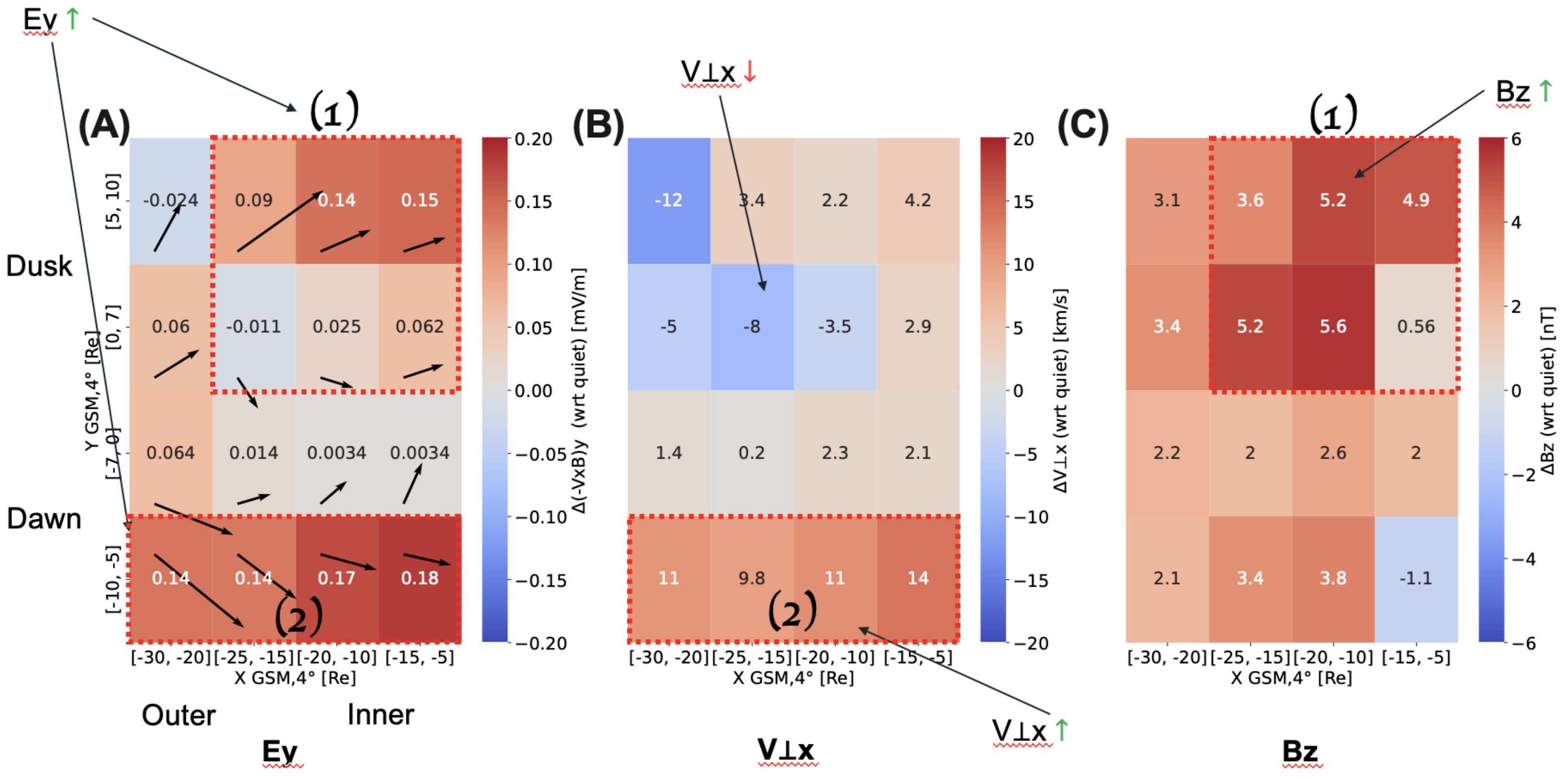
- Wiltberger et al., 2015 [JGR] vs Ohtani et al, 2004 [JGR]
  - LFM simulations: Superposed epoch analysis of the flows seen in the magnetotail during 90 min of sustained southward IMF in the solar wind.
  - This analysis used the same selection criteria as the Ohtain2004 analysis of Geotail observations.
  - BBF velocity, magnetic field, and density are qualitatively similar to those seen in the observations. However, there is a major difference in the density characteristics is the magnitude of the density drop after the BBF passage, attributed to the selection of data from the center of the LFM plasmasheet





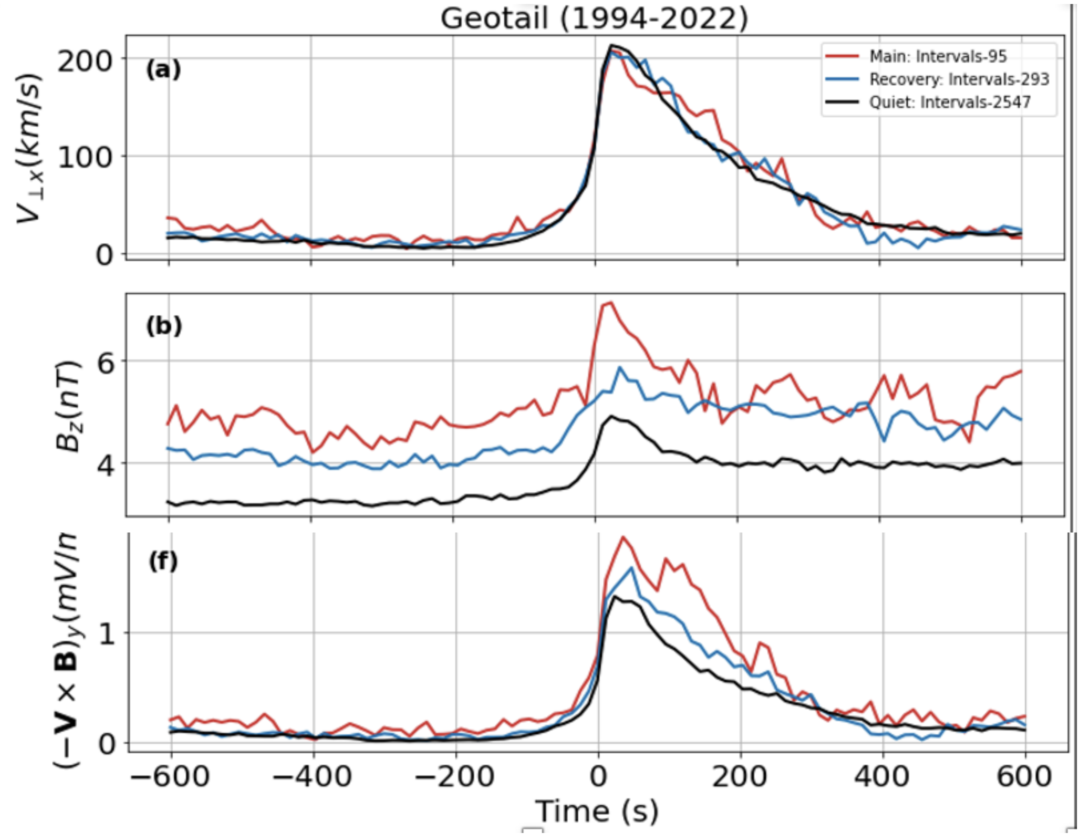
Plasma Sheet Magnetic Flux Transport During Geomagnetic Storms

- *Raptis et al., 2024 [JGR]:* Statistical Geotail plasma sheet properties study (1994-2022); data chosen close to the central plasma sheet
- Plasma sheet properties normalized to quiet times, along with the median flow of ions during main storm phase.
- Elevated Ey at the Inner Dusk side and at the Dawn side, with very limited changes in the midnight sector.
- This elevated Ey is realized through a velocity enhancement at dawn and a Bz enhancement at the dusk
- Relatively lower velocity at the dusk side



Superposed Epoch Analysis of Bursty Bulk Flows (BBFs) in the Plasma Sheet During Geomagnetic Storms

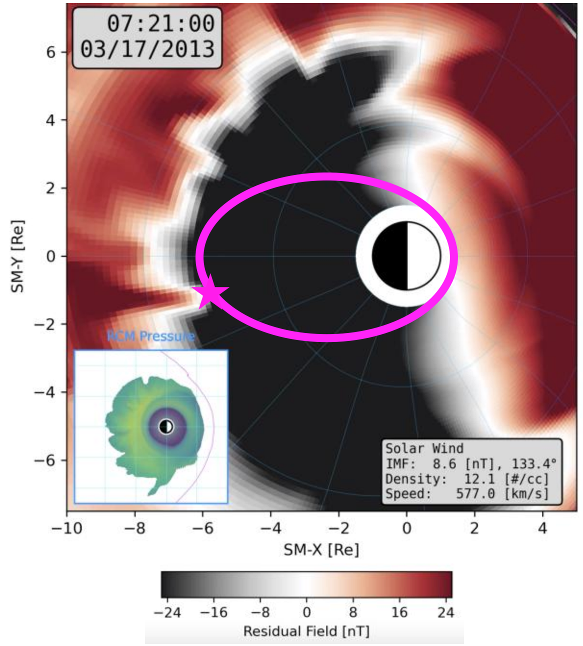
- Devanandan et al. (in prep): List of BBFs from the entire available Geotail dataset (1994-2022).
  - A BBF interval starts when $V_{\perp x}$ > 100 km/s and ends when $V_{\perp x}$ < 100 km/s with at least one point within the interval where $V_{\perp x}$ >250 km/s.
  - -15 RE <YGSM< 15 RE and -5 RE <XGSM< -31 RE.
- The variations of magnetic field and plasma parameters during BBFs are similar during storms and quiet time.
- No significant difference in $V_{\perp x}$ is observed between storm-time and quiet-time BBF intervals.
- Bz is elevated throughout the epoch window for storm-time BBFs due to enhanced magnetic field in the plasma sheet during storms.
- Comparing quiet-time and storm-time BBFs, the relative increase in magnetic flux transport is primarily due to an elevated magnetic field.

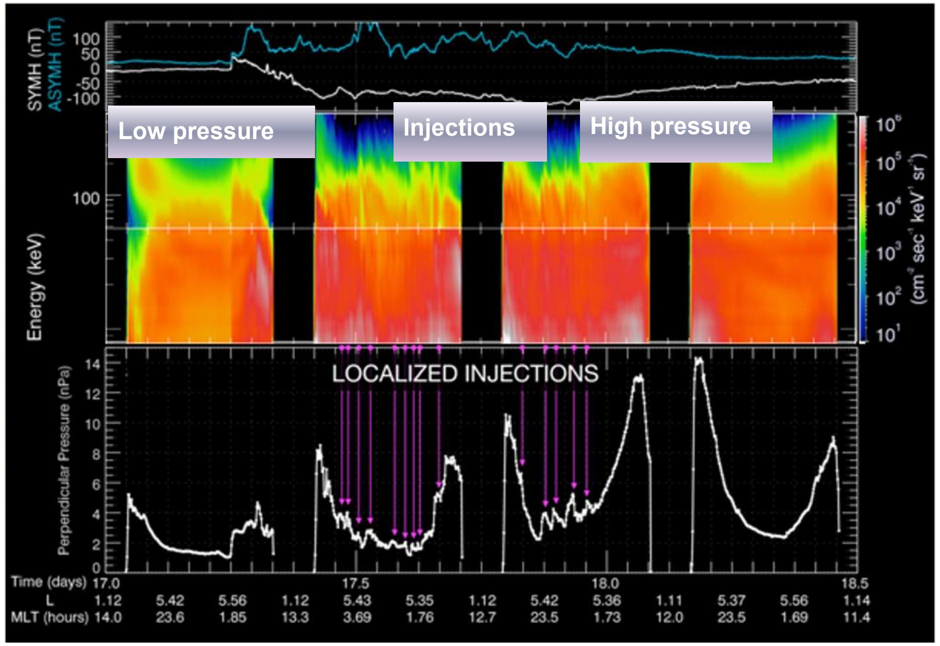


Future work: Do we find similar behavior in simulations?

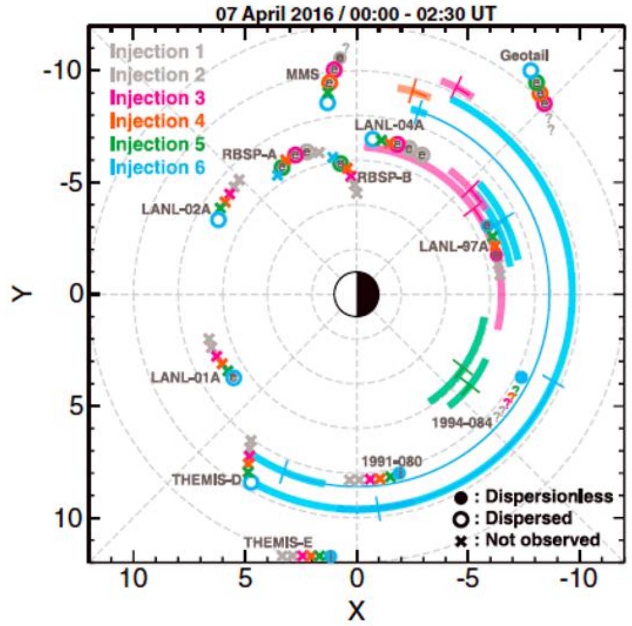
THE CHALLENGE

Assessing observationally the connection between mesoscale structures and inner magnetosphere injections the role of ion injections in building the storm-time ring current, due to spatially confined nature of the in-situ observations, which lack global context.

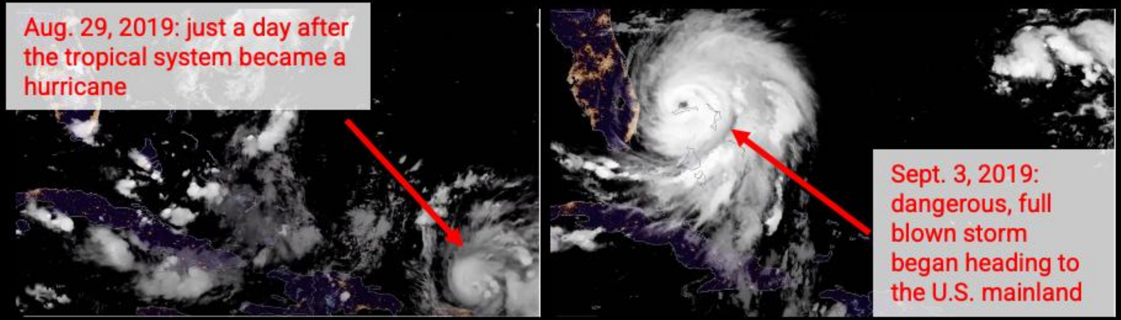


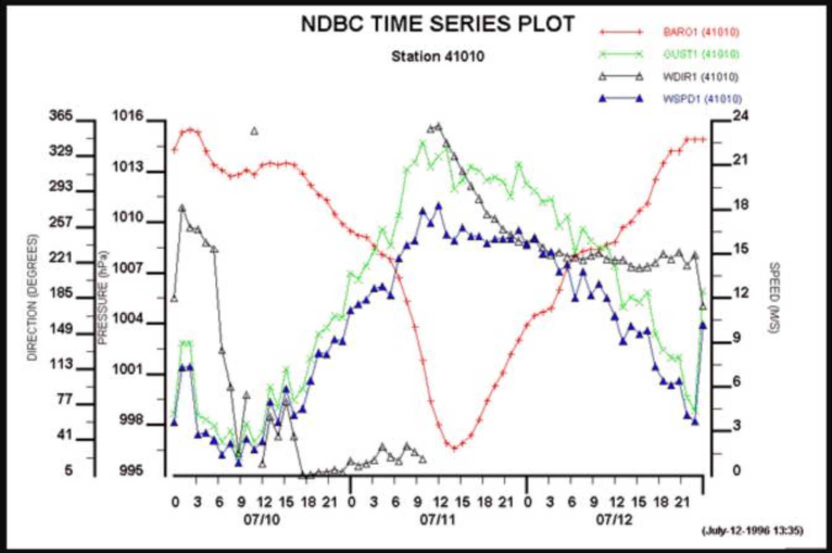


Gkioulidou et al., 2014 [JGR]: Attempt to estimate contribution of mesoscale injections to the ring current: ~30% with a lot of assumptions and caveats



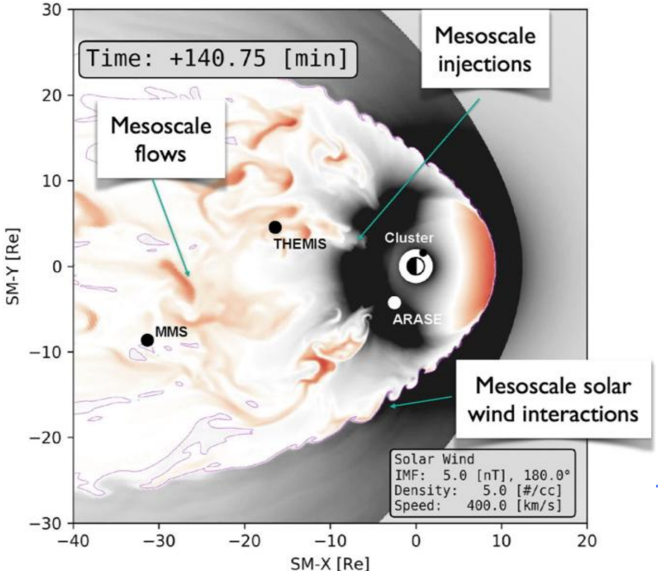
Turner et al., 2017 [JGR]: Attempt to estimate injection extent and evolution using 16 (!) spacecraft (rather serendipitous conjunction): "Due to the discrepancy between the number, penetration depth, and complexity of electron versus ion injections, this event presents challenges to the current conceptual models of energetic particle injections"

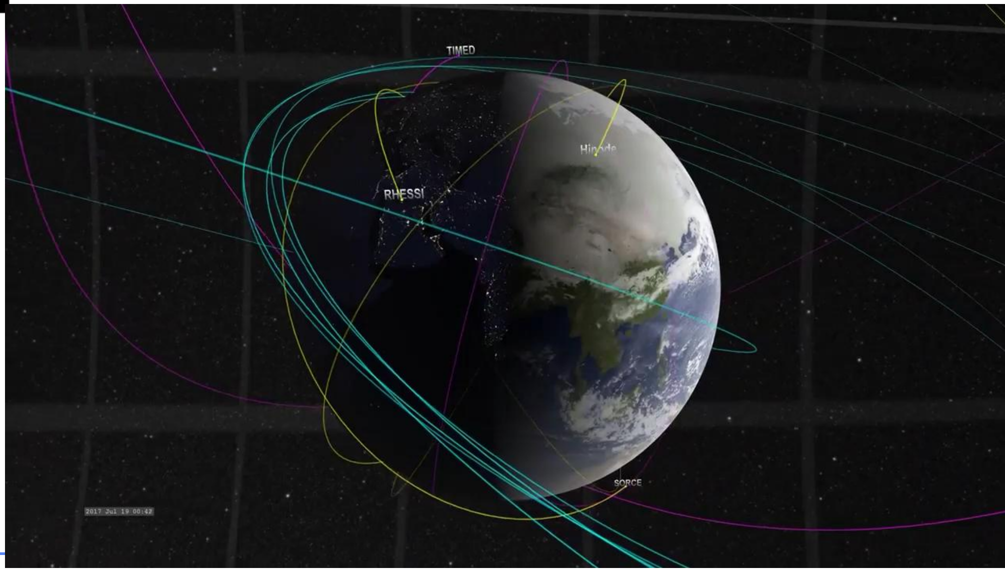




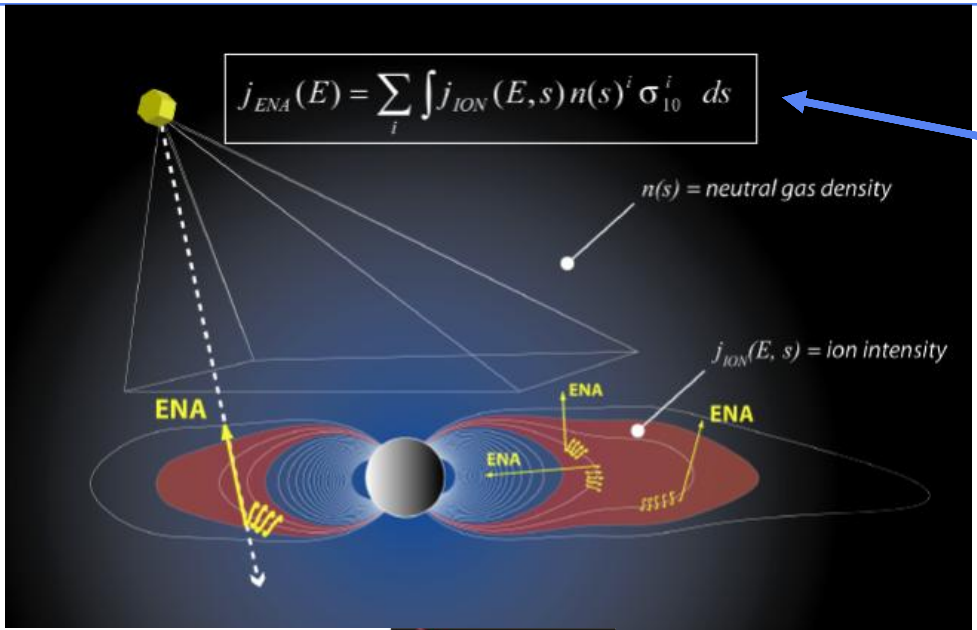
It's like trying to understand the evolution of a hurricane taking measurements from a single weather station. *-Dave Sibeck*

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

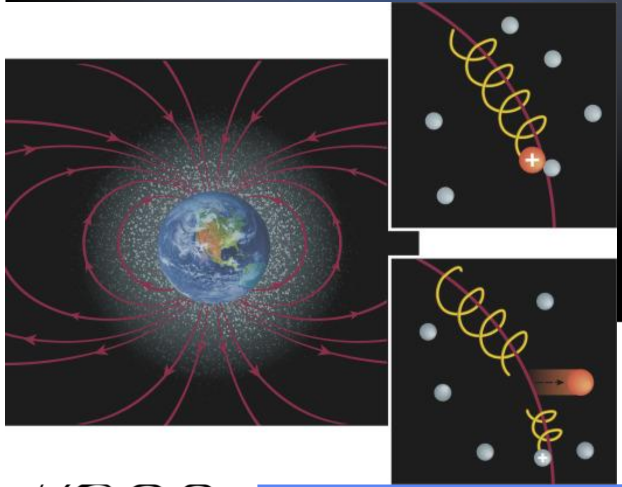




Seeing is Believing: Energetic Neutral Atom (ENA) Imaging



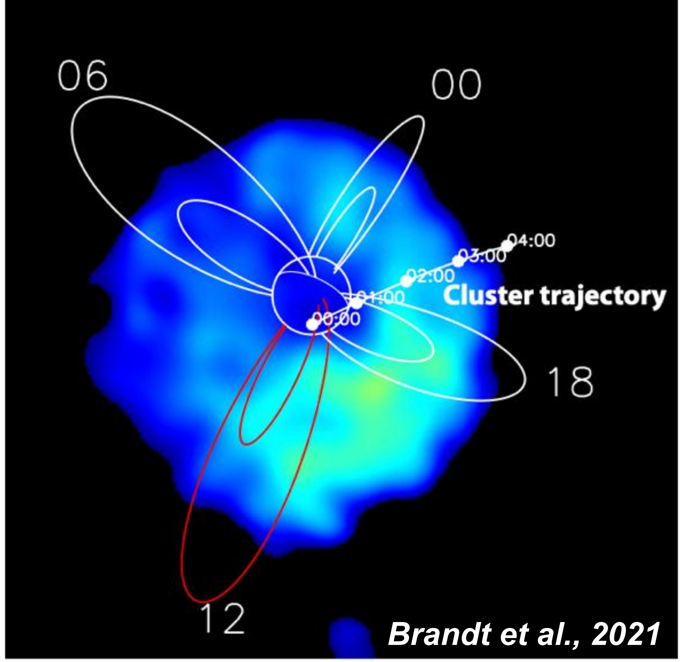
Brandt et al., 2021


Ilie, 2020

The ENA emissions from ring current and plasma sheet are optically thin and can be expressed as line integrals of underlying ion distribution as they experience charge exchange with the geocorona.

We can “see” plasmas with ENA imaging

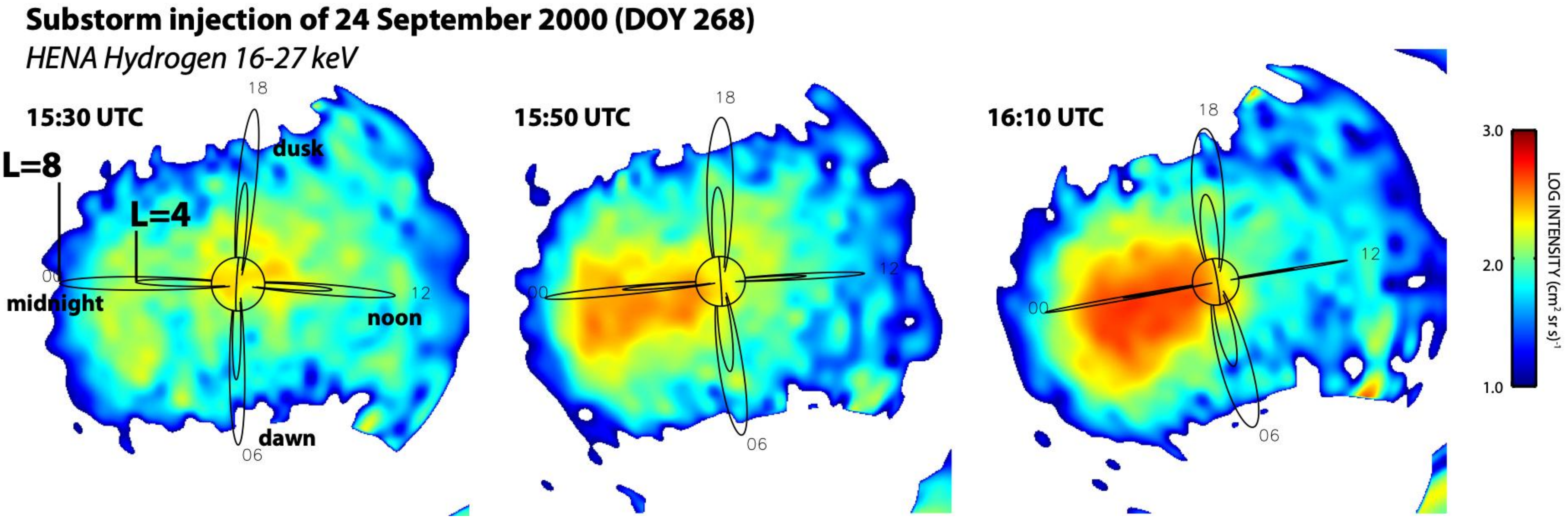
ENA imaging vs in-situ observations



Brandt et al., 2021

ENAs provide not only a global image of the ion distribution but also compositional and spectral information about that distribution, just like photons reveal information about their source

Limited Temporal and Spatial Resolution of Previous ENA Observations

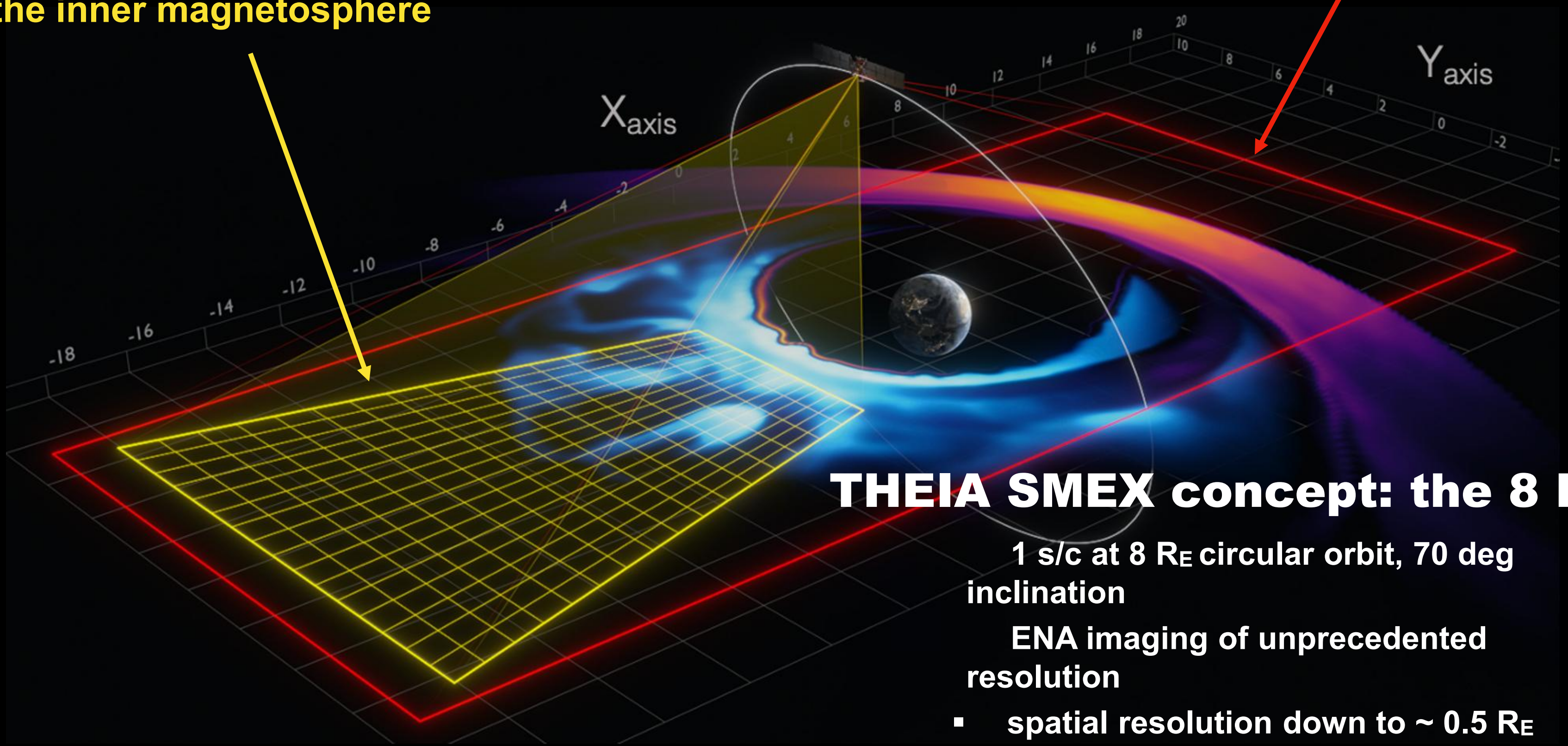


Brandt et al., 2021

Can we Observe Mesoscale Ion Injections with ENA Imaging? *YES WE CAN!*

Narrow FOV ENA camera (NENA), with 10x higher sensitivity than any previously flown 2D ENA camera, captures mesoscale ion injections from the plasma sheet to the inner magnetosphere

Wide FOV Ring current ENA camera (WRENA) sees the buildup of the ring current (Heritage: JUICE/JENI, IMAP-Ultra)



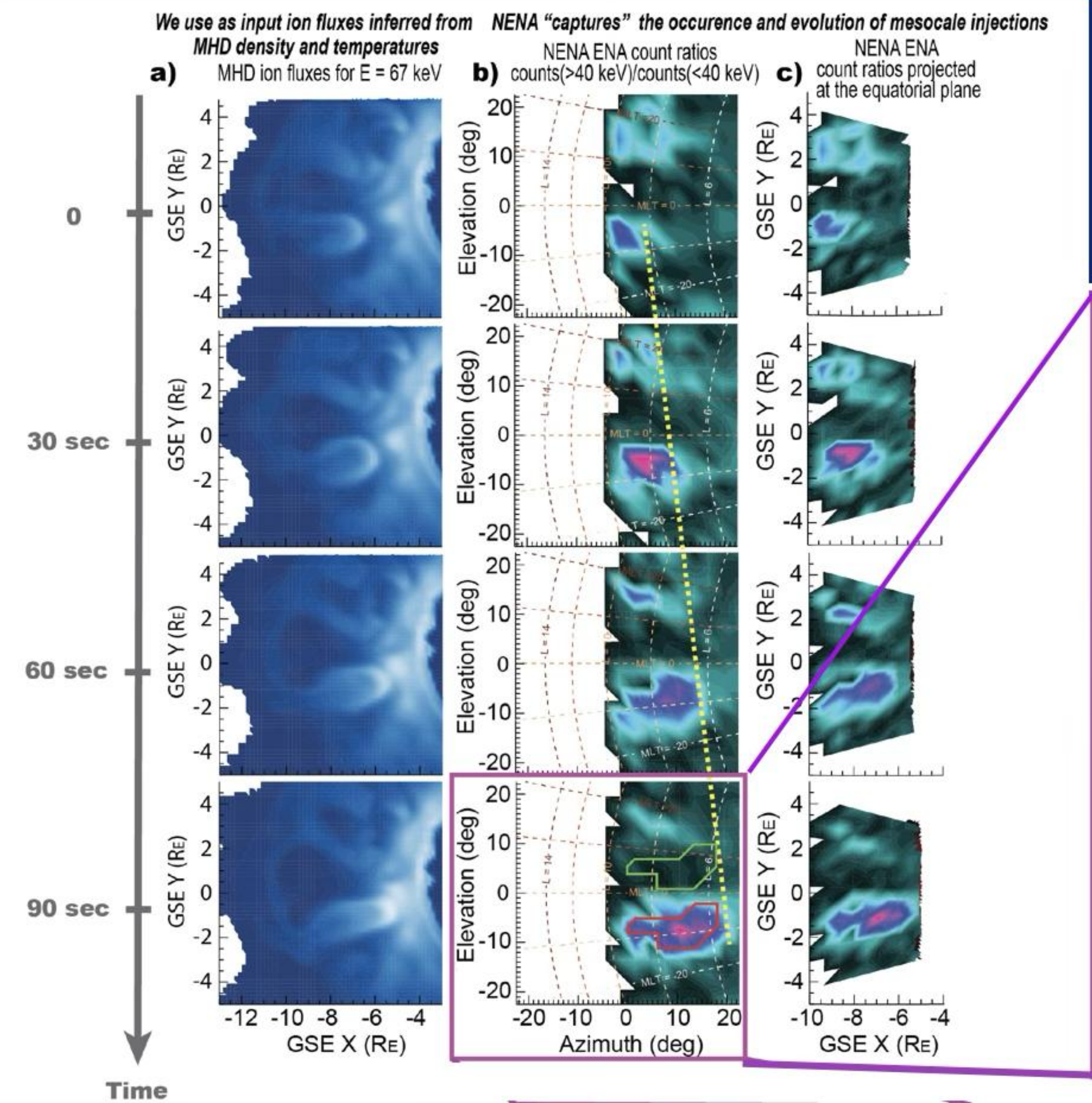
THEIA SMEX concept: the 8 R_E view

1 s/c at 8 R_E circular orbit, 70 deg inclination

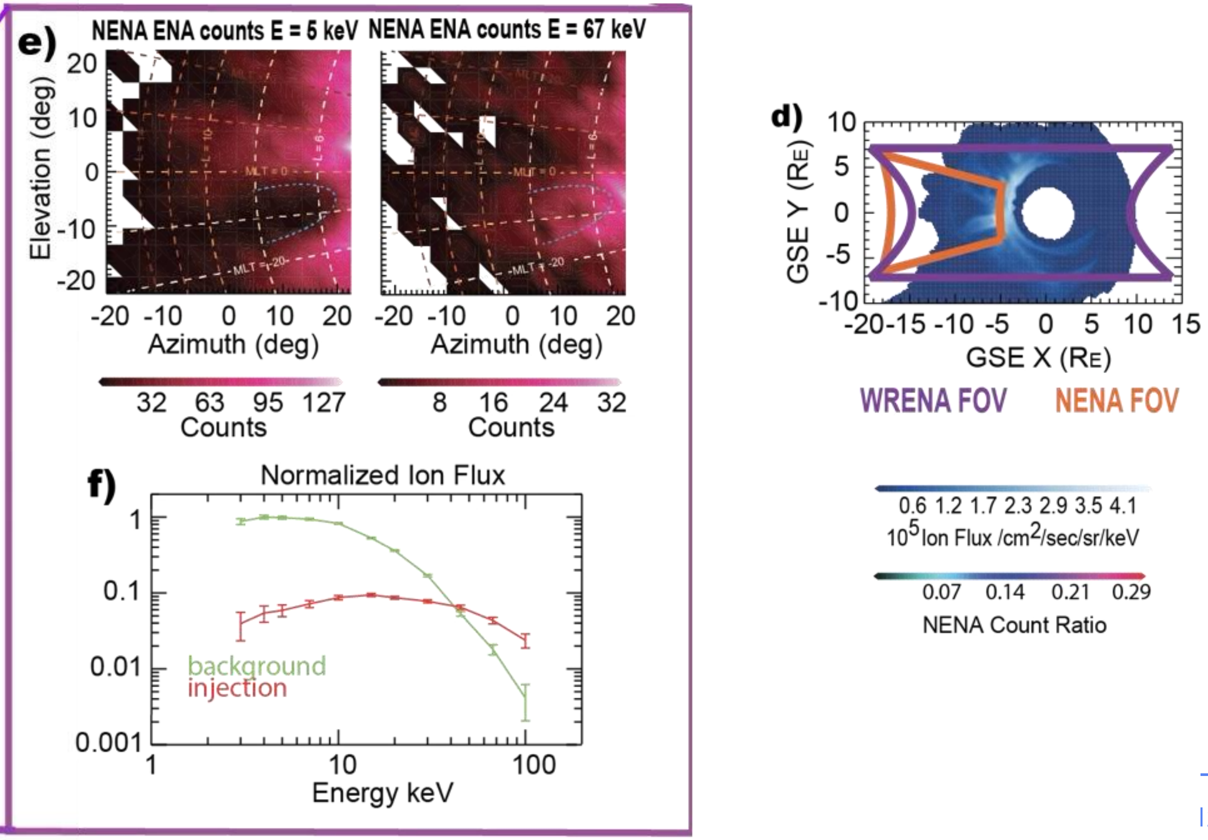
ENA imaging of unprecedented resolution

- spatial resolution down to ~ 0.5 R_E
- temporal resolution as fast as ~ 30 sec

Can we Observe Mesoscale Ion Injections with ENA Imaging?
YES WE CAN!



Observing System Simulation Experiment (OSSE), using MHD simulations ion fluxes as an input, demonstrates that the NENA ENA camera, from an example vantage point along a dawn-dusk oriented orbit, at YGSE = 0, can capture mesoscale ion injections and their properties as they move from the plasma sheet to the inner magnetosphere



Can we Observe Mesoscale Ion Injections with ENA Imaging?
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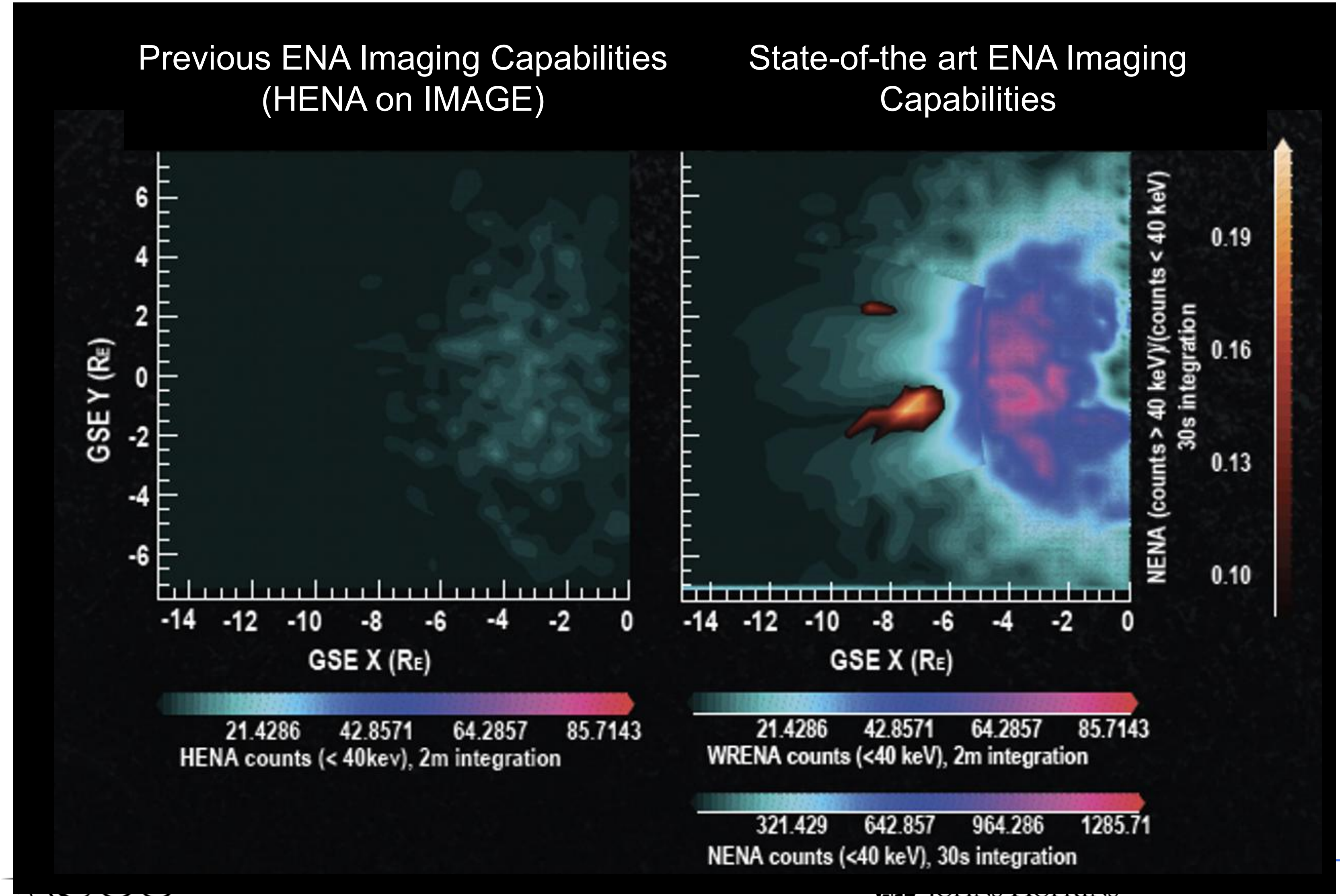
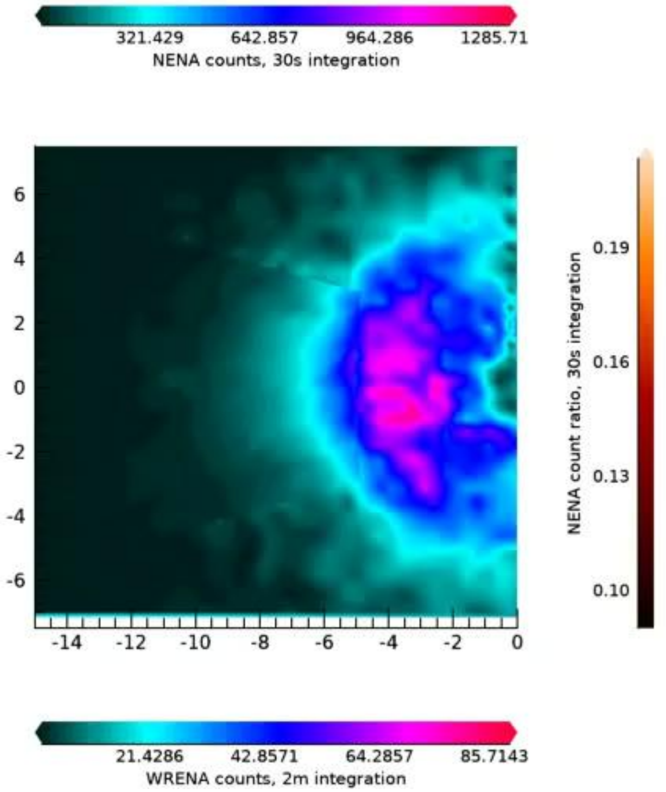
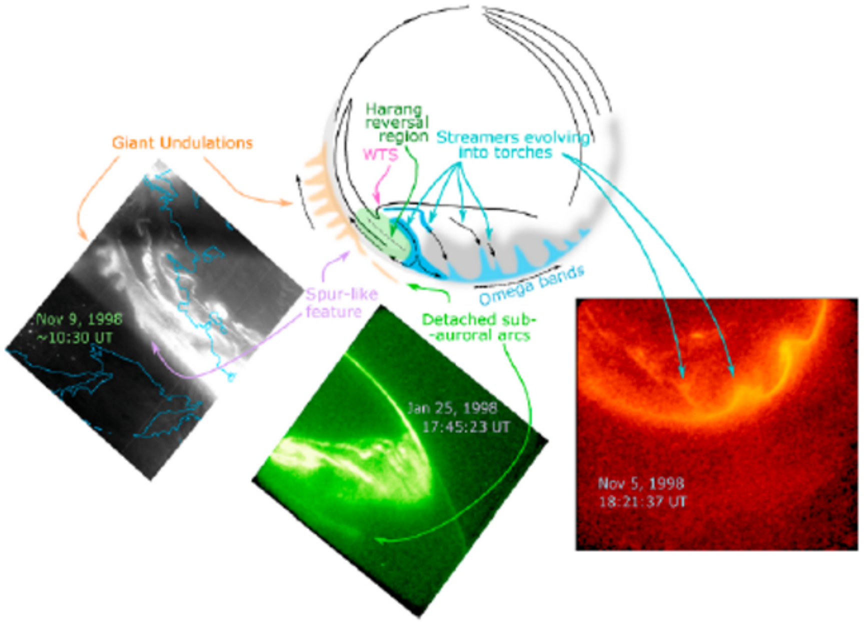




What We Know: Mesoscale Ionospheric/Auroral Phenomena

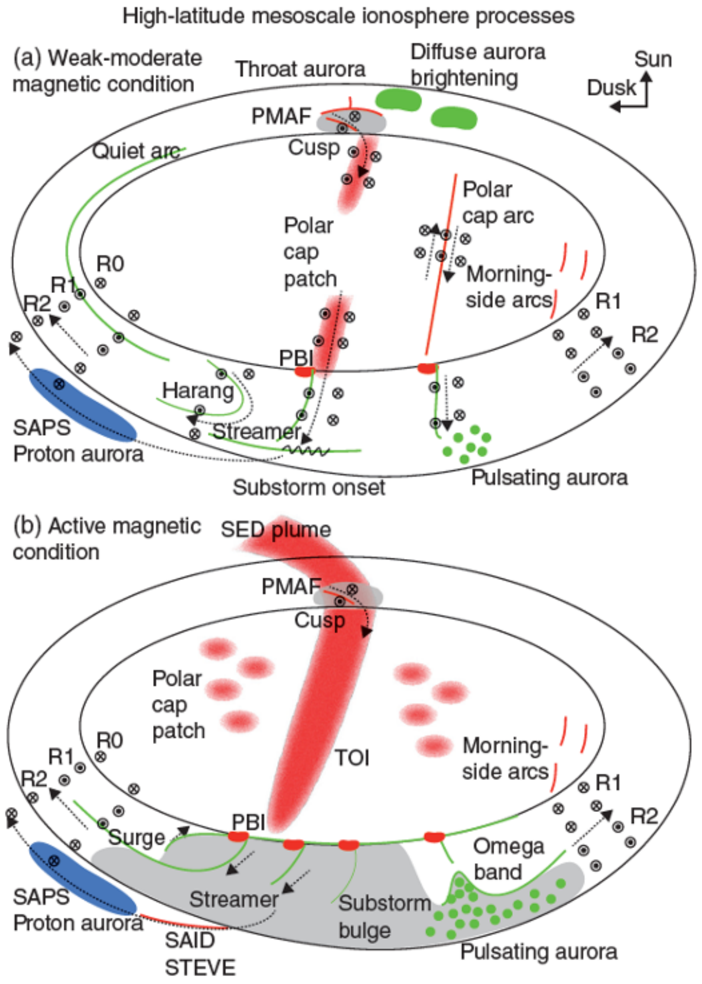


Henderson et al., 2021 [Geophysical Monograph Series]

Auroral phenomena, ranging from mesoscale auroral streamers to the global brightening of an auroral substorm, are a manifestation of both the energy deposition within the strongly coupled M-I system and the ionospheric conditioning itself.

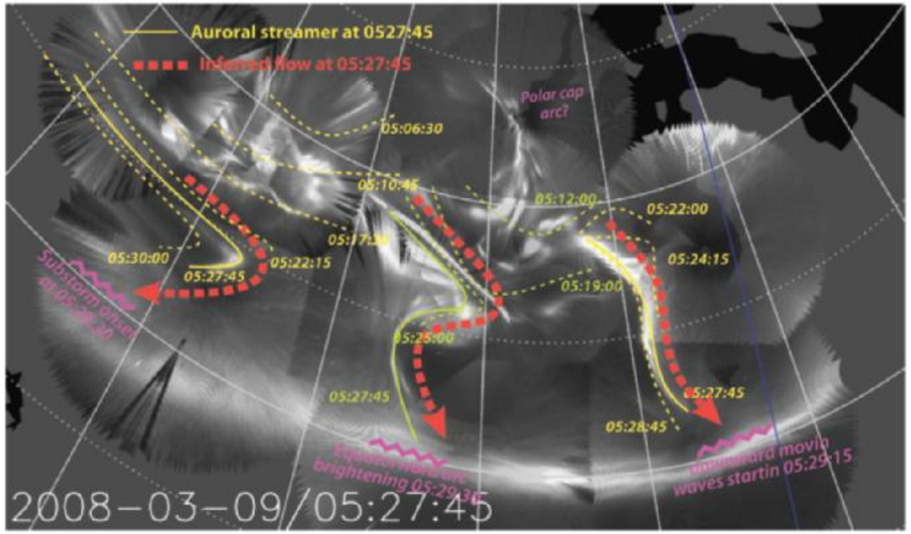
Years of observations have uncovered myriad auroral mesoscale phenomena:

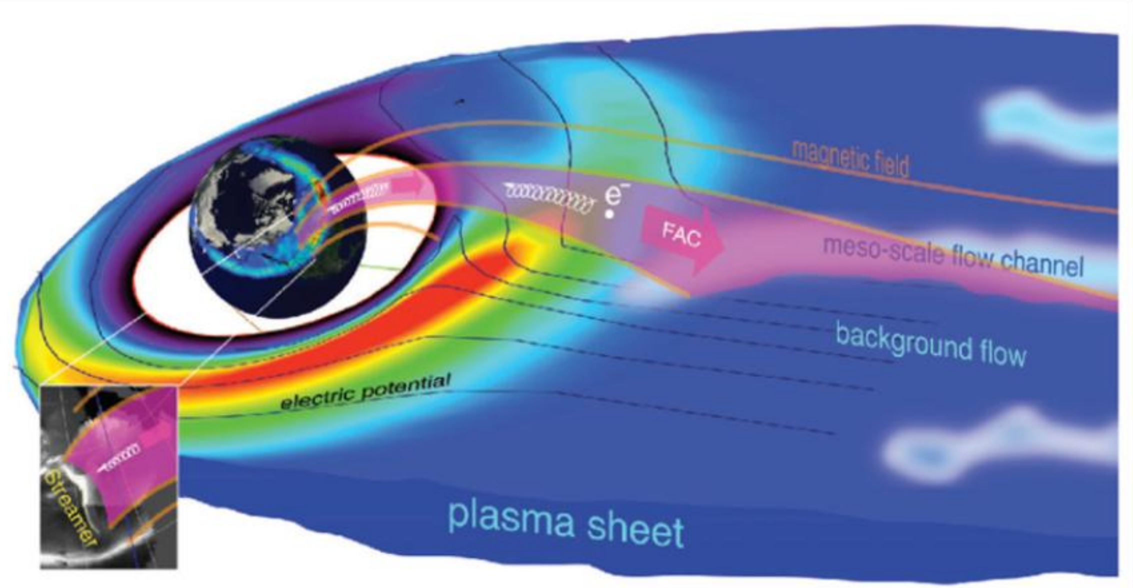
- Polar cap patches
- Poleward Boundary Intensifications (PBIs)
- Streamers
- Arcs
- Surges
- Omega bands
- Substorm beads
- Corresponding flow channels/Field Aligned Currents (FACs)/conductance.



Nishimura et al., 2021 [Geophysical Monograph Series]

WHAT WE DON'T KNOW: RELATION BETWEEN MAGNETOSPHERIC MESOSCALE PROCESSES AND MESOSCALE AURORAL PHENOMENA



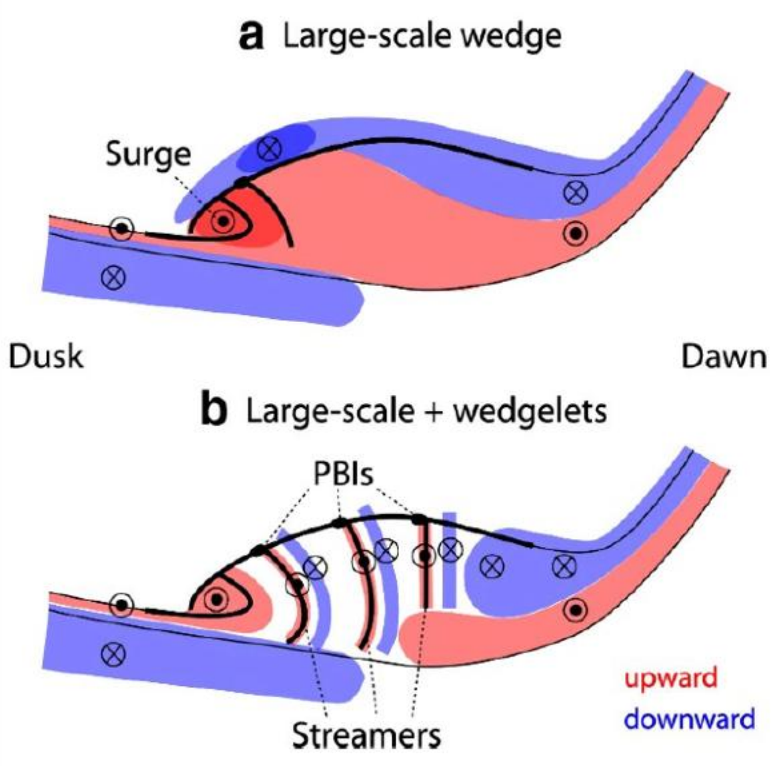


Lyons et al., 2012 [Geophysical Monograph Series]

For example:
How do auroral streamers evolve spatially and temporally with respect to the plasma sheet mesoscale structures (BBFs, DFs, particle injections) under different geomagnetic conditions?

THE CHALLENGE: ASSESSING OBSERVATIONALLY THE GLOBAL CONSEQUENCES OF MESOSCALE PROCESSES

- Is the Substorm Current Wedge (SCW) buildup a result of smaller scale upward and downward current systems driven by streamers (aka wedgelets) *[Liu et al. 2015; JGR]* or is it a globally coherent system, where wedgelets are probably not a primary constituent *[Ohtani and Gjerloev 2020; JGR]*?
- The mesoscale, fast burst component of the substorm evolution is a key factor in the excitation of Geomagnetically Induced Currents (GICs) during a geomagnetic storm *[Kozyreva et al., 2018; Earth, Planets and Space]*.



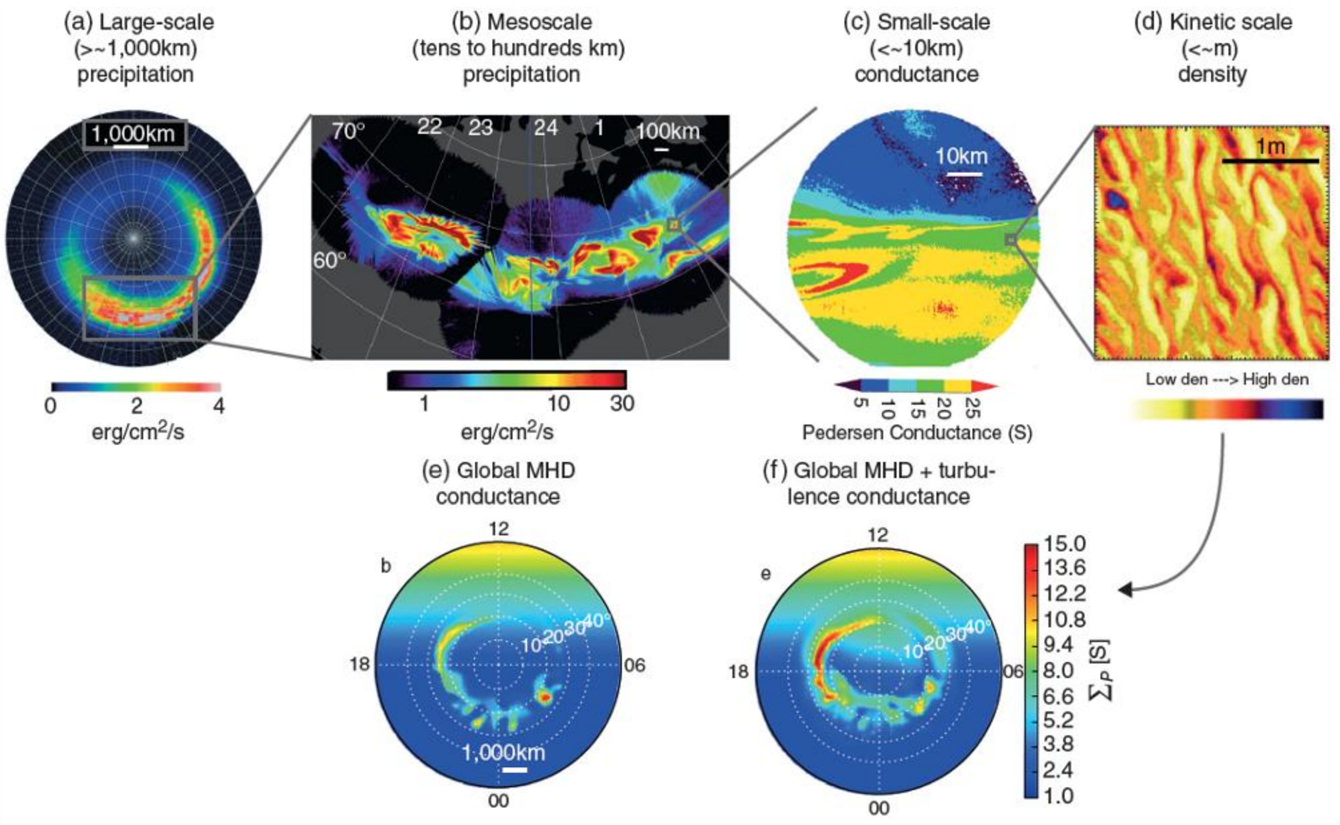
Nishimura et al. 2020 [Earth Planets Space]

The Challenge: Assessing Observationally The Global Consequences Of Mesoscale Processes

Precipitation associated with mesoscale aurora, and its global effects is poorly understood. Using ground based auroral All-Sky Imagers:

- *Nishimura et al., 2021 [Geophysical Monograph Series]; Gabrielse et al., 2021 [Frontiers]:* significant mesoscale precipitation contribution to the total energy flux during expansion phase of substorm.

However, ground-based imaging cannot address how much mesoscale precipitation impact global total precipitation, or how mesoscale precipitation varies with the hemispheres and seasons.

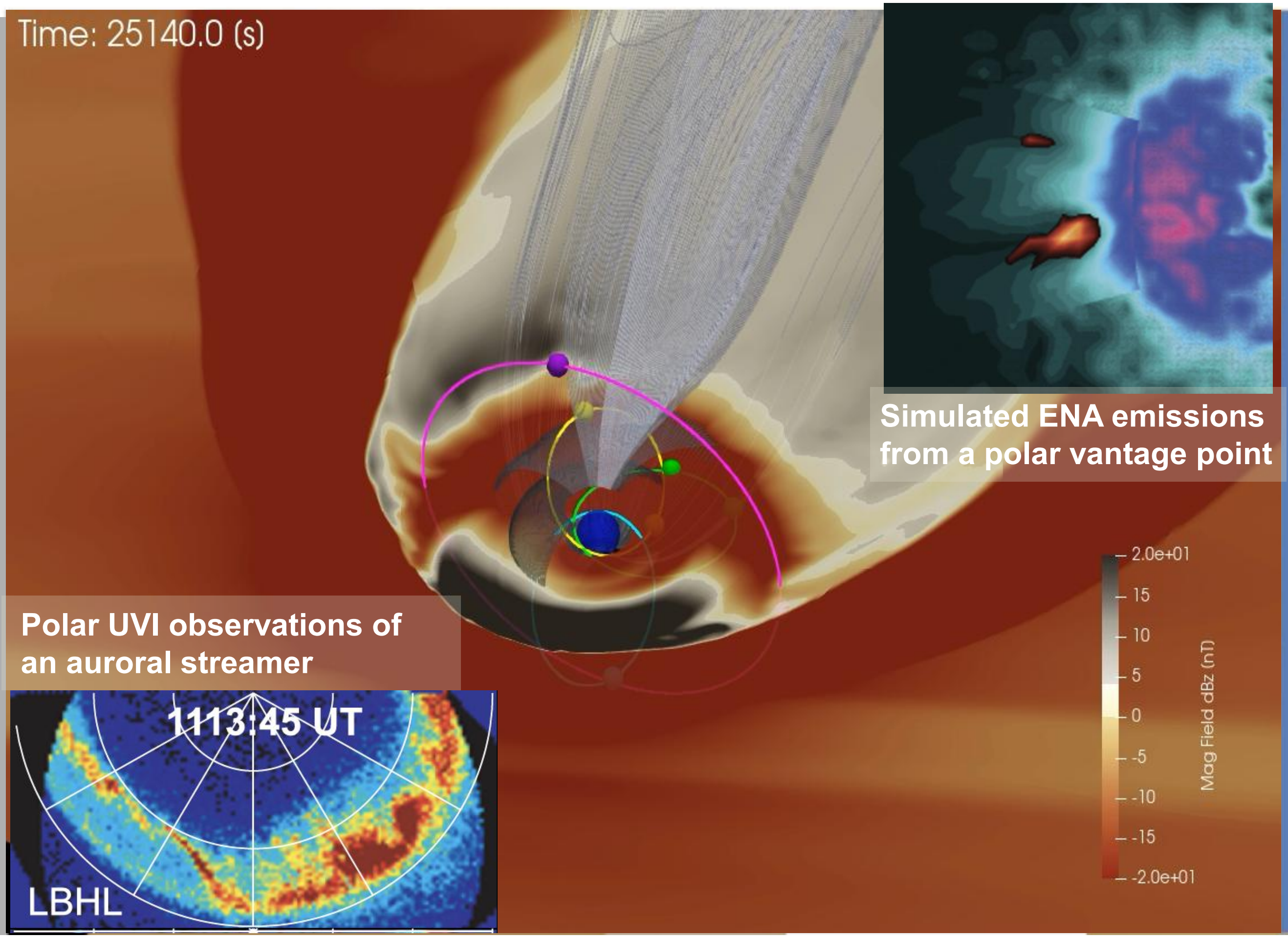


Nishimura et al., 2021 [Geophysical Monograph Series]

PARAGON: Plasma Acceleration, Reconfiguration, and Aurora Geospace Observation Network

“Seeing” the Global Geospace at Mesoscale resolution

Matina Gkioulidou
Brandt, Pontus C.
Cohen, Ian
DeMajistre, Bob
Donovan, Eric
Gabrielse, Christine
Goldstein, Jerry
Henderson, Michael
Kepko, Larry
Keesee, Amy
Liang, Jiang
Michael, Adam
Mitchell, Don
Nikoukar, Romina
Nishimura, Toshi
Paxton, Larry
Roelof, Ed
Runov, Andrei
Sotirelis, Tom
Sorathia, Kareem
Spanswick, Emma
Turner, Drew



Simulated ENA emissions from a polar vantage point

Polar UVI observations of an auroral streamer

PARAGON in a nutshell:

Remote sensing platforms:

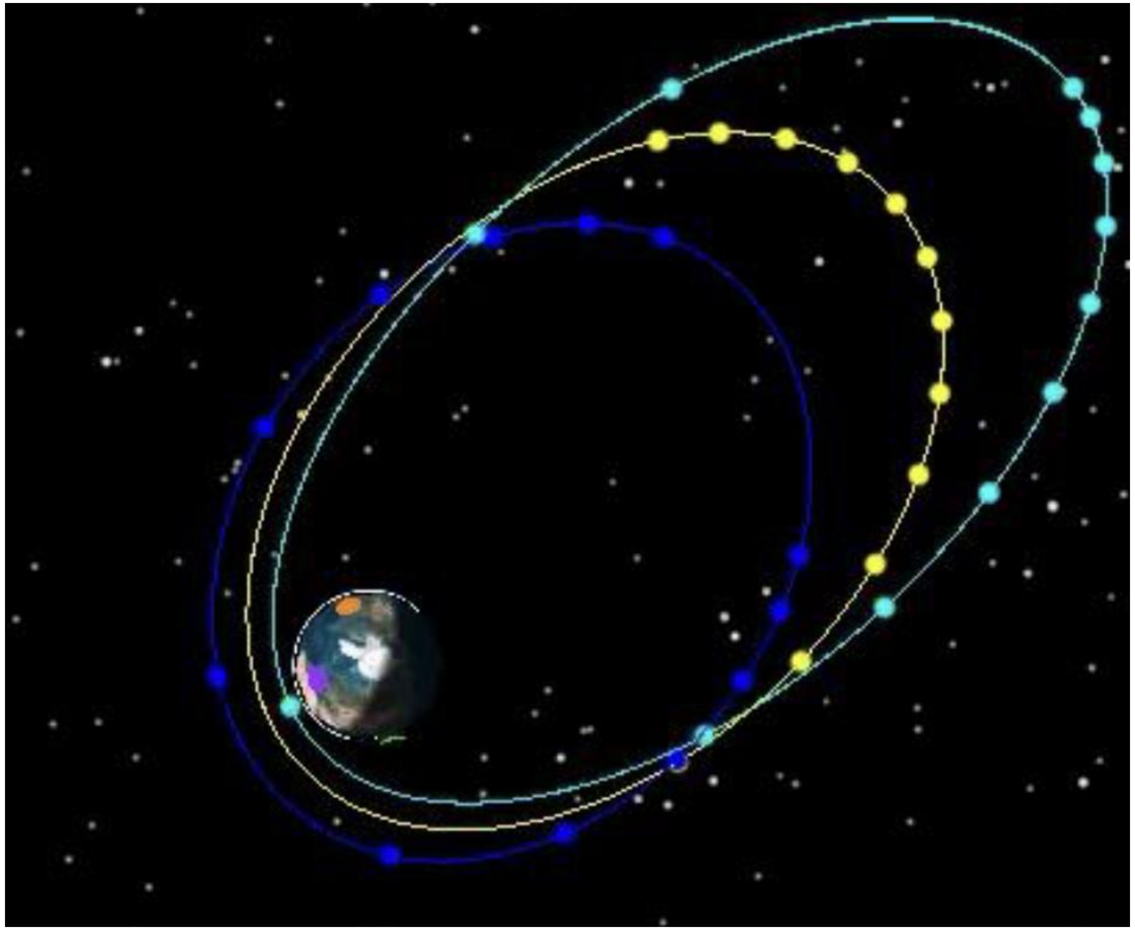
- 3 three-axis-stabilized S/C in common, polar, circular orbit of 9 R_E (magenta orbit)
- Unprecedented spatial and temporal resolution imaging of the ring current and the plasma sheet, the aurora, and the plasmasphere.
- Simultaneous, dual-hemisphere imaging of the auroral ovals

In-situ platforms:

- 4 spinning small satellites, in near-equatorial, elliptical orbits (yellow, green, cyan example orbits)
- Plasma, energetic particles, and magnetic field measurements

https://doi.org/10.3847/25c2cfeb.973ef1d2

Magnetospheric Constellation (MagCON)



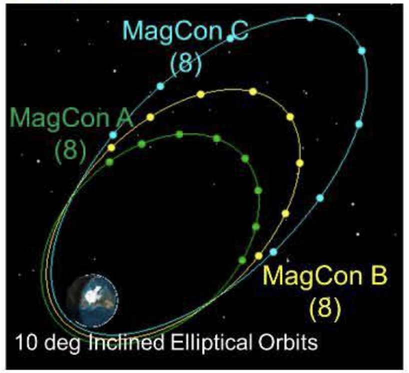
Orbit	Apogee (RE)	Perigee (km)	Period (hours)	Deorbit (m/s)
A (blue)	8.24	6,237	16.26	422
B (yellow)	10.79	3,725	21.67	239
C (cyan)	15.00	1,400	32.52	99

- 36 spacecraft
- Plasma, Magnetic Field measurements & Energetic particles

PARAGON + MagCON = Links

Links Mission

Links:



MagCon Constellation

PARAGON Constellation

Key Features:

- MagCon (24 satellite constellation)
  - ***Payload:*** *Magnetometer (MAG), Solid State Telescope (SST), Electrostatic Analyzer (ESA), Charge/Discharge Sensor (CDS)*
  - ***Flight System:*** *39-month life spacecraft, S-band communications up to 2.5 Mbps, Hydrazine propellant system, microsat avionics, spinning satellite, powered by body-mounted solar panels*
- Launch: **Vulcan VC4S**, injection orbit: 1.1Re x 10.79 Re at 10 deg inc, nominal launch: 2031
- Orbits: A: 1.49Re x 8.24Re, B: 1.29Re x 10.79Re, C: 1.11Re x 15Re at 10 deg inclination
- PARAGON (2 satellite constellation)
  - ***Payload:*** *Energetic Neutral Atom Wide Angle Camera (ENA WAC), Energetic Neutral Atom Narrow Angle Camera (ENA NAC) x 2, Far Ultraviolet Imager (FUV) x 2, Charge/Discharge Sensor (CDS)*
  - ***Flight System:*** *39-month life spacecraft, S-band communications up to 4.5 Mbps, Hydrazine propellant system, smallsat avionics, 3-axis stabilized, powered by deployed solar panels*
- Launch: **Falcon 9**, nominal launch: 2031
- Orbit: 9Re circular at 70-90 deg inclination

Scientific Objectives:

- Discover, quantify, and understand the global impact of mesoscale processes in the flow of mass, momentum, and energy through geospace
- Understand mesoscale energy input at the dayside magenetopause and flanks (e.g., the extent and temporal evolution of magnetopause reconnection)
- Understand the global impact of mesoscale magnetospheric energy flow:
  - How do plasma sheet mesoscale structures transport and energize plasma from the plasma sheet to the inner magnetosphere? Under what conditions and to what extent do they contribute to the buildup of the storm-time ring current?
- Observe the global impact of mesoscale MI coupling:
  - How does the aurora respond to transient mescale plasma sheet structures?

Key Challenges:

- Capacity for building a fleet of 24 MagCon instrument suites and spacecraft may exceed the resources of many potential suppliers
- High tempo early orbit operation of a 24 MagCon satellite constellation in highly elliptical 10 deg inclined orbit without crosslinks and with limited direct communications capability

Technical Risk Rating is Medium-Low

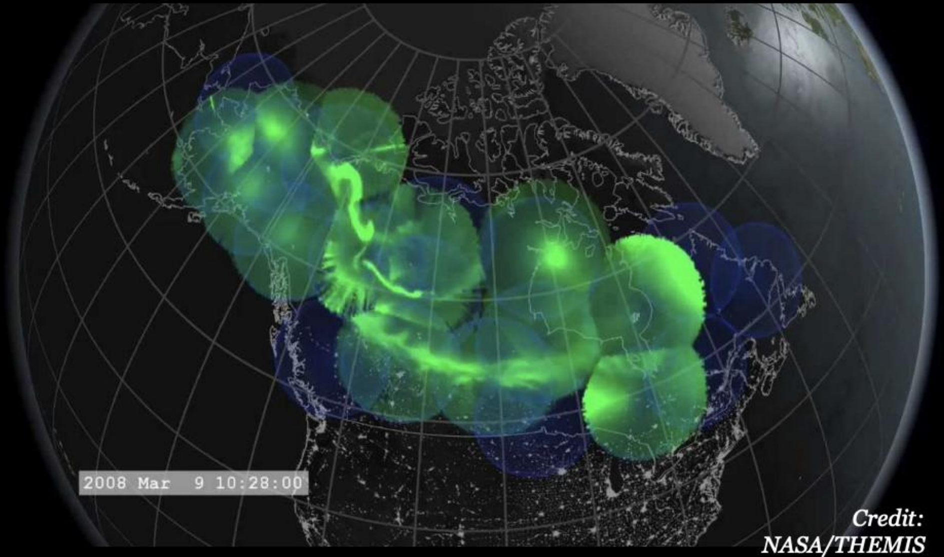
PARAGON = Plasma Acceleration, Reconfiguration, and Aurora Geospace Observation Network
MagCon = Magnetospheric Constellation

CGS

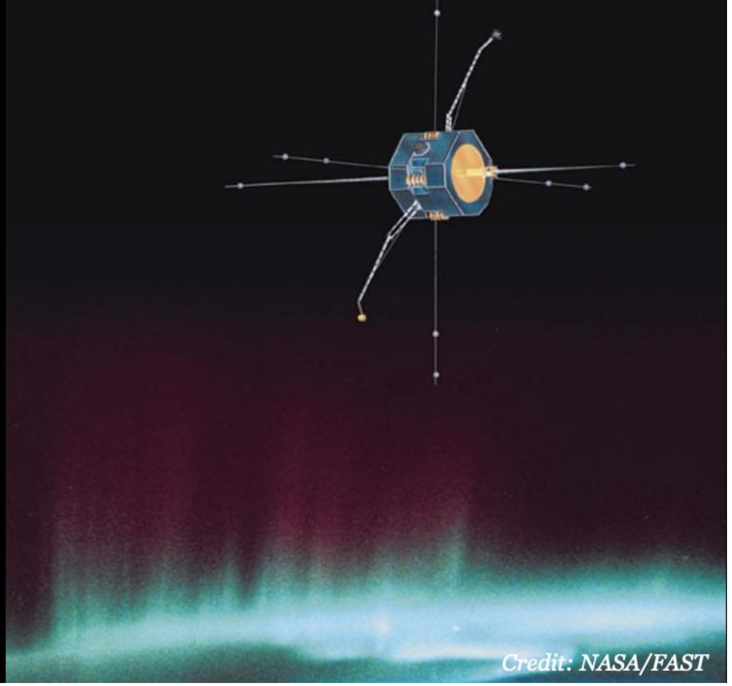
Can we apply the physical insight gleaned from comprehensive measurements at Earth to other systems?

Sounding rockets

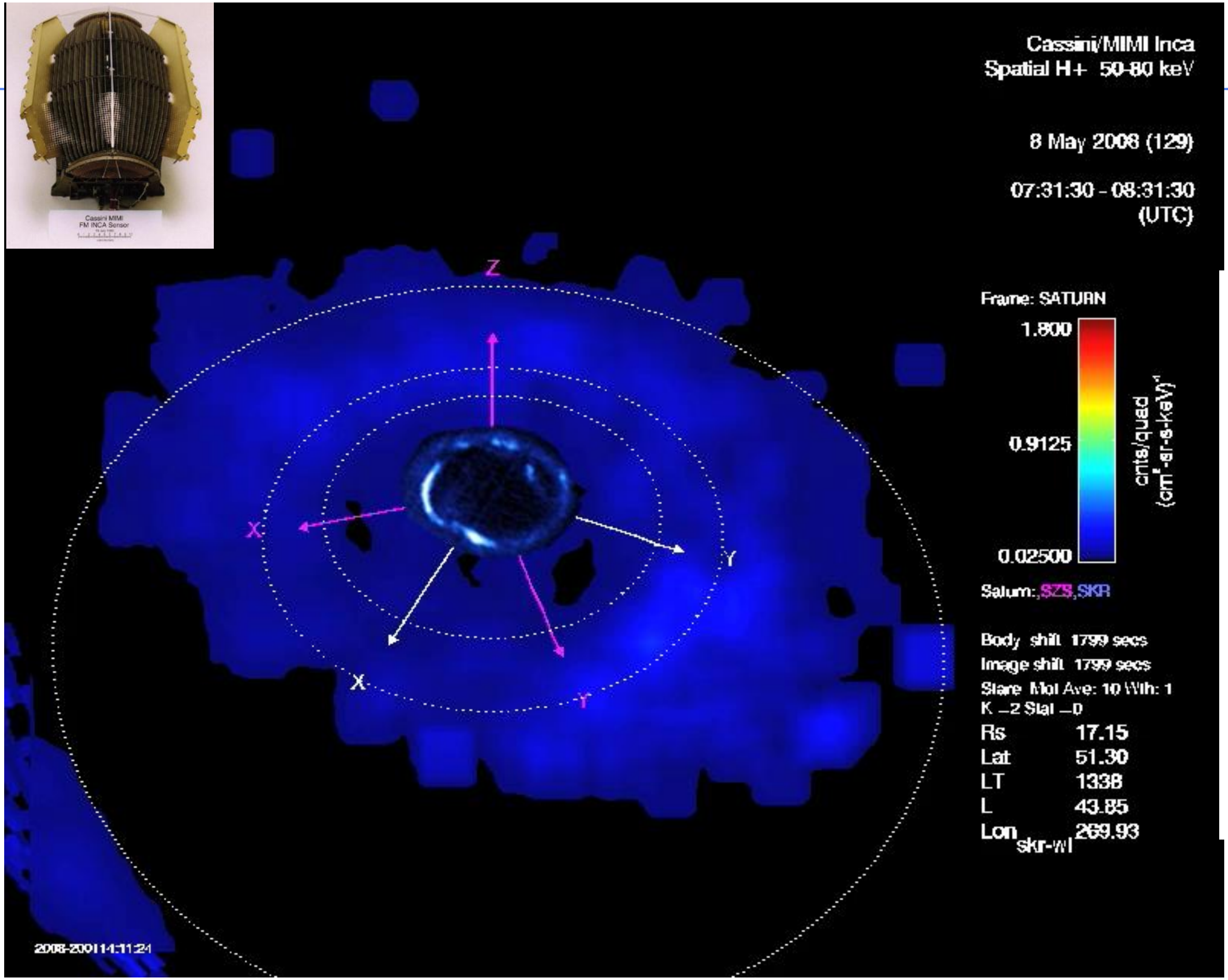
Network of all sky imagers



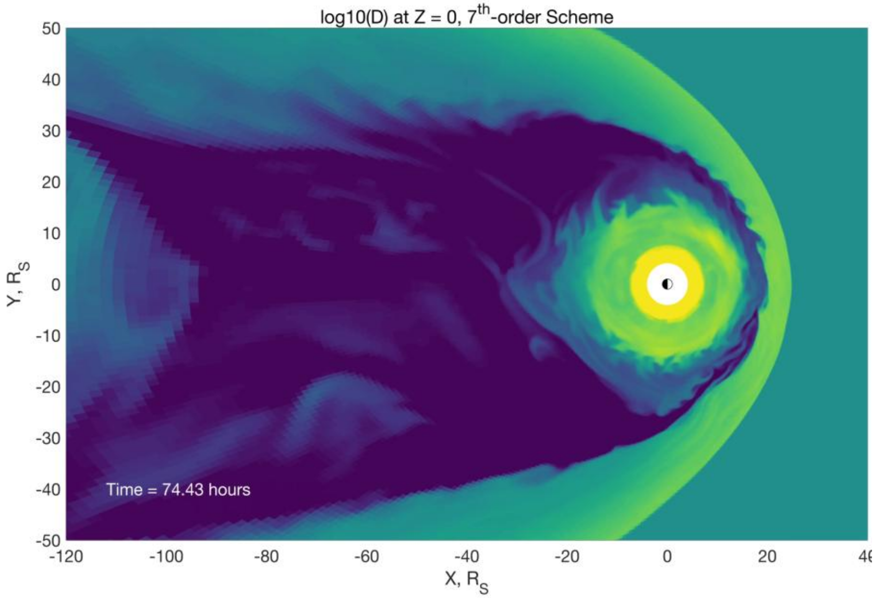
Magnetospheric & auroral observatories



AURORAL MANIFESTATION OF SATURN PERIODIC INJECTIONS

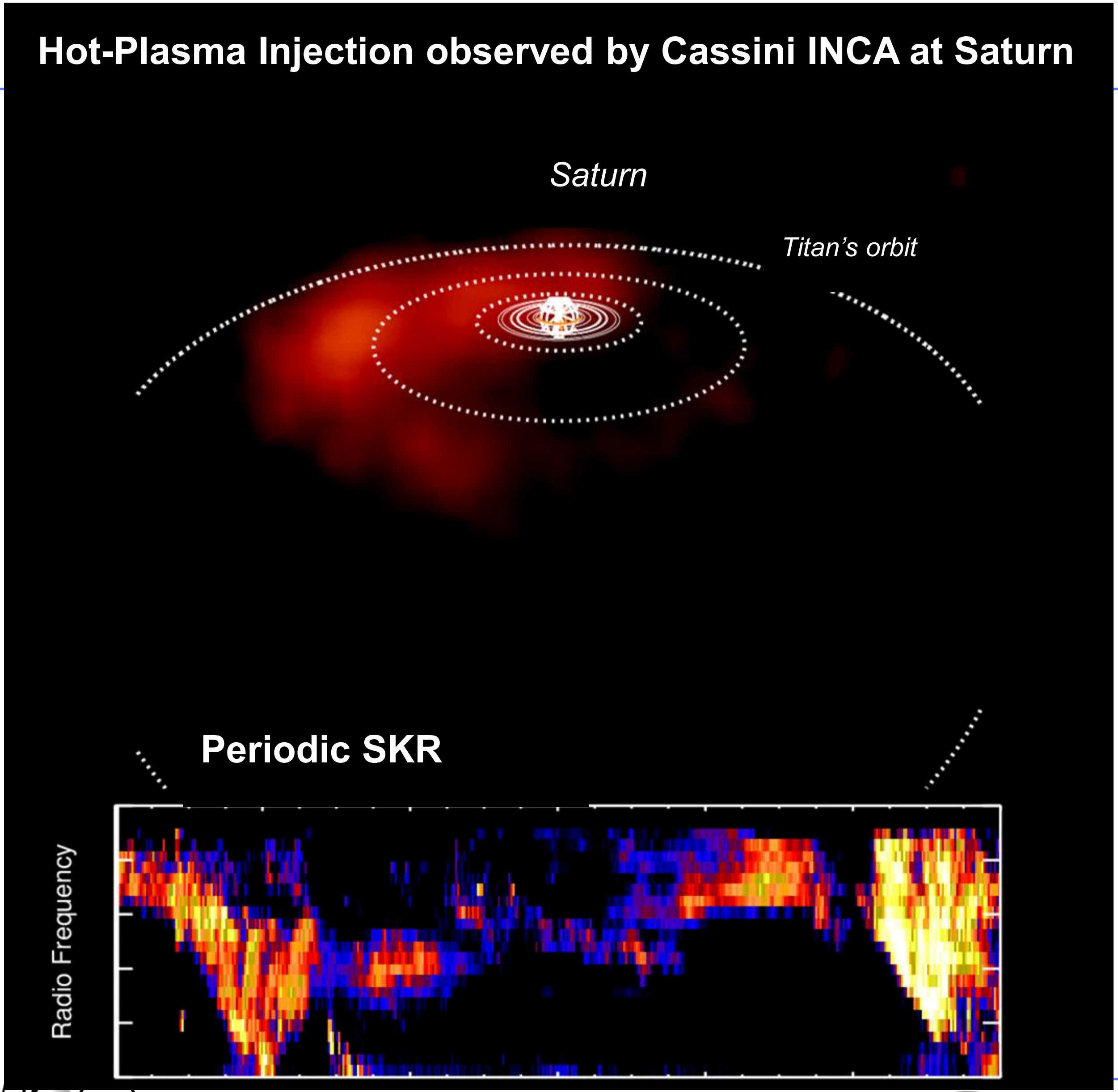


Can Saturn's corotational magnetospheric periodicity be driven by radial interchange injections?



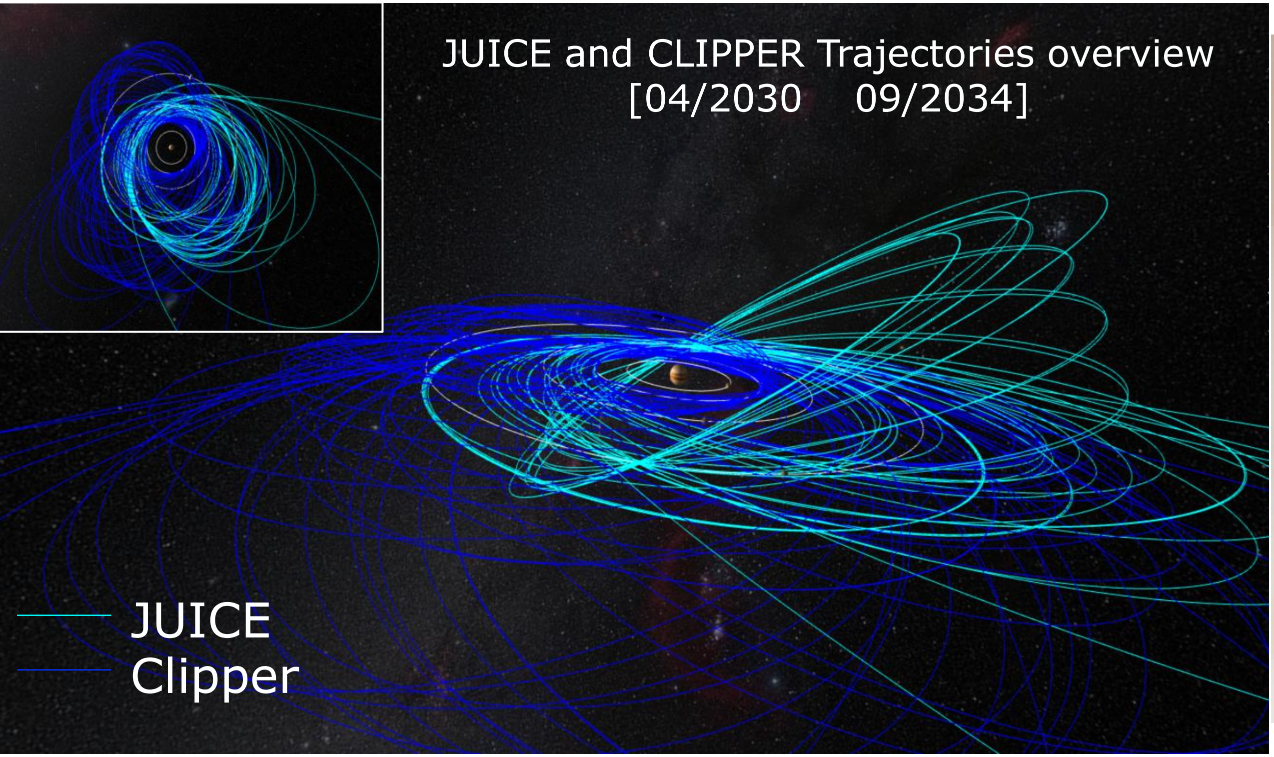
Caggiano, Sciola+ 2024

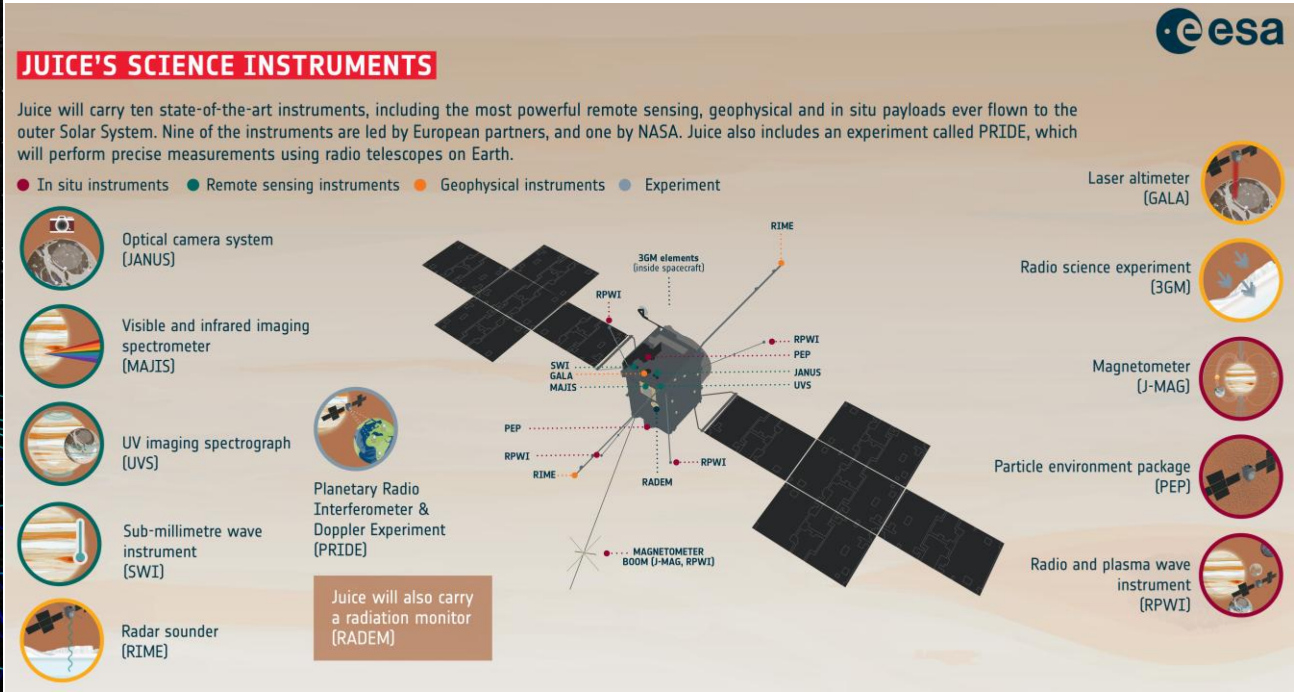
SATURN PERIODIC INJECTIONS & RADIO EMISSIONS



- Correlation between Saturn large-scale injections (observed by Cassini/INCA ENA camera) and kilometric radiation (Wing et al., 2020; Brandt et al., 2021)
- Are large-scale injections the engine behind periodic planetary radio emissions?
- Is this a universal process and can we apply it observed radio periodicities at brown dwarfs?

Jupiter Icy Moons Explorer (JUICE) Mission

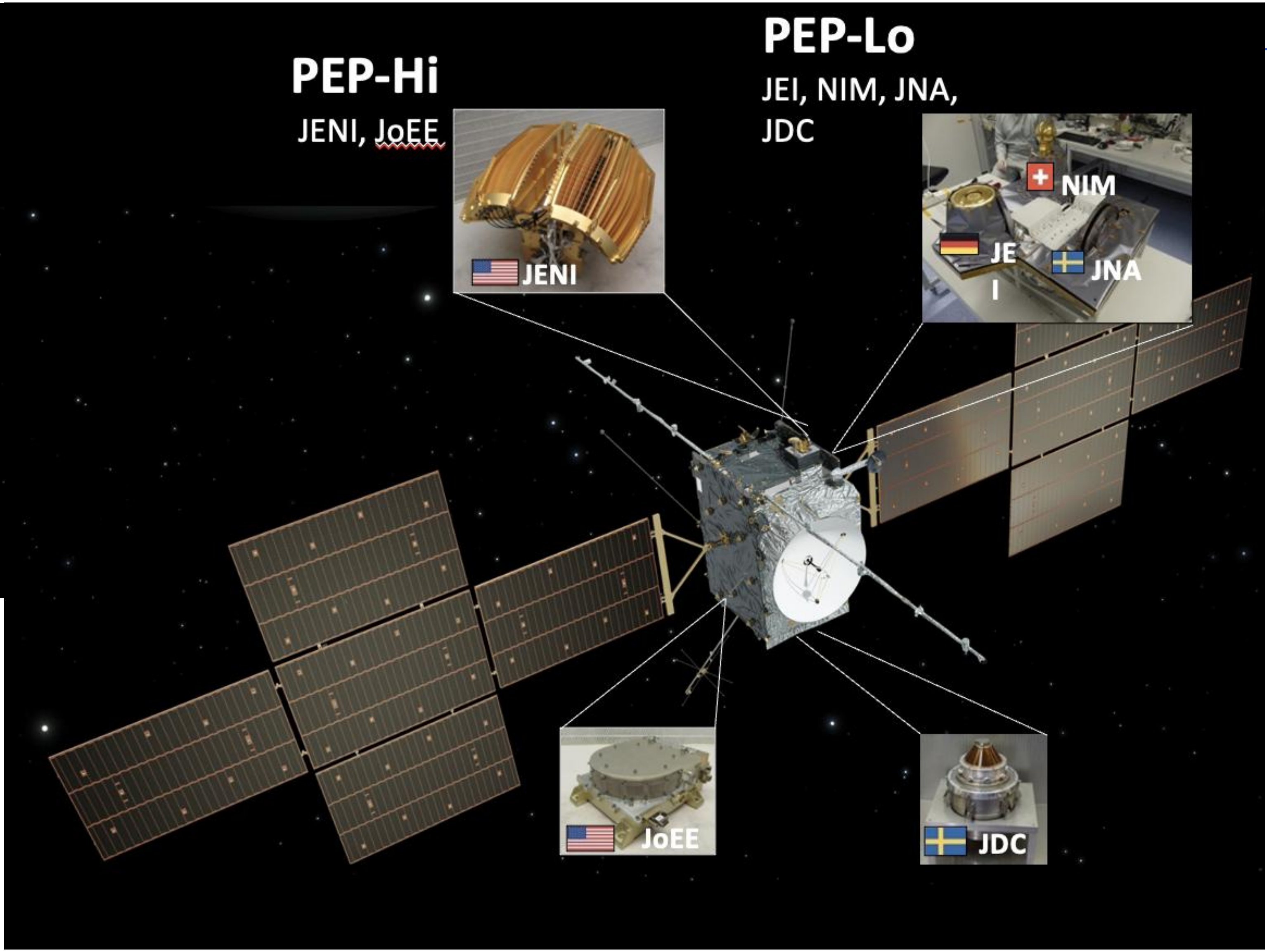




JUICE SPACECRAFT & PEP PAYLOAD

PEP-Hi/JENI ENA imaging performance

Parameter	Performance
Energy Range	1 keV – 165 keV (H ENA) 1.5keV/nuc – 165 keV (Heavy ENAs) 1 keV – 5 MeV (H^+) 1.5 keV/nuc – 5 MeV (Heavy ions) 30 – 300 keV (electrons)
FoV	≥92°x120.6° (MCPs) ≥70°x120° (SSDs)
Angular Resolution	≤5° : E≥12 keV H ≤2.5° : E≥170 keV H and N
Species Determination	Ions and ENAs: H and heavies : E = 5 – 25 keV/nuc H : E≥30 keV O : E≥100 keV S : E≥150 keV



JUPITER'S MOONS – MAGNETOSPHERE INTERACTION

- A common characteristic among these moons (relevant to this presentation) is that they act as obstacles in Jupiter's partially corotating plasma & magnetic field
- ENAs are generated via charge exchange collisions between energetic ions and any neutral gases or other obstacles such as the moons)

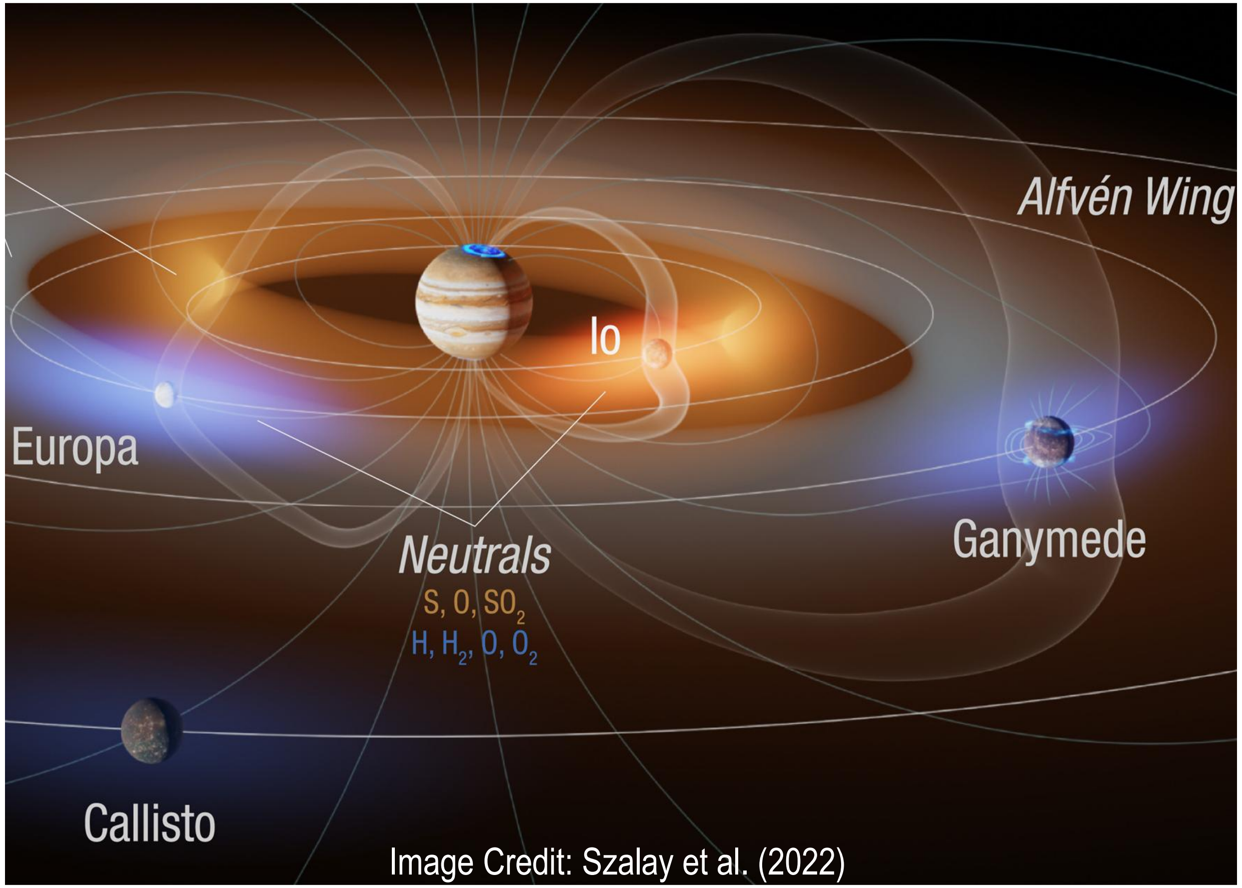


Image Credit: Szalay et al. (2022)

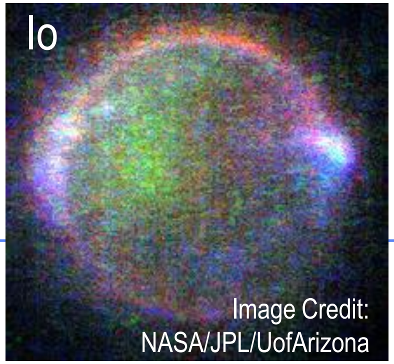


Image Credit: NASA/JPL/UofArizona

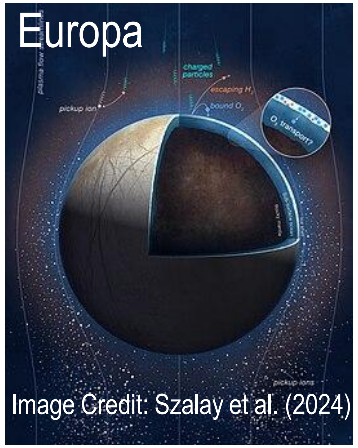


Image Credit: Szalay et al. (2024)

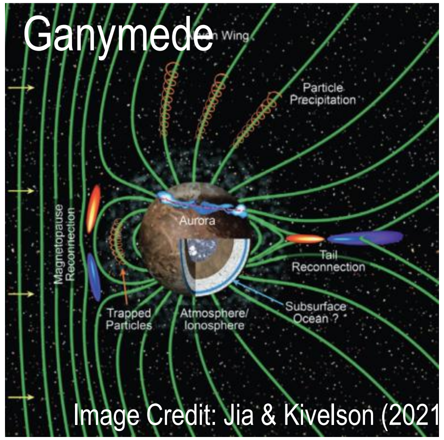
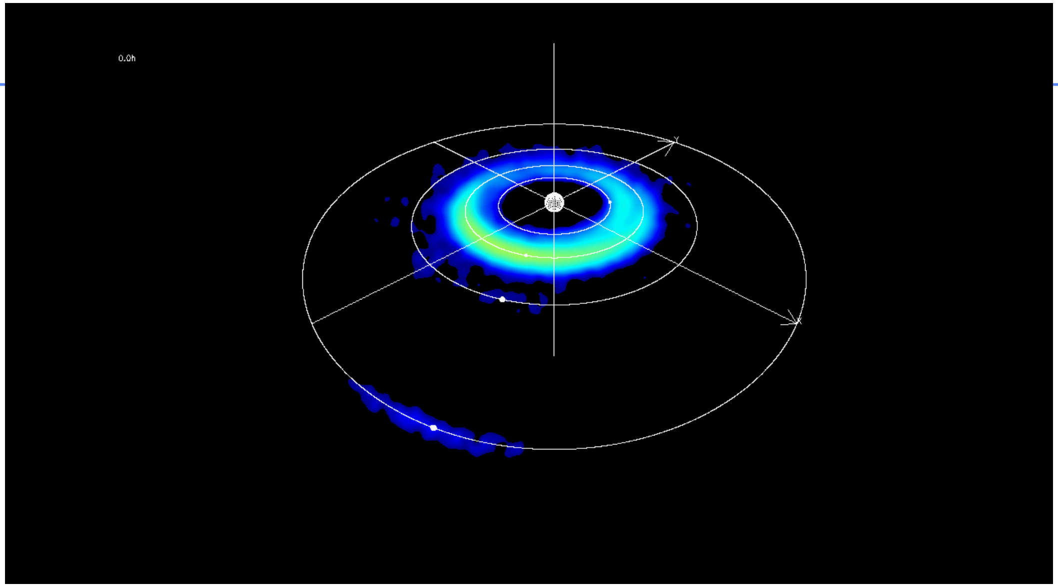
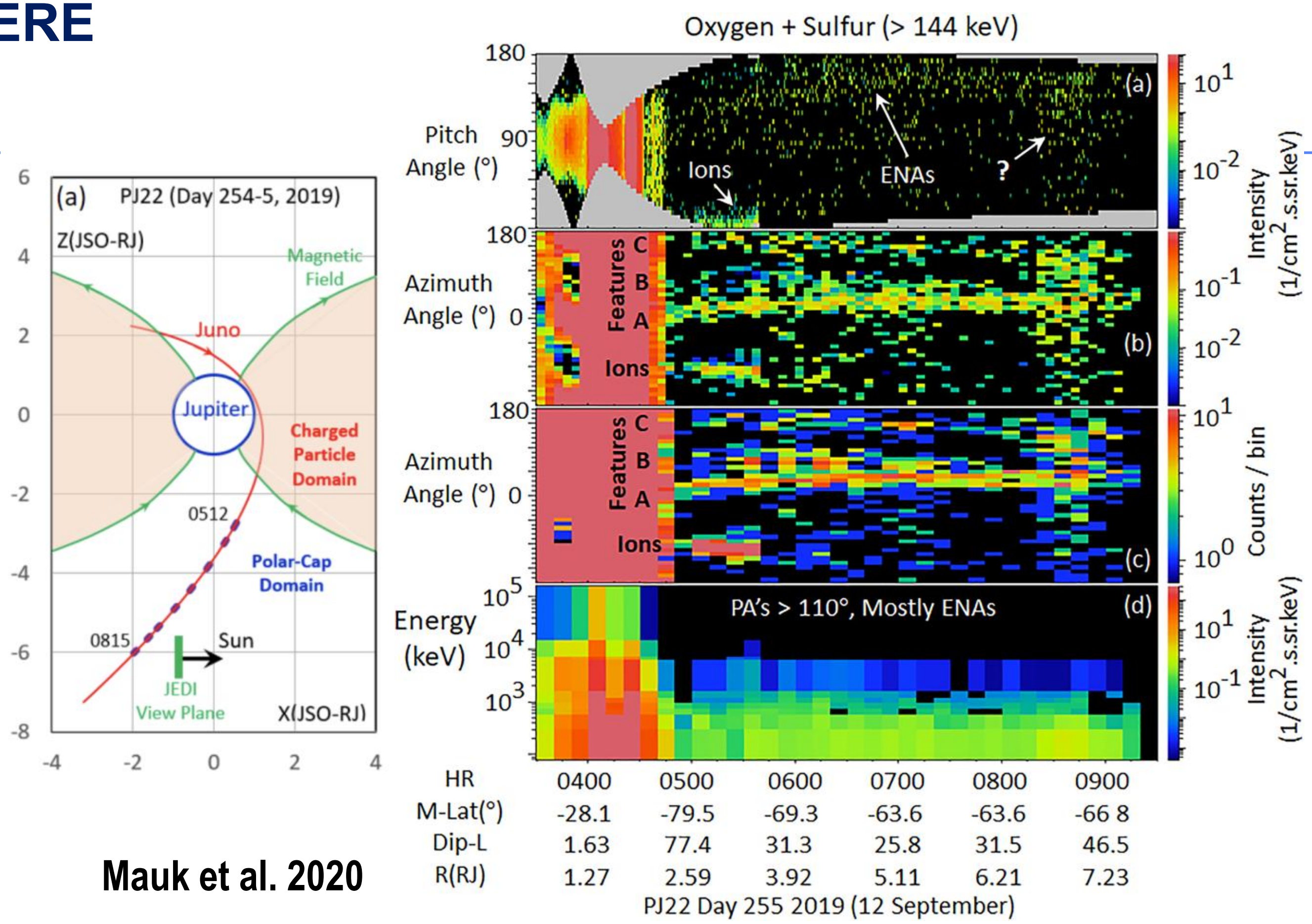


Image Credit: Jia & Kivelson (2021

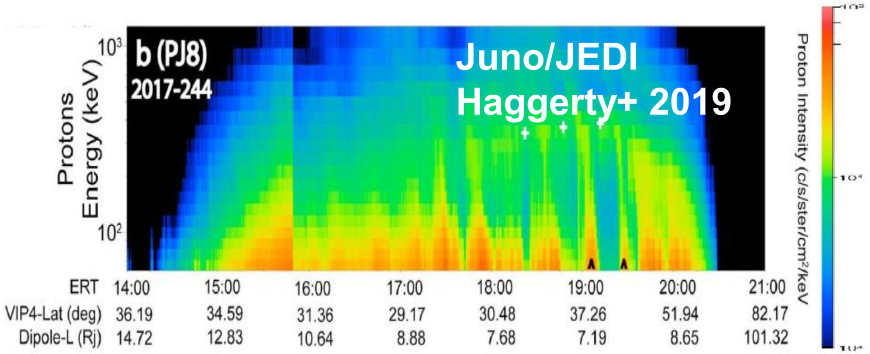
IMAGING OF THE JUPITER'S MAGNETOSPHERE



The ESA JUICE Mission to Jupiter will observe the system in ENAs, UV and radio frequencies.



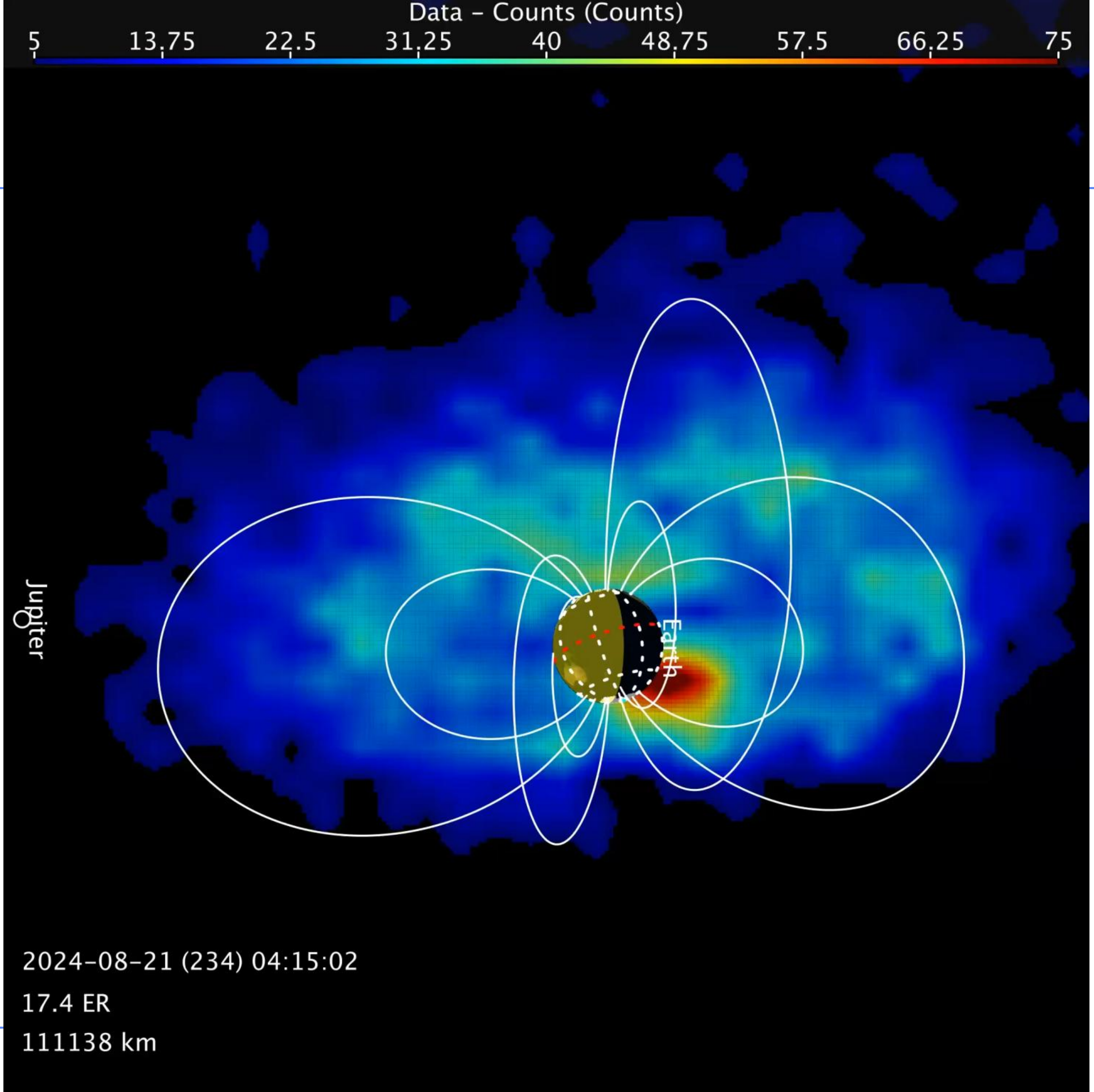
Mauk et al. 2020



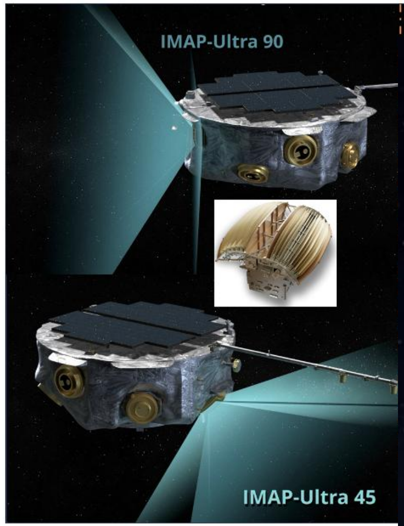
- **Juno/JEDI:** First non-equatorial observations of ENA emissions from Jupiter → revealed distinct emissions coming from the orbit of Io, the orbit of Europa, and from Jupiter itself
- The emissions from the orbits of Io and Europa are azimuthally asymmetric. Time variability of the emissions over several hours reveals smaller-scale azimuthal structure

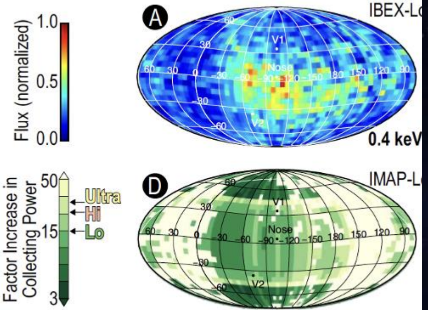
JUICE Lunar-Earth Flyby

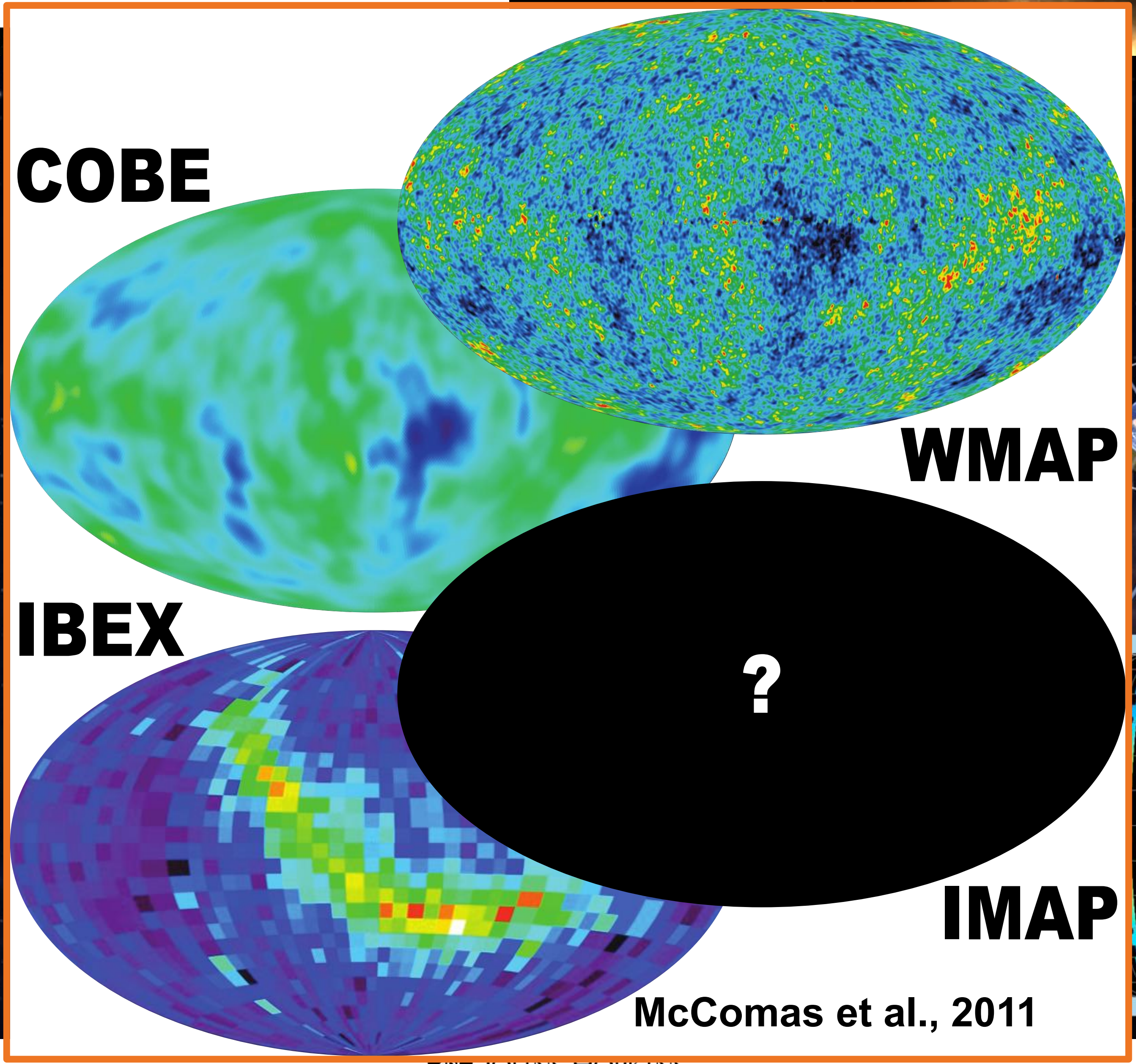
JENI ENA observations of the Earth's magnetosphere!

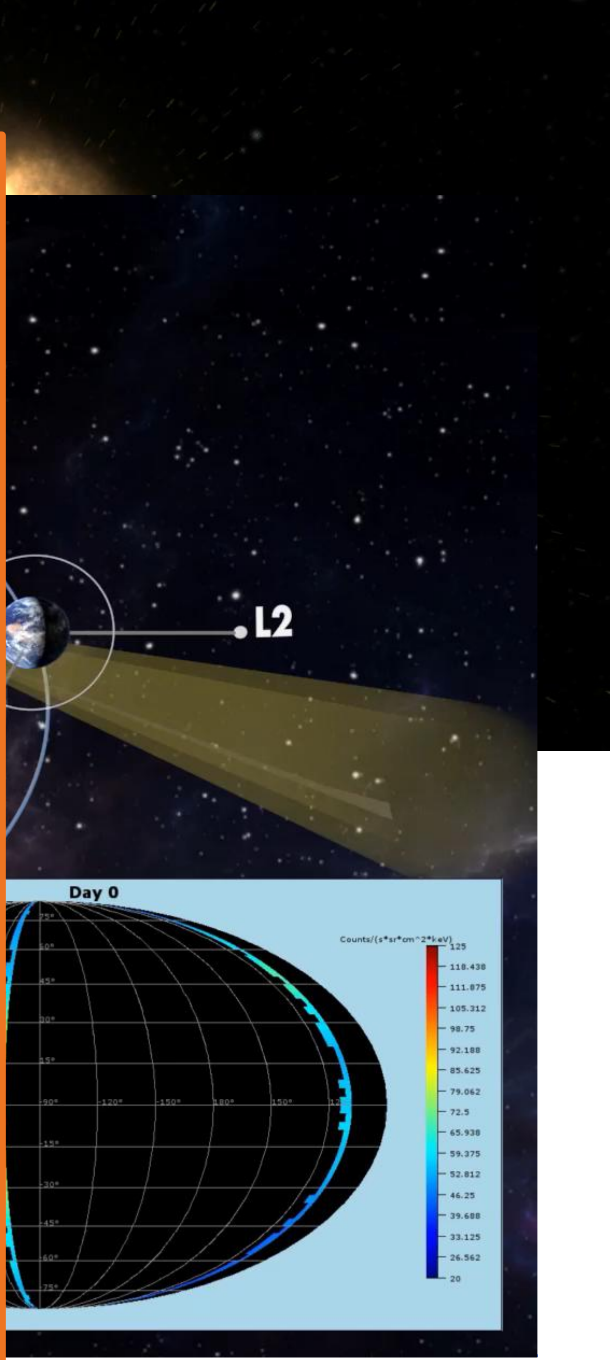


Imaging the Outer Heliosphere









Bringing it back to Earth: In Conclusion?

- Simulations have outrun observations!
- Huge leaps in high resolution global model development in the last decade give us predictions of how nature might be working
- We need to be as bold and visionary with our future space missions, in order to acquire the observations that will tell us how nature really works
  - multipoint observations combining both in-situ and remote sensing of the coupled magnetosphere-ionosphere system