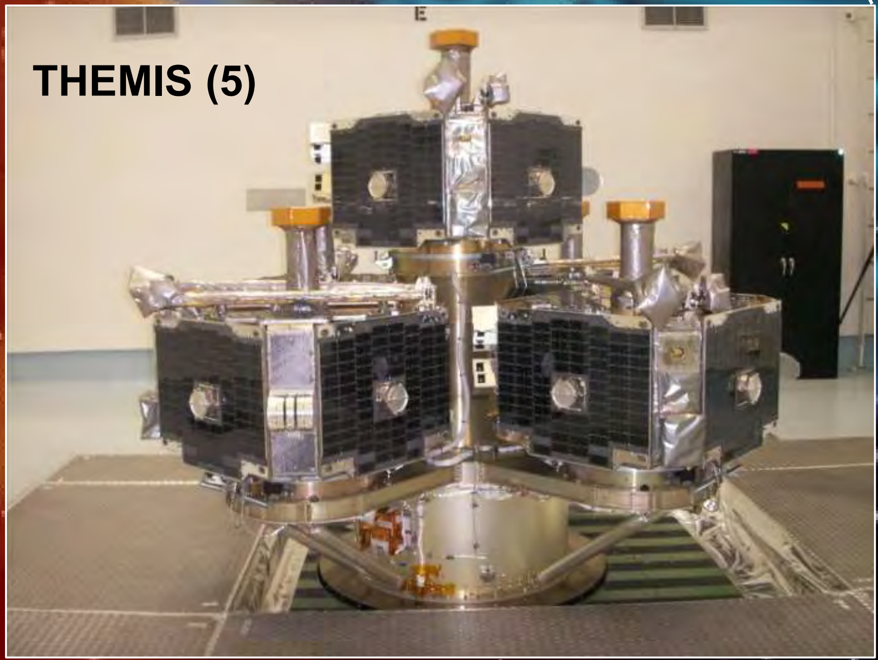
Plasma acceleration in near-Earth space

Vassilis Angelopoulos, UCLA

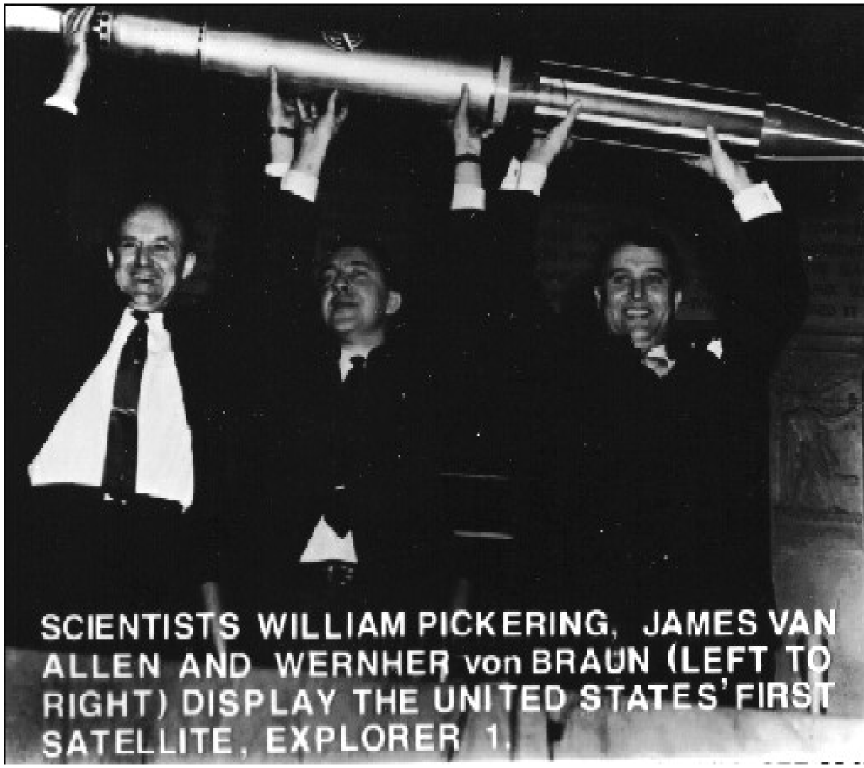


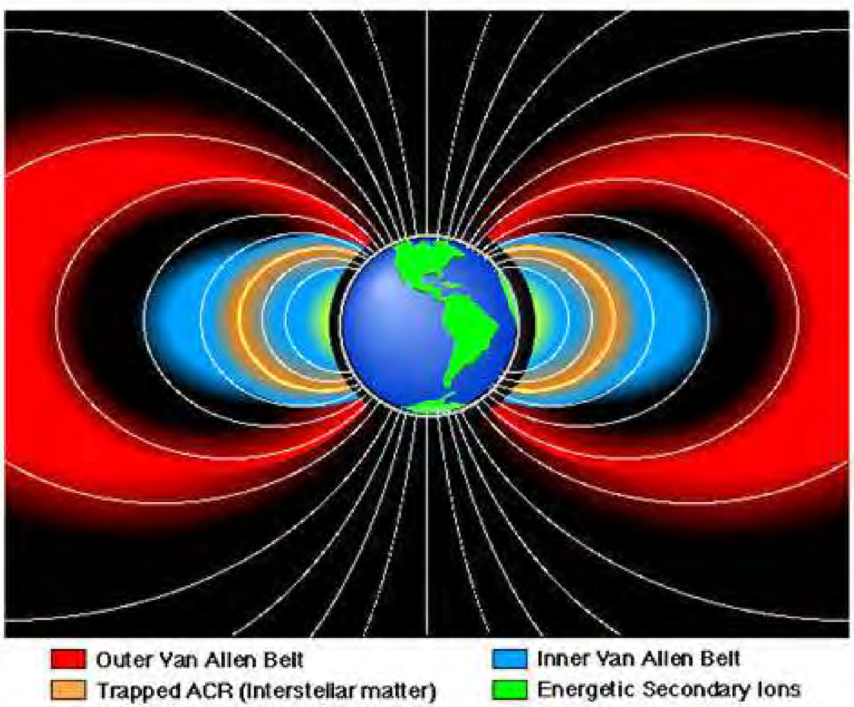
Humans are borne explorers.

"Exploration is in our nature. We began as wanderers, and we are wanderers still. We have lingered long enough on the shores of the cosmic ocean. We are ready at last to set sail for the stars."
— Carl Sagan, Cosmos

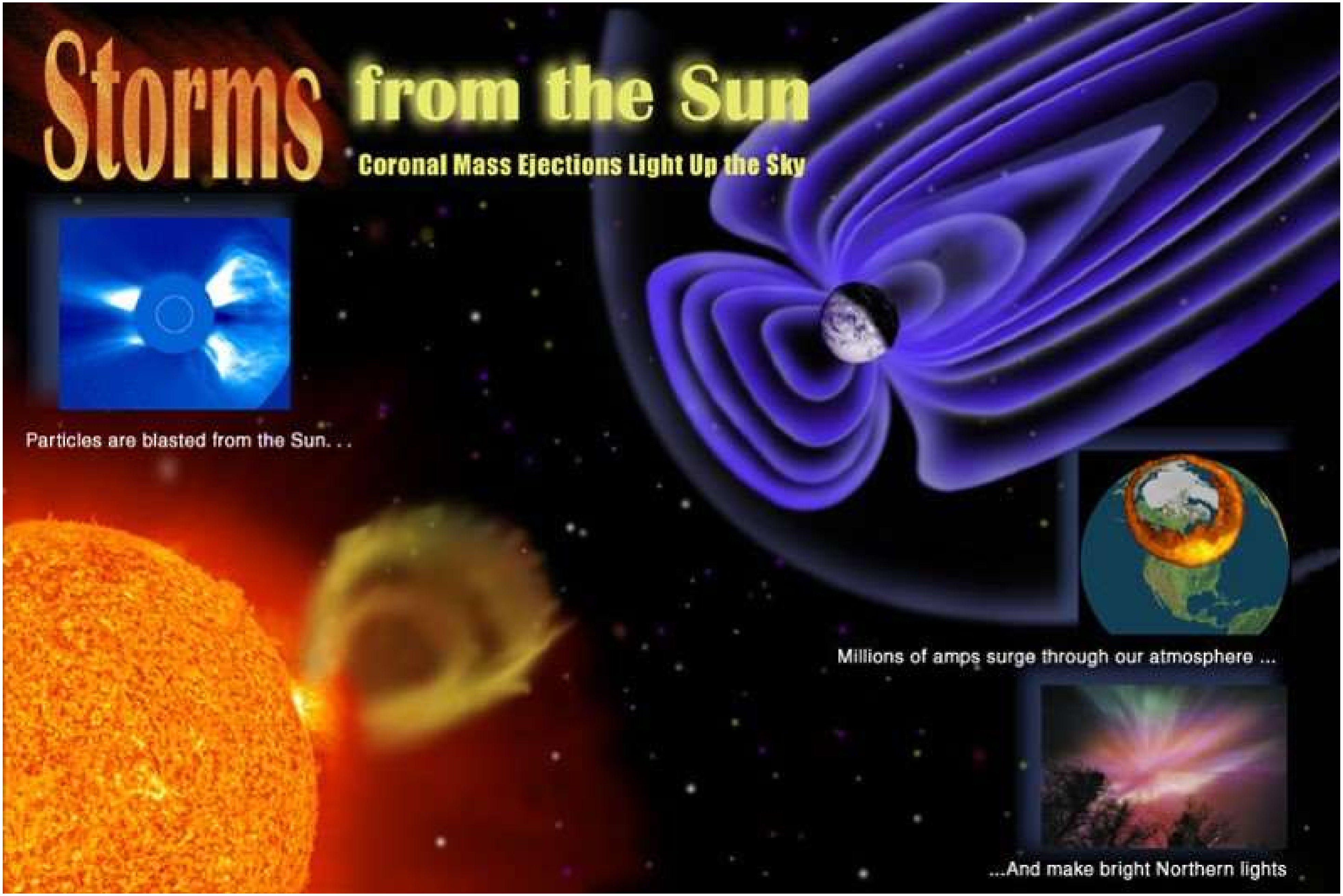
Perilous Space Radiation

Explorer 1, 1958 discovers Earth's "radiation" belts: Space is "radioactive"!

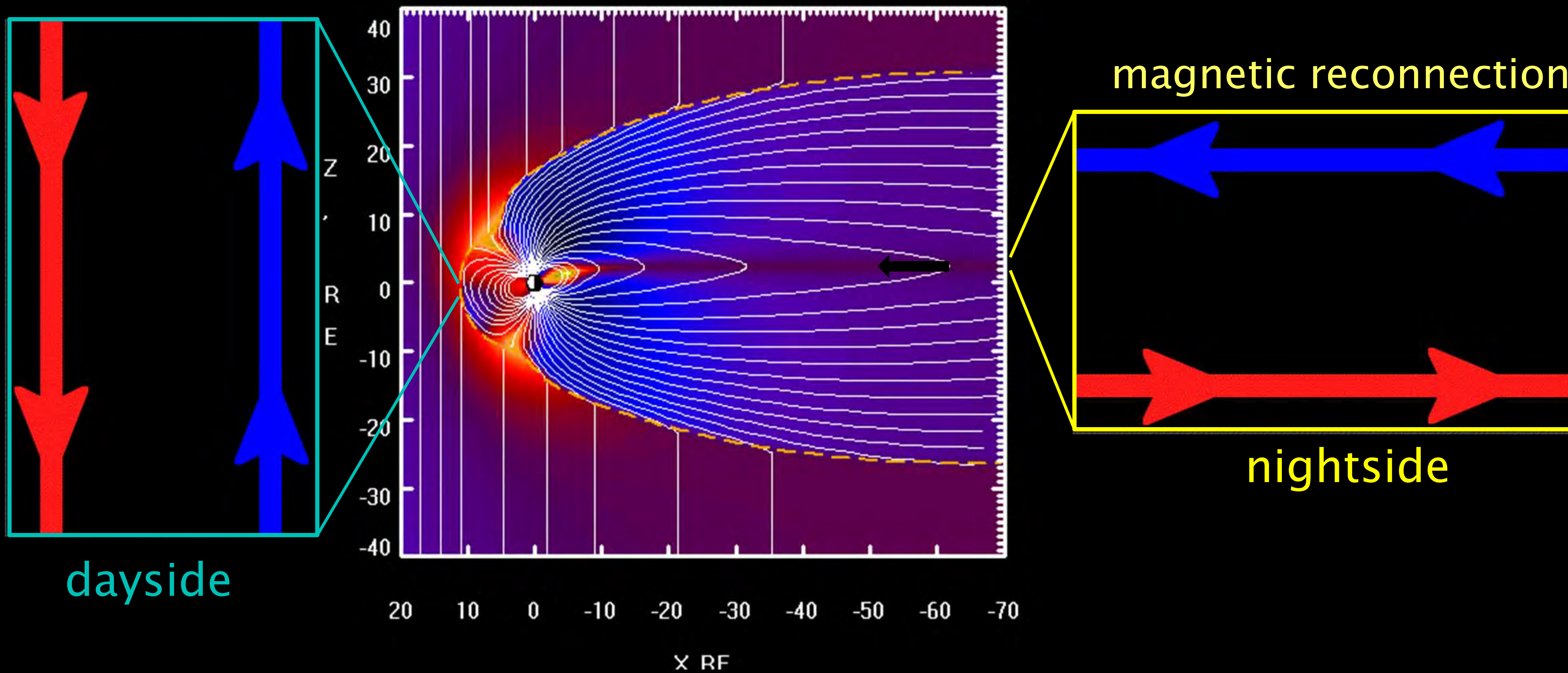




The Earth's space environment is buffeted by the dynamic solar wind, causing "space weather"

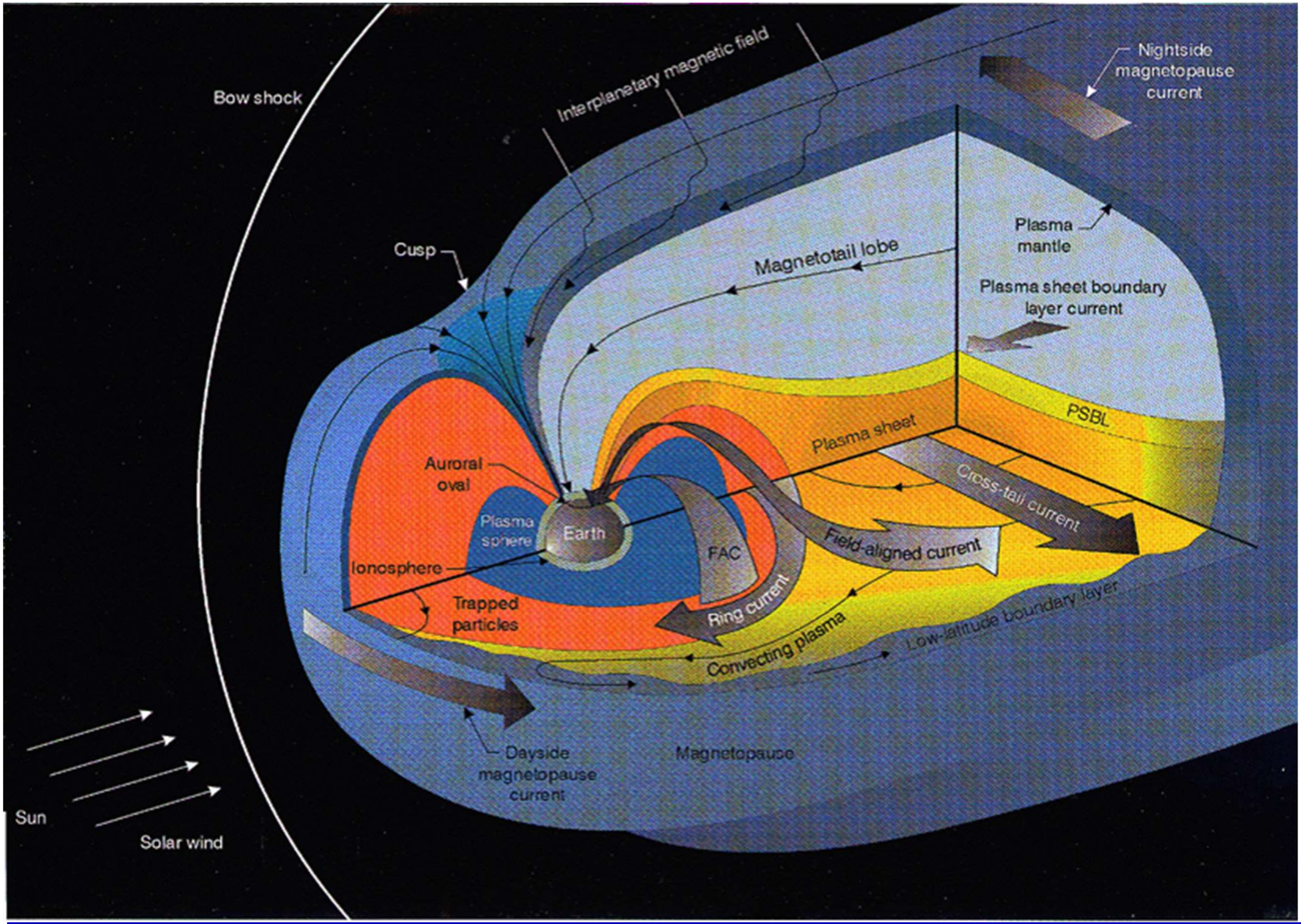

Storms from the Sun
Coronal Mass Ejections Light Up the Sky
Particles are blasted from the Sun. . .
Millions of amps surge through our atmosphere ...
...And make bright Northern lights

Penetration of solar wind energy

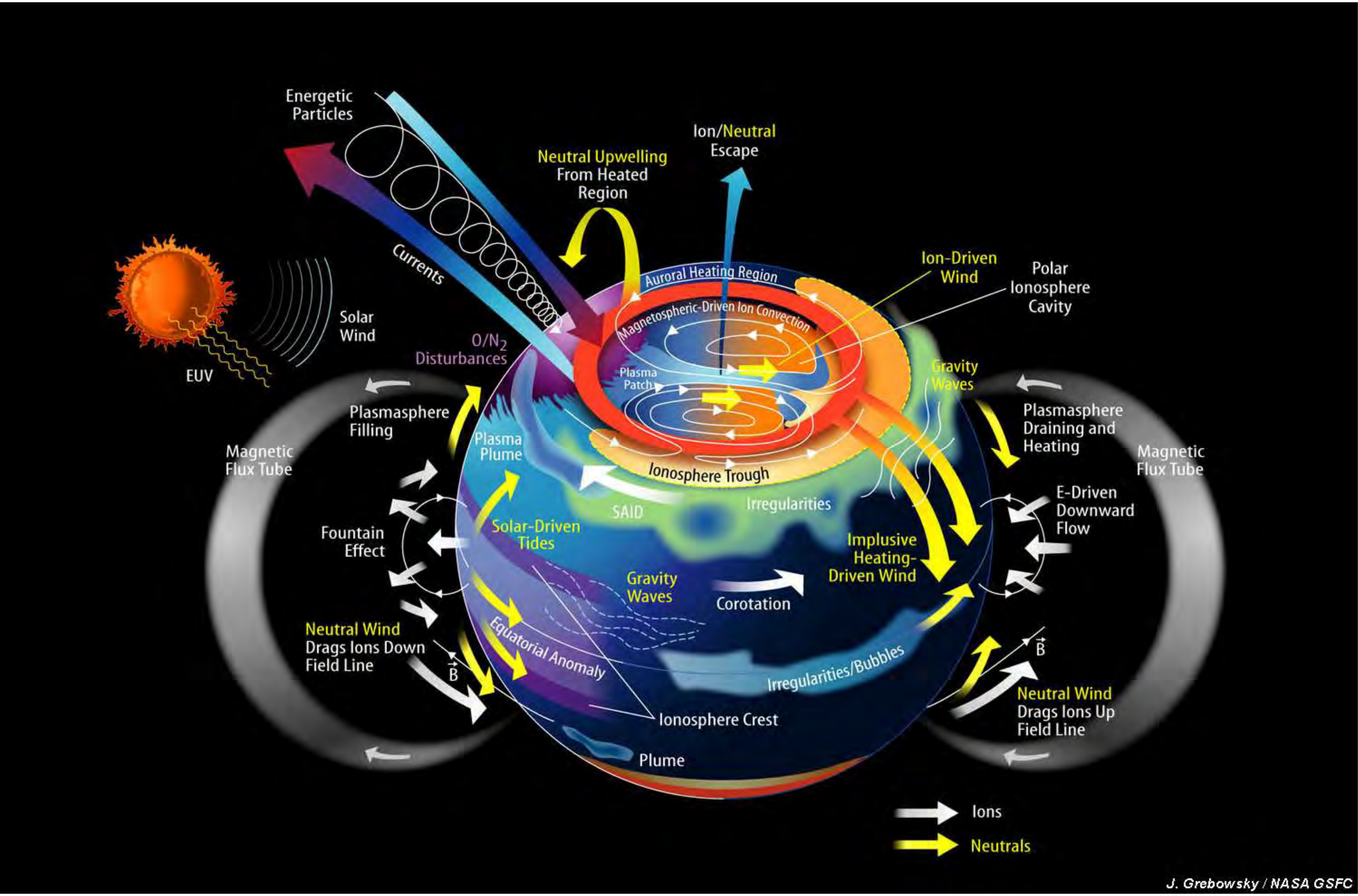


- About 10% of solar wind energy enters magnetosphere due to magnetic reconnection stripping away flux tubes at dayside.
- Nightside reconnection then jets plasma toward Earth

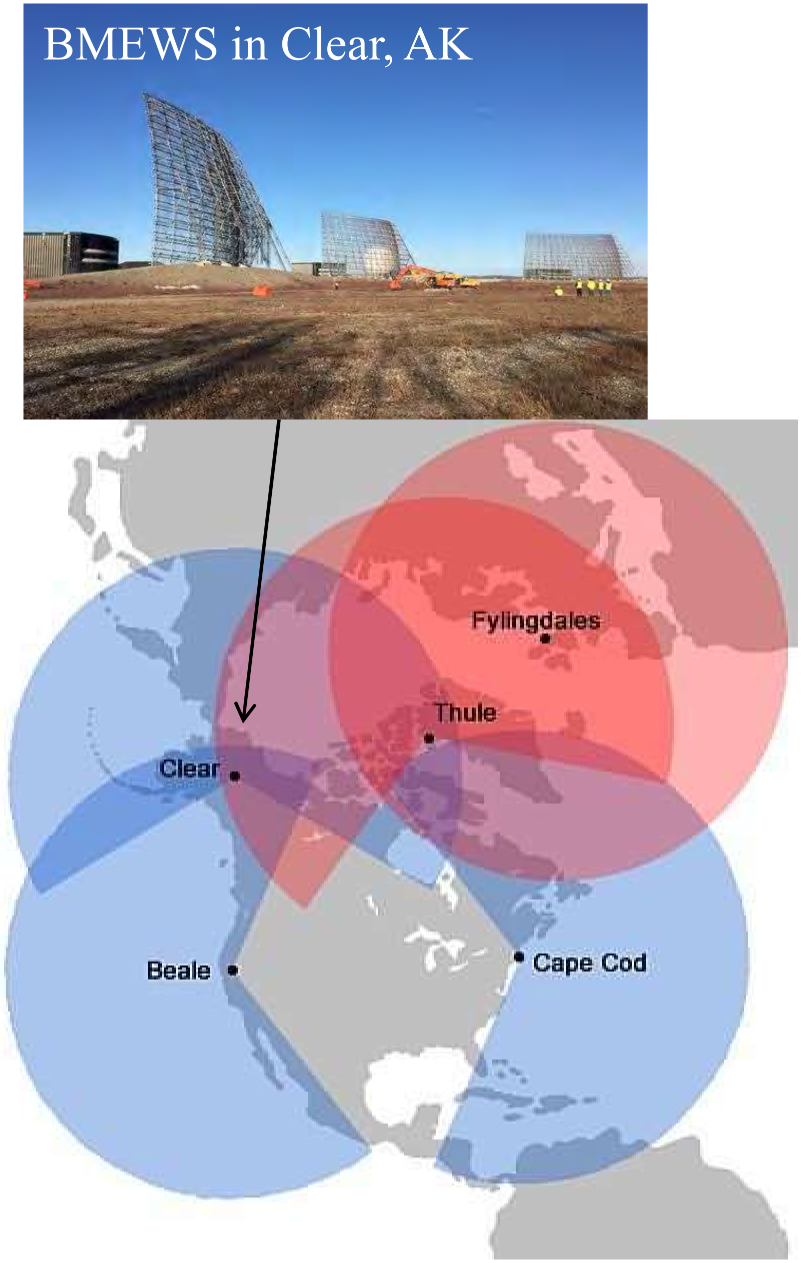
The Earth's space environment including its ionosphere are thus set into motion by the solar wind, causing space currents



During geomagnetic storms and less intense but recurrent substorms, space currents and ionospheric flows intensify causing space weather



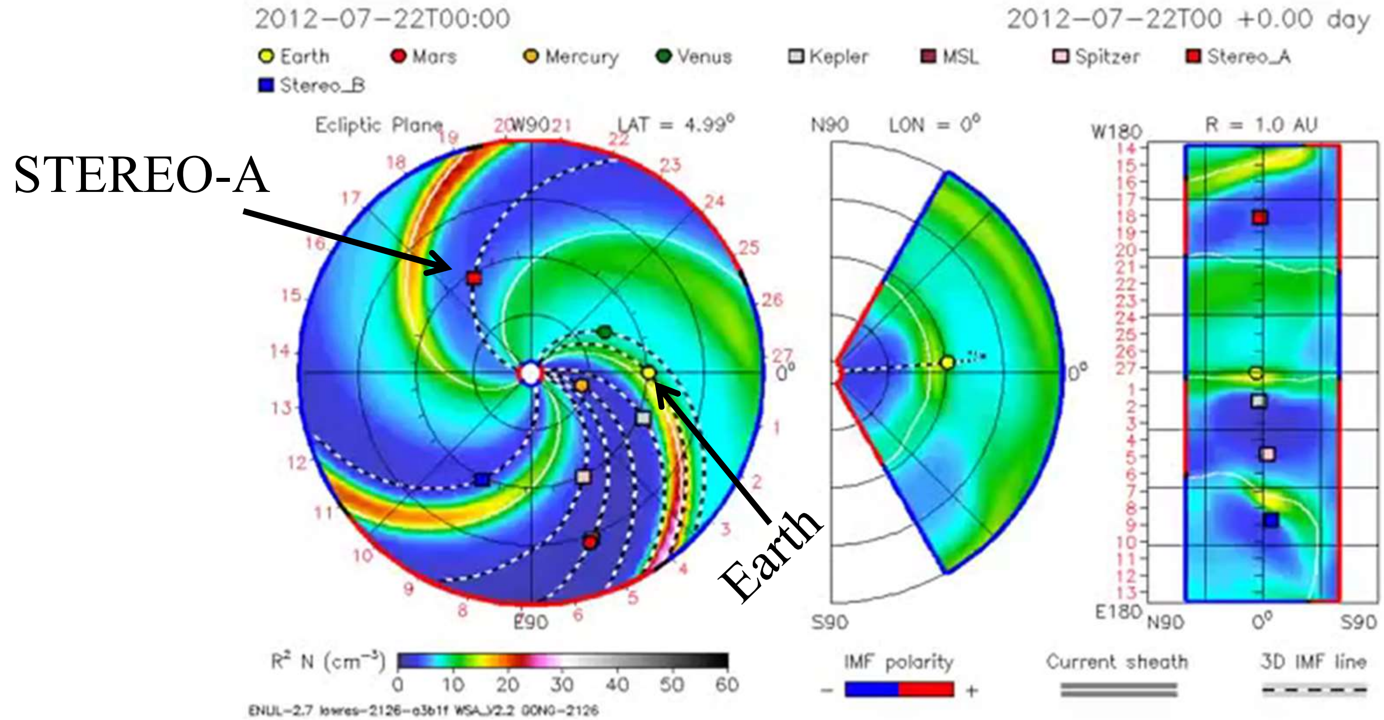
In 1967 a powerful storm blinded 3 NORAD ballistic missile early warning system radars, and came close to a nuclear crisis



B52s equipped with nuclear warheads were ready to take off

The crisis was averted when space weather officers explained away the radar "malfunction" as an ongoing space weather event.
[Knipp+, Space Weather, 2016]

In 2012 a CME detected by STEREO-A was deemed comparable to the Richard Carrington event of 1859, missed Earth by just 7 days.



[Baker+, Space Weather, 2013]

The energy released can wreak havoc to satellites, endanger astronauts and future space tourists, and ground power systems

Image Credit: L. J. Lanzerotti, Bell Laboratories, Lecent Technologies, Inc.

Location	Commercial	Military	Research	Total
LEO	273	94	70	437
MEO	19	101	12	132
GEO	308	51	8	367
Totals:	600	245	91	936

- Total Satellite Fleet (ca Dec, 2004)………… ~ 936
- Total hardware + launch cost………………. ~ $ 230 billion
- GEO Transponder Capacity………………….. ~ 6,800
- GEO industry annual revenue………………. $ 87 billion
- LEO + MEO satellite annual revenue……… $ 10 billion
- Satellite Industry annual revenue…………. $ 225 billion

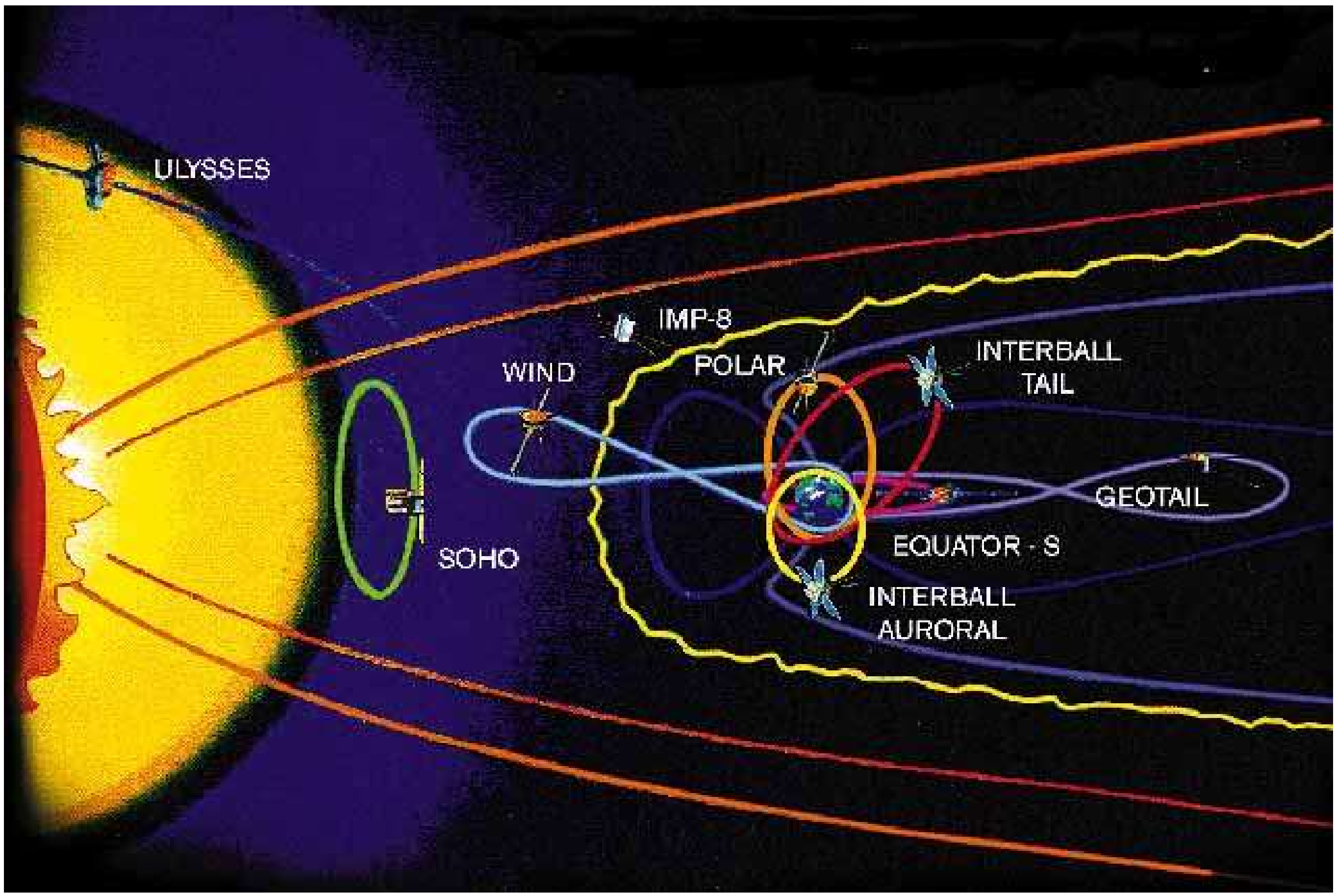
A large space storm in 1989 caused currents which damaged this transformer and shut off power for six million people for nine hours.

Vassilis Angelopoulos, UCLA

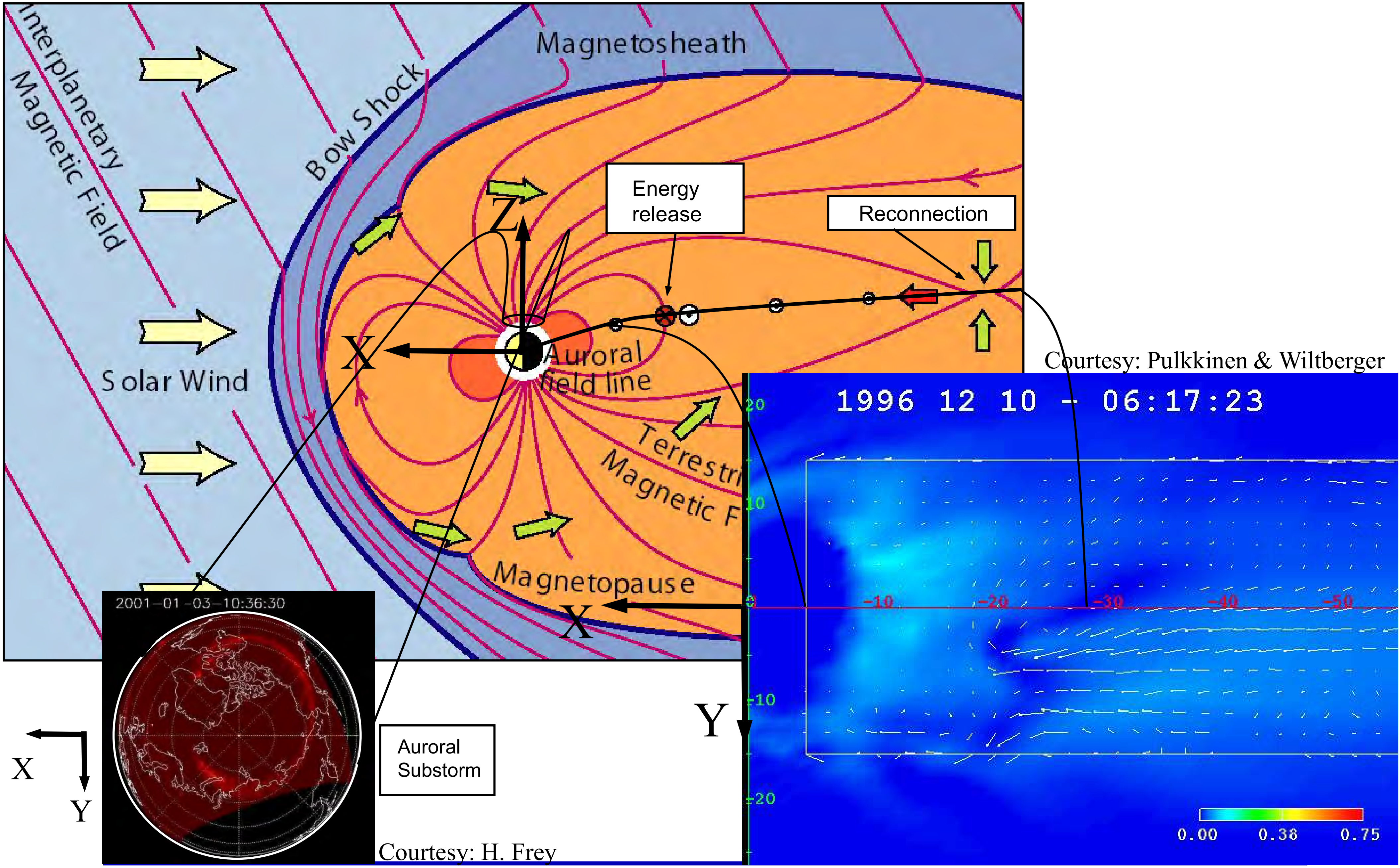
ISTP (c. 1990): explored "climate" of space

Studied mass, momentum and energy flow through the magnetosphere "on average".
Taught us a lot about how globally inter-connected magnetosphere is. Cost: ~$5B.

- Missions were single S/C: aliasing
- Spacecraft launched in separate times – overlap only fortuitous.
- Equator-S lost in few months.

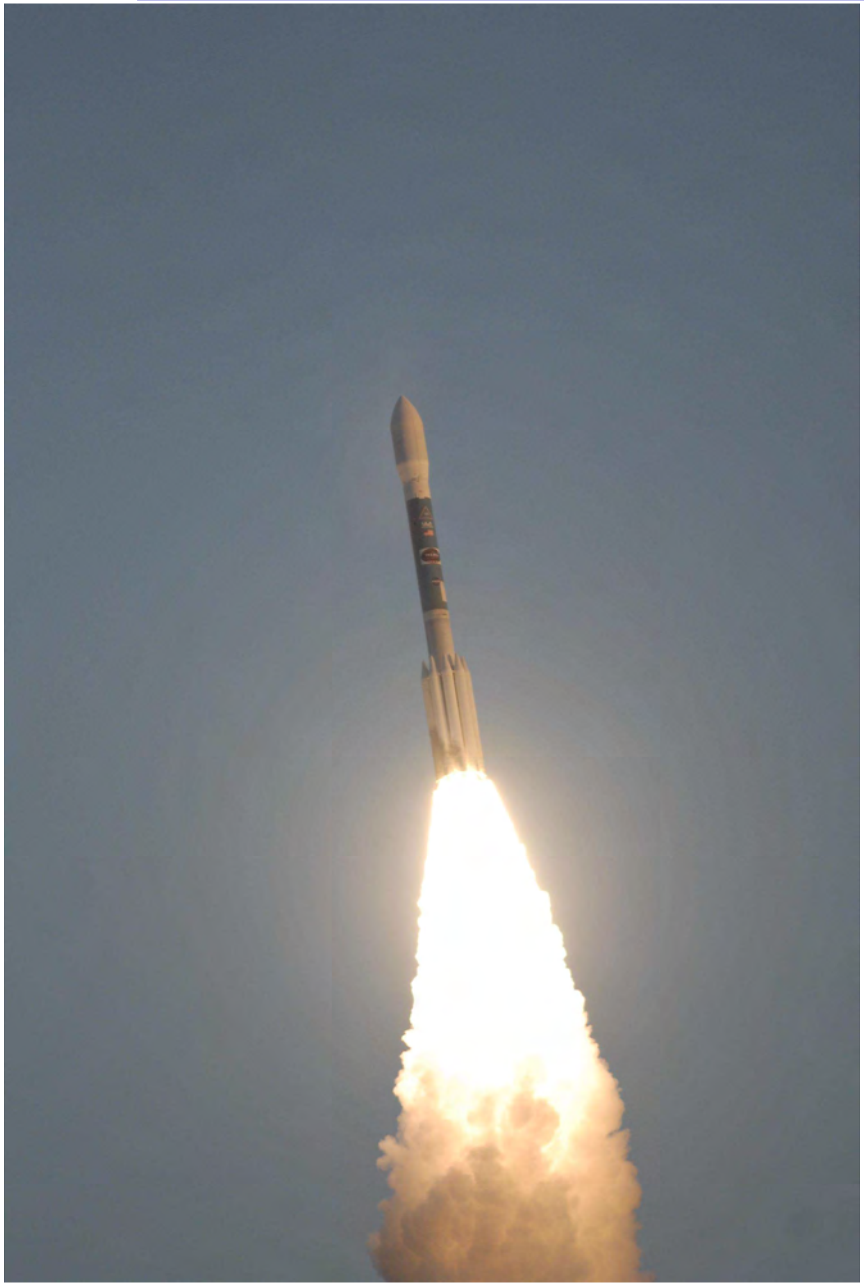


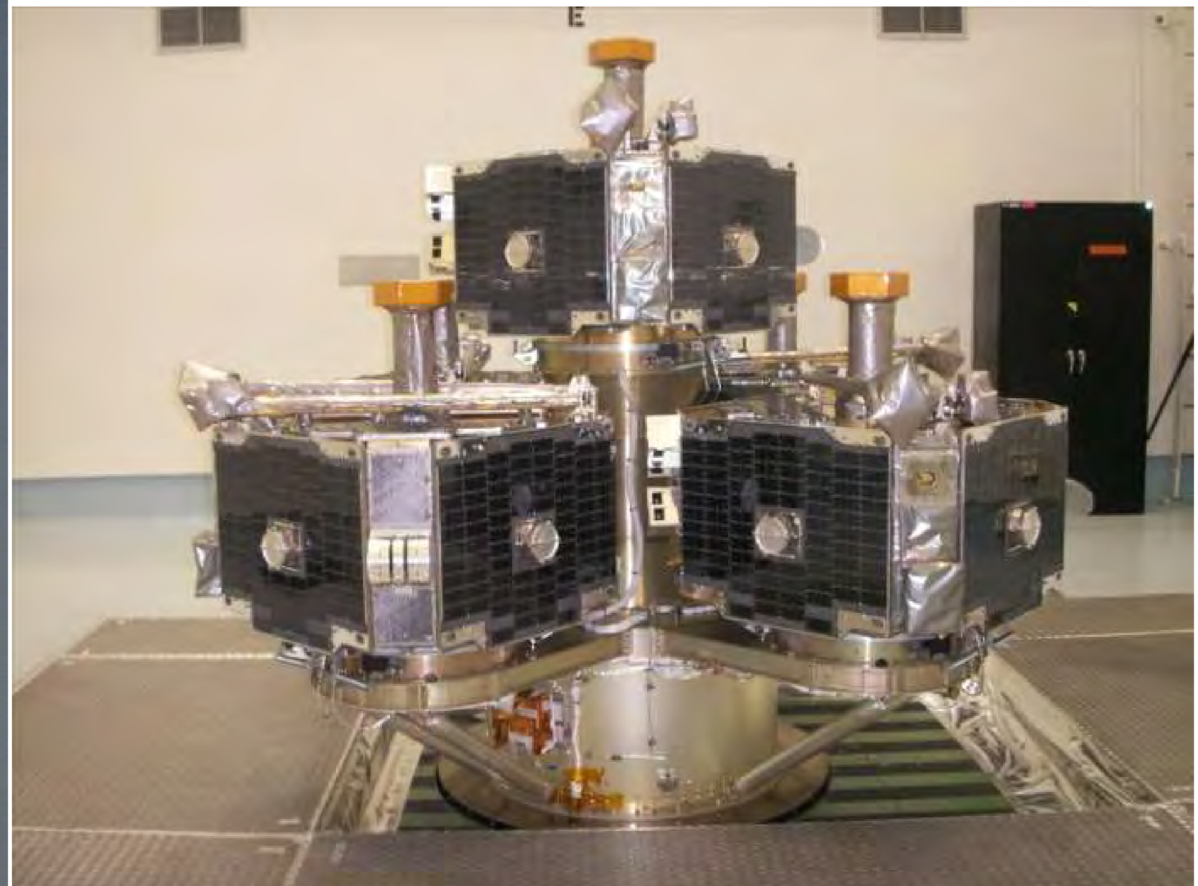
Since then, we have realized that the solar wind energy circulation is localized and bursty. It is organized in two major modes of space weather: “storms” and “substorms”



THEMIS designed to address: what triggers substorms?

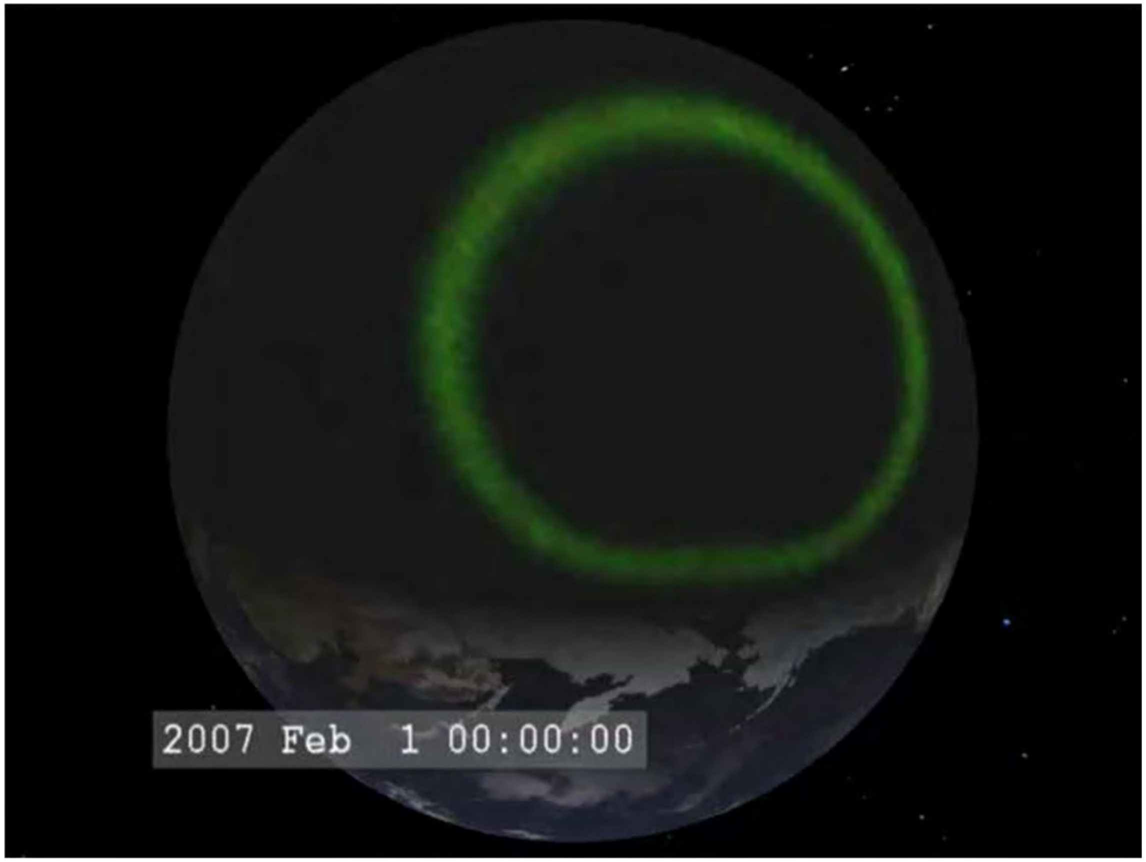
Multi-Probe Mission: Probe Alignments and Ground Conjunctions can Solve the Mystery





THEMIS (c. 2007): a constellation pathfinder

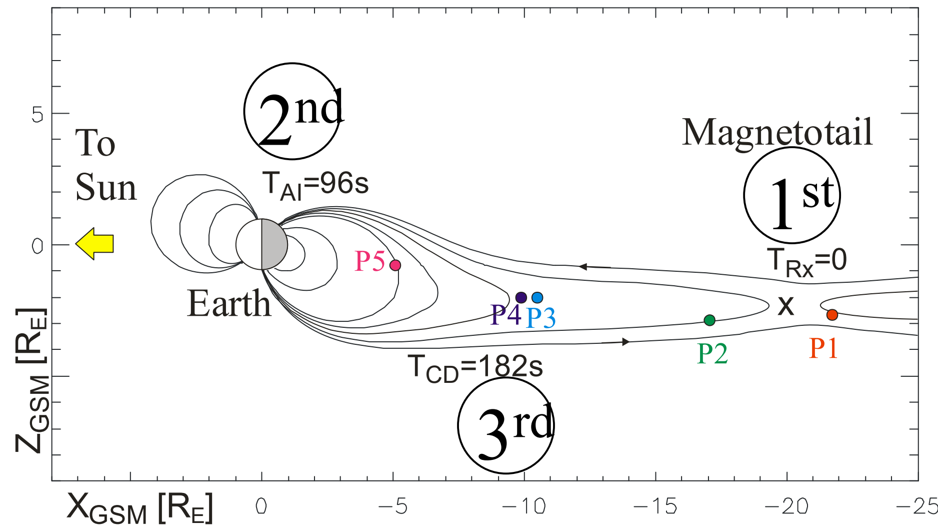
Cost: $0.25B. Probes on resonant orbits (once/4 days) resolved the substorm mystery.



Simulation: J. Raeder, UNH

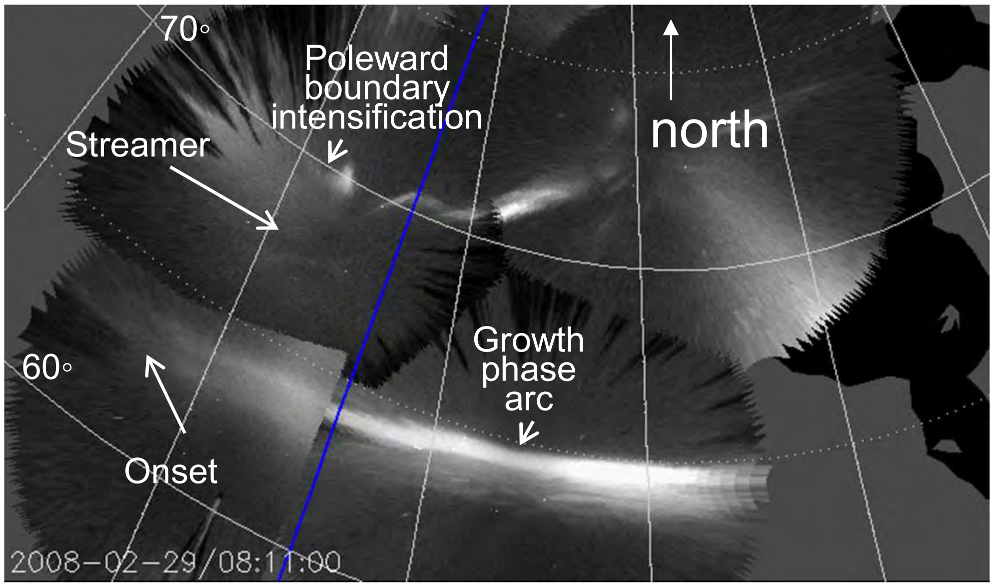
Visualization: Tom Bridgman, GSFC/SVS

Angelopoulos et al., Science, 2008

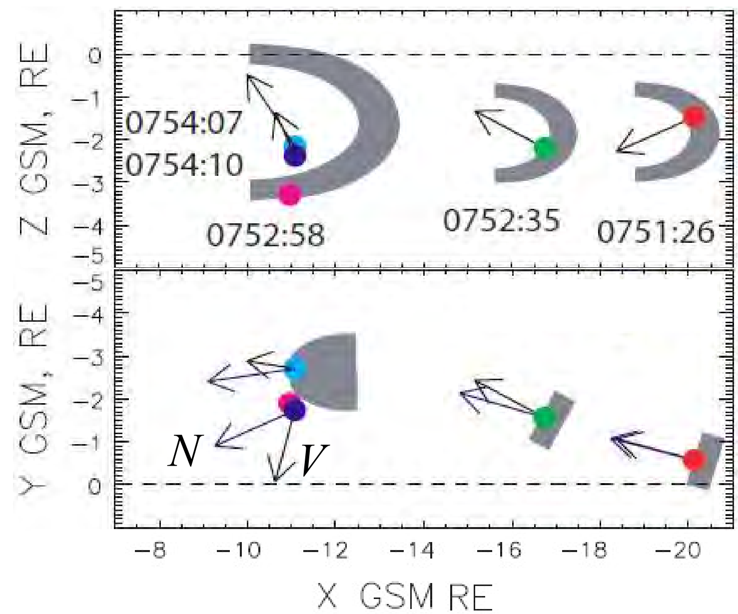


Magnetotail reconnection (Rx) leads to fast flows, that cause auroral "streamers"

Tail energy dissipation is a localized version of global convection sequence:
Reconnection → Fast flows → Interaction w/ tail-dipole Interface → Auroral Expansion
Sequence imaged with ground based observatories!



Nishimura et al., 2011



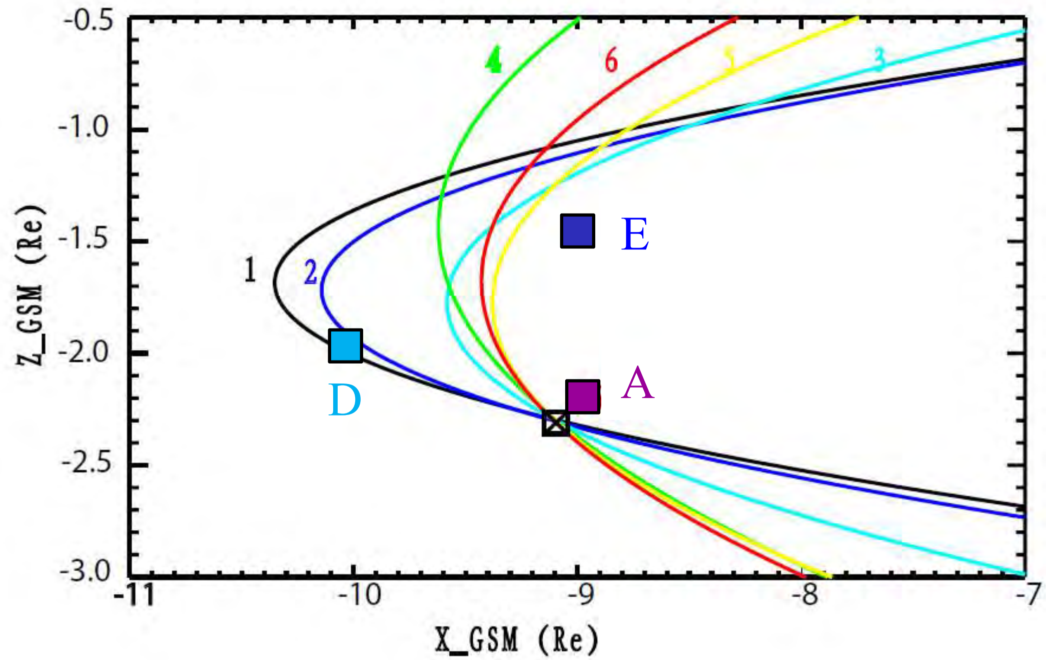
Runov et al., 2009,10,11

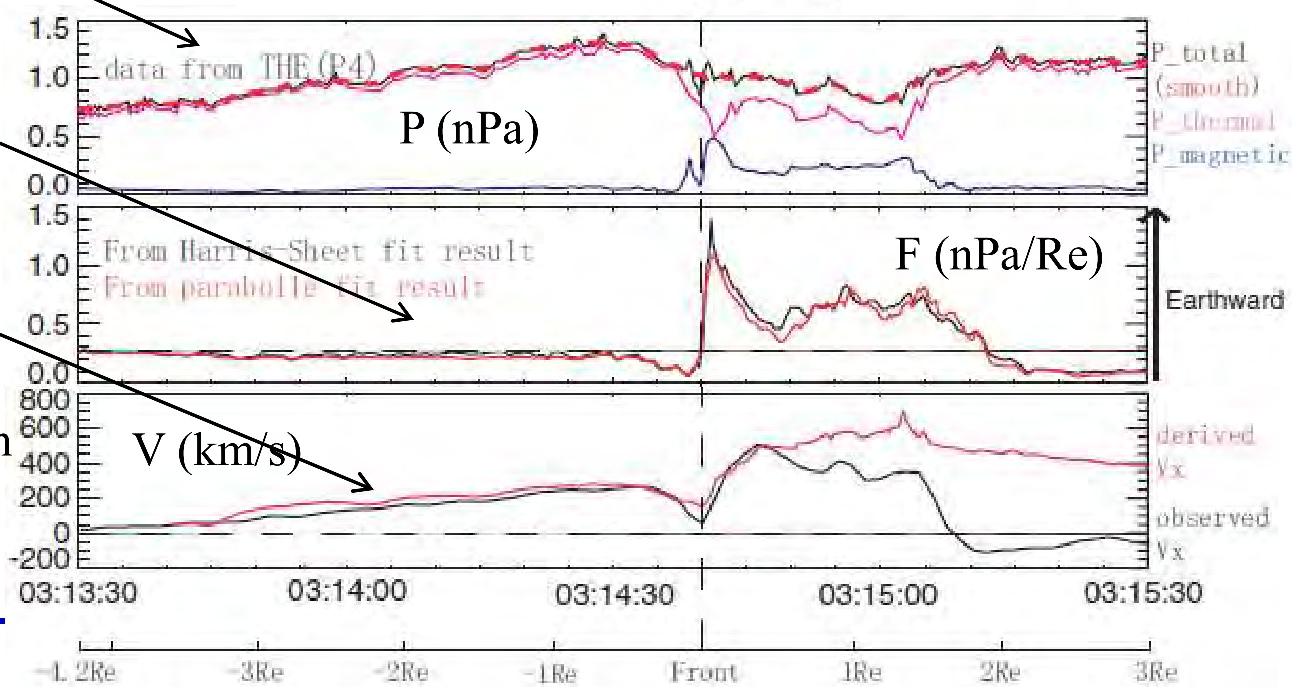
Flow burst (a.k.a., dipolarizing flux bundle) propelled by the curvature force, not the inertia of the reconnection jets (*S. –S. Li et al. JGR 2011)*

Multi-spacecraft analysis reveals how low density flux bundles push through ambient plasma:

- Low density inside results in high Bz
- JxB force increases (increased Bz)
- Pressure builds up ahead of flux tube.
- ∇P force density accelerates ions ahead of front
- Integrated (modeled) force density in good agreement with observed velocity.

"Bubble model" is proven right despite its "slow flow" approximation because is based on energy principle and conservation laws.

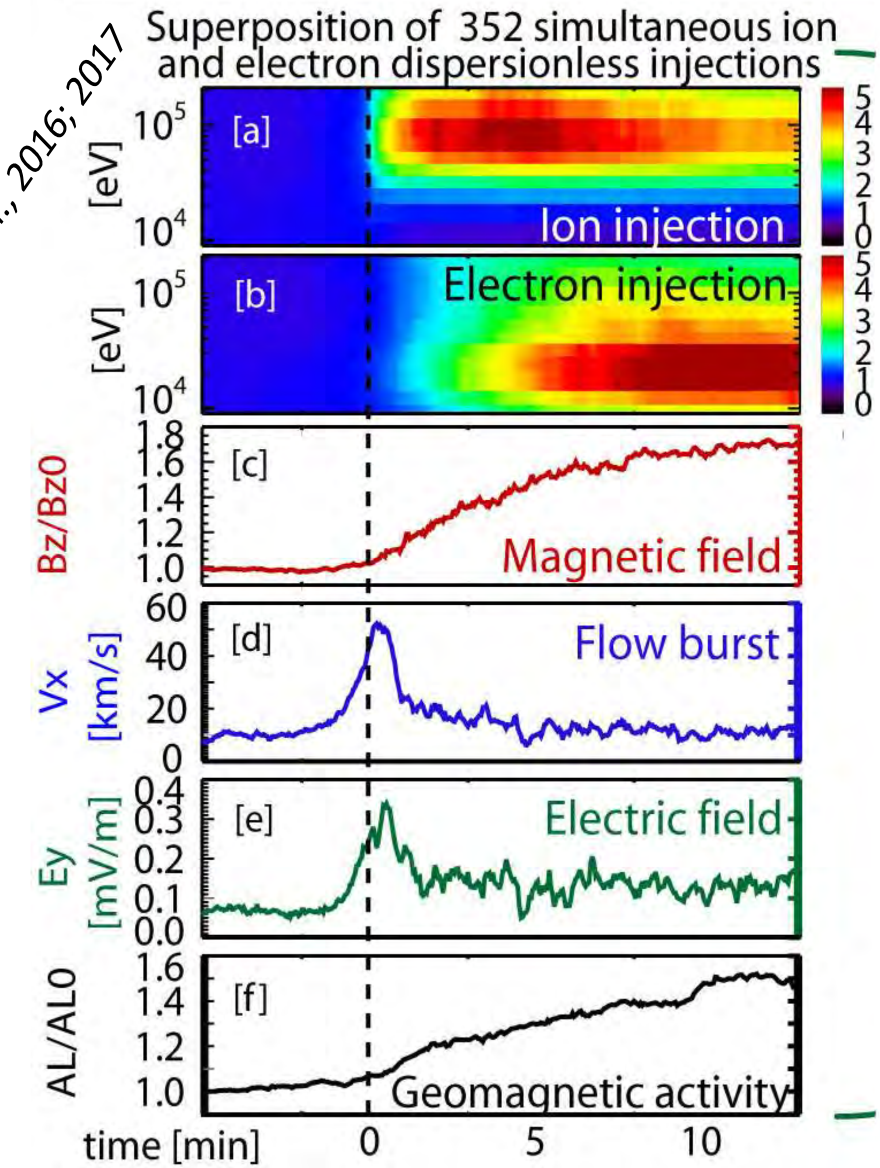


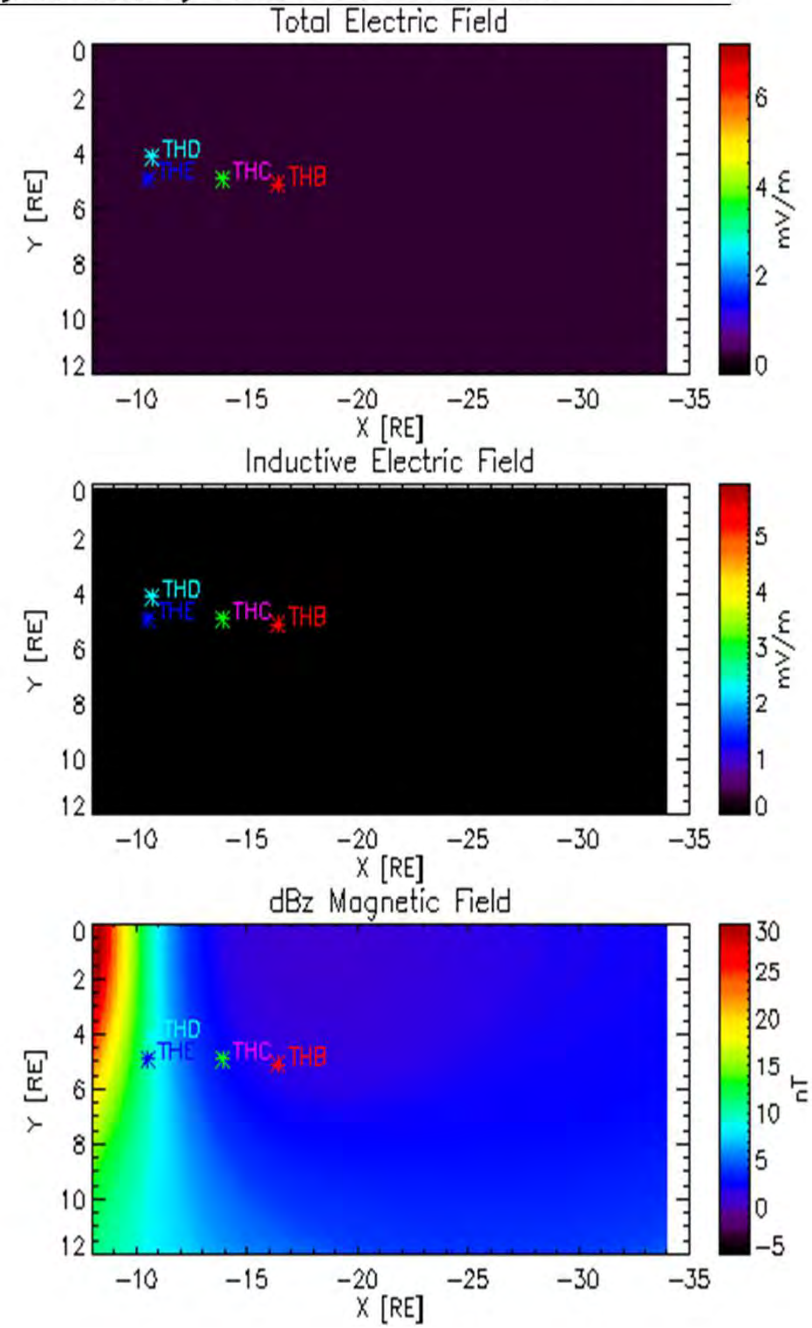


E-field pulses responsible for injections and flux transport. Their cumulative plasma heating at the tail-dipole transition region can be significant.

Particle Transport and Energization (Injection) by Narrow Fast Flows

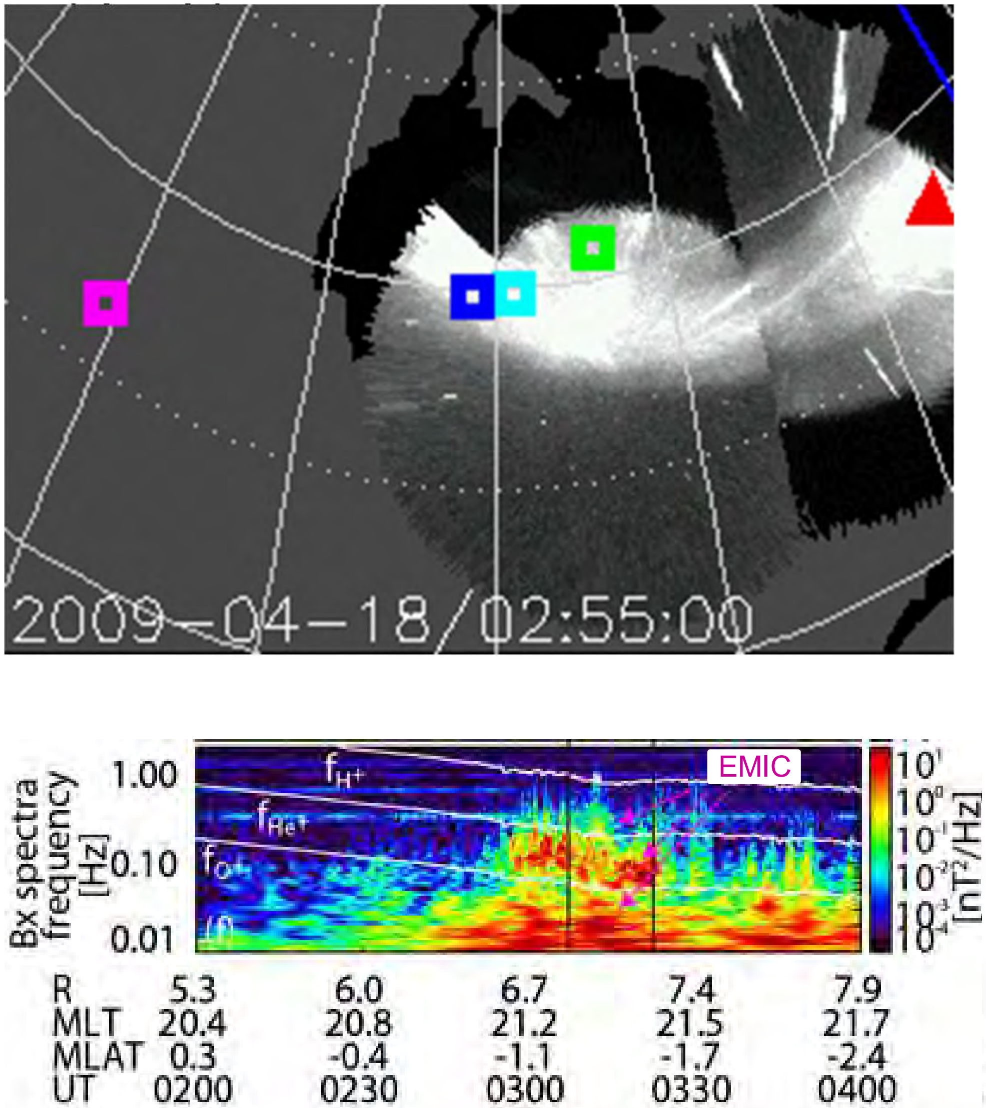
Gabrielse et al., 2016; 2017





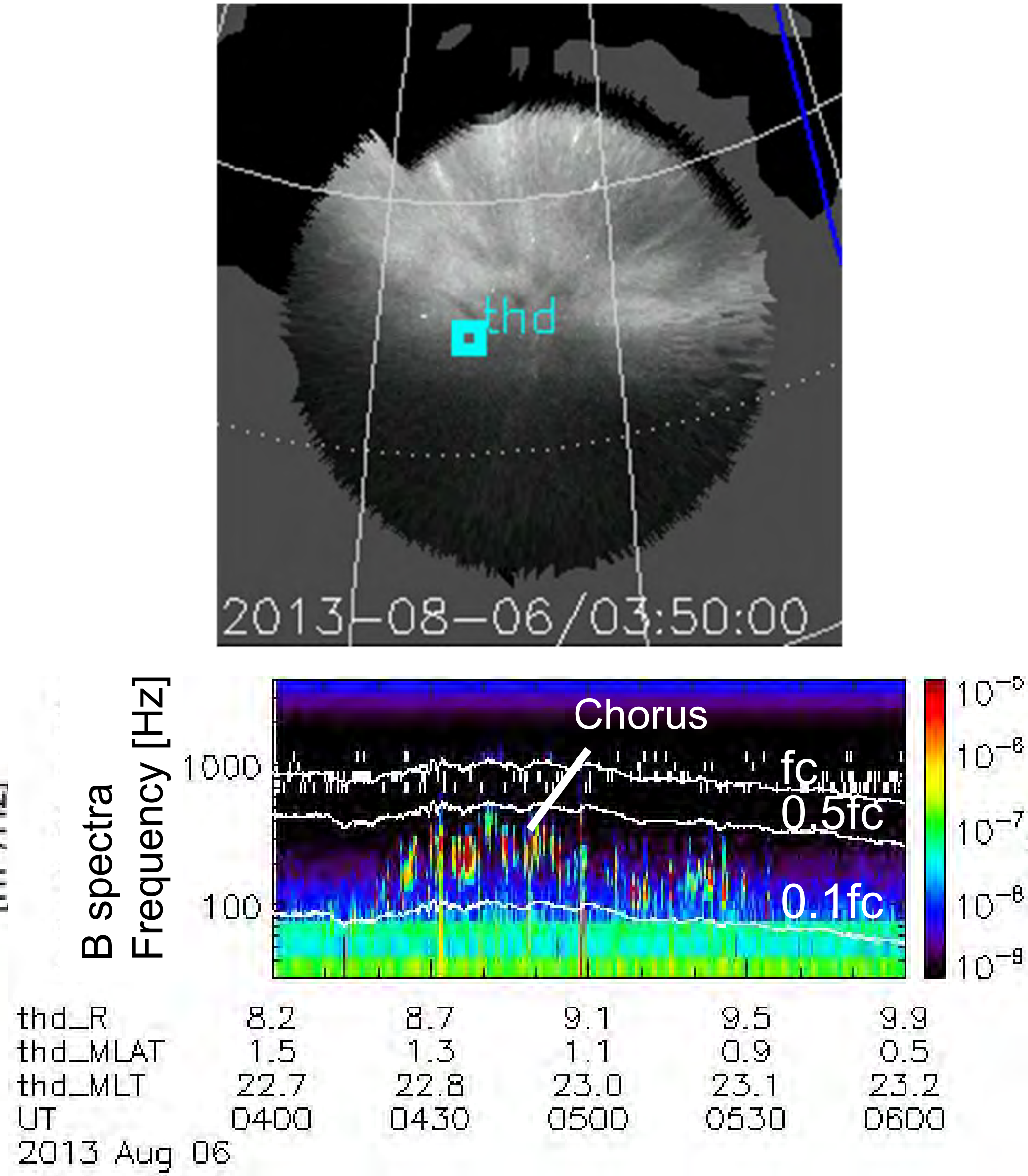
Flow bursts (dipolarizing flux bundles, DFBs) cause injections, waves, aurora

Streamer driving proton aurora

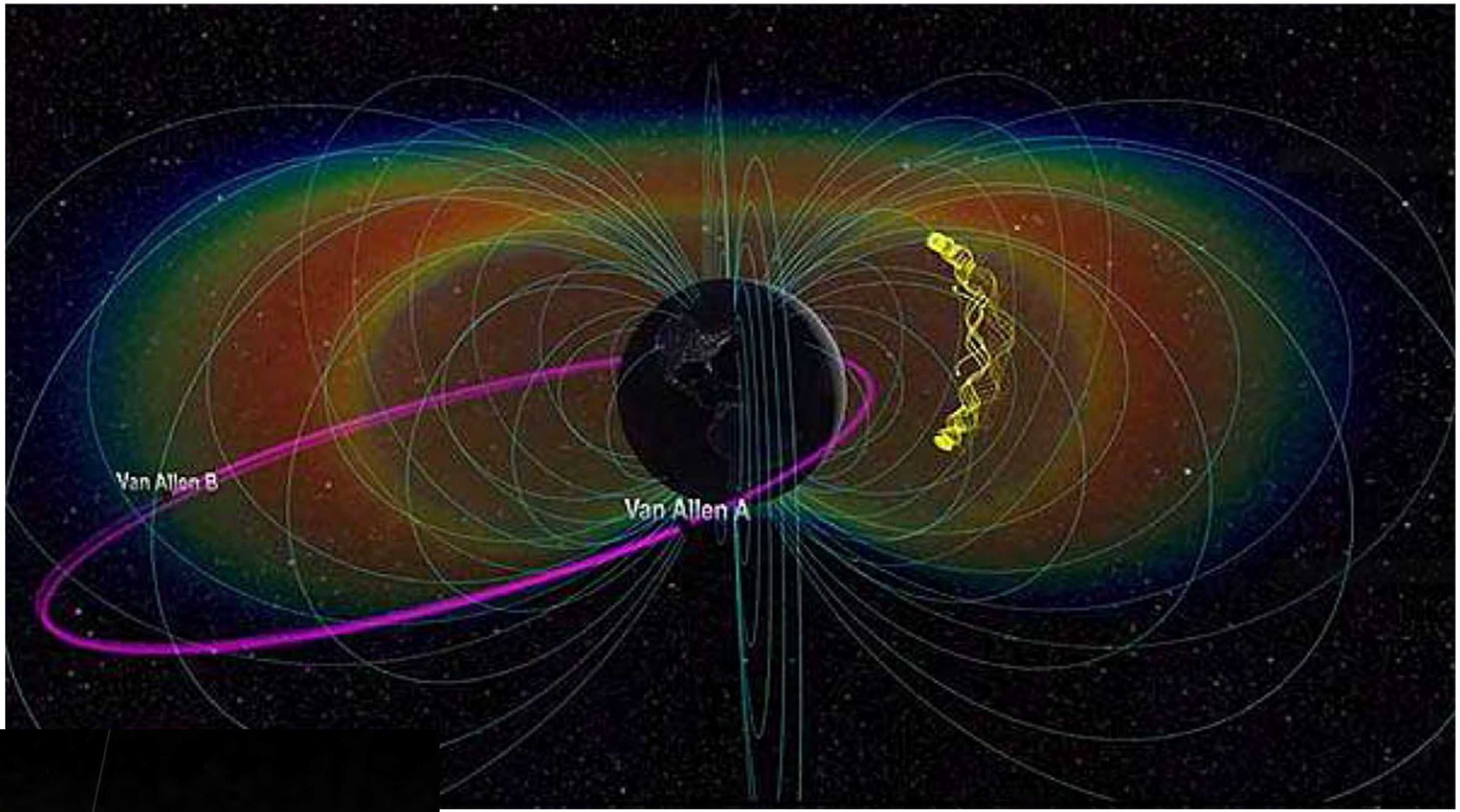


Nishimura et al., 2014

Streamer driving pulsating aurora



Van Allen Probes, in 2012-2019, addressed how the incoming energy accelerates radiation belt electrons



Demonstrated that acceleration of energetic electrons by waves (mostly produced by injections) is the dominant contributor to the radiation belt electron energization.

From THEMIS to ARTEMIS: the power of reconfigurability

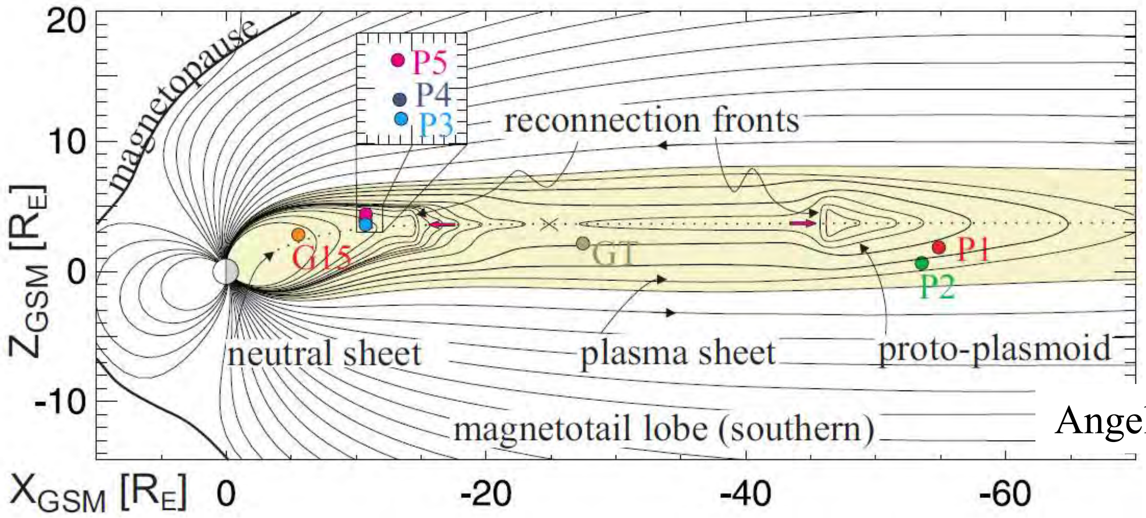
In 2010 NASA took the two most distant THEMIS probes to the moon (going from $30R_E \rightarrow 60R_E$):

- First 2-satellite mission at moon
- Addressed new science objectives

ARTEMIS showed that the dominant substorm energy dissipation occurs at "reconnection fronts" (our version of meteorology's "weather fronts") maximizing near Earth.

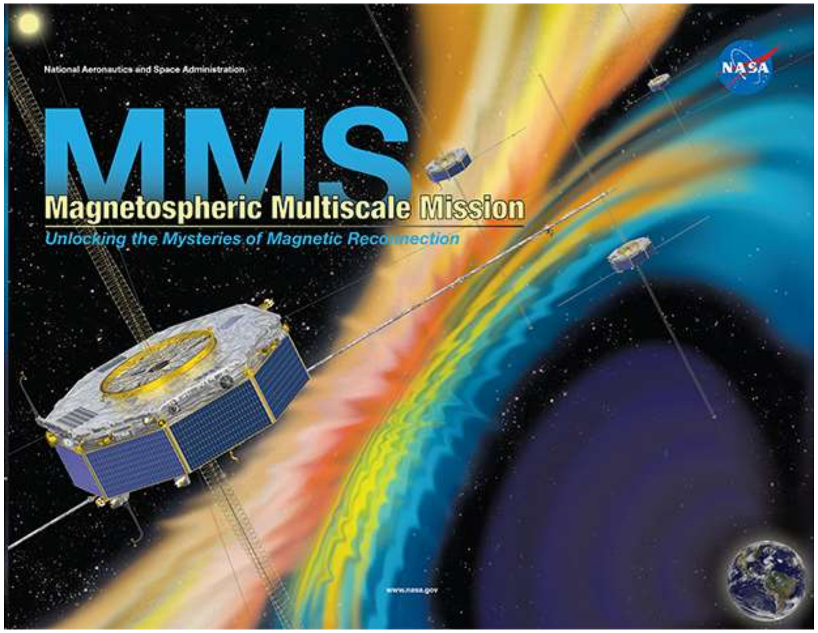
Messages: small/micro-satellite constellations:

- **are resilient (long-lasting) by their numbers …**
- **they can contribute uniquely to space weather monitoring**
- **if reconfigurable (agile) they stay relevant for a long time**

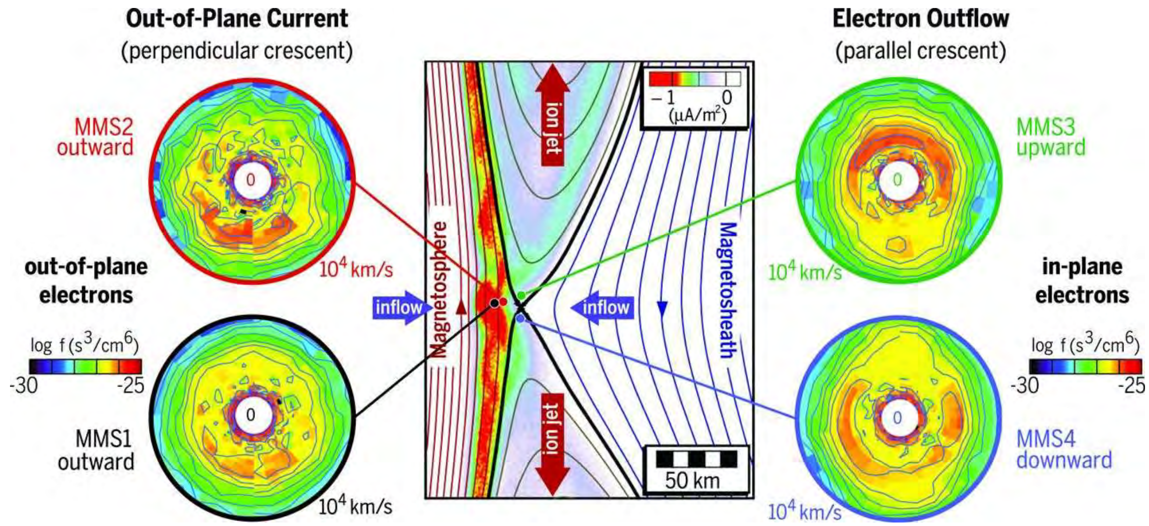


Angelopoulos et al., Science, 2013

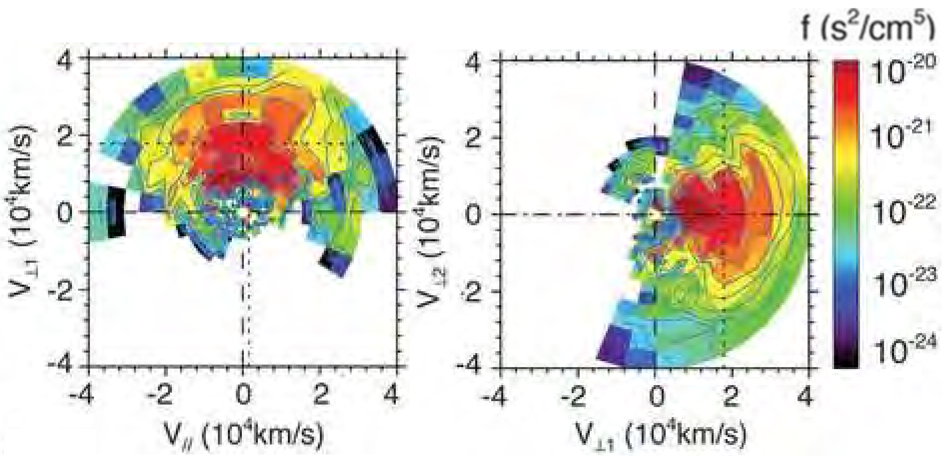
The microphysics of reconnection, that initiates the energy conversion was revealed by MMS, a 4-satellite constellation (L:2015)

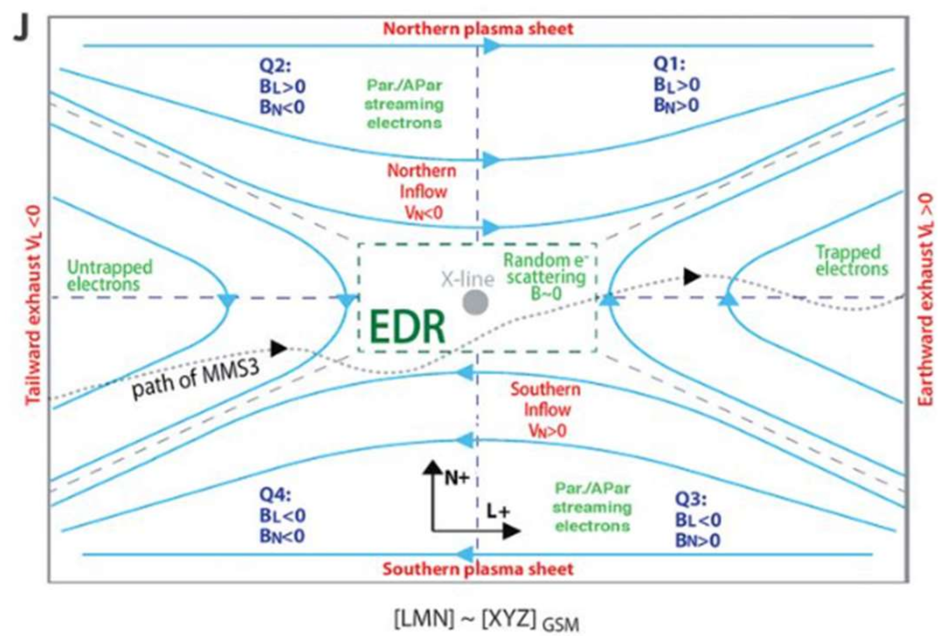


At the dayside magnetopause [*Burch et al., 2016, Science*]



And in the magnetotail [*Torbert et al., 2016, Science*]

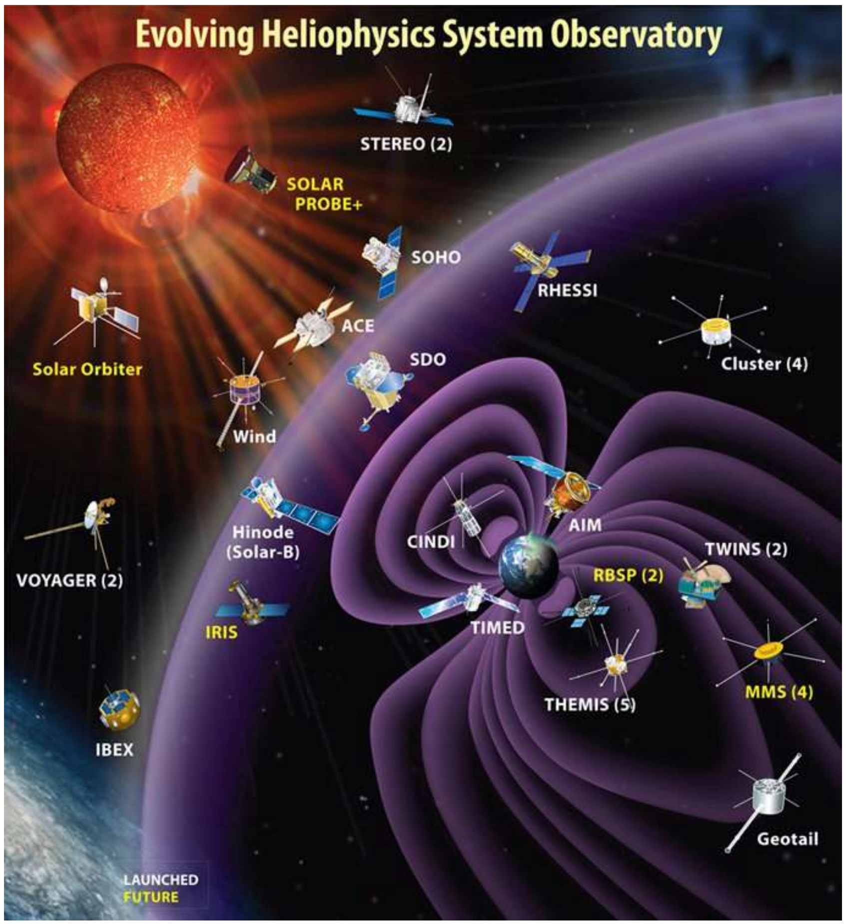




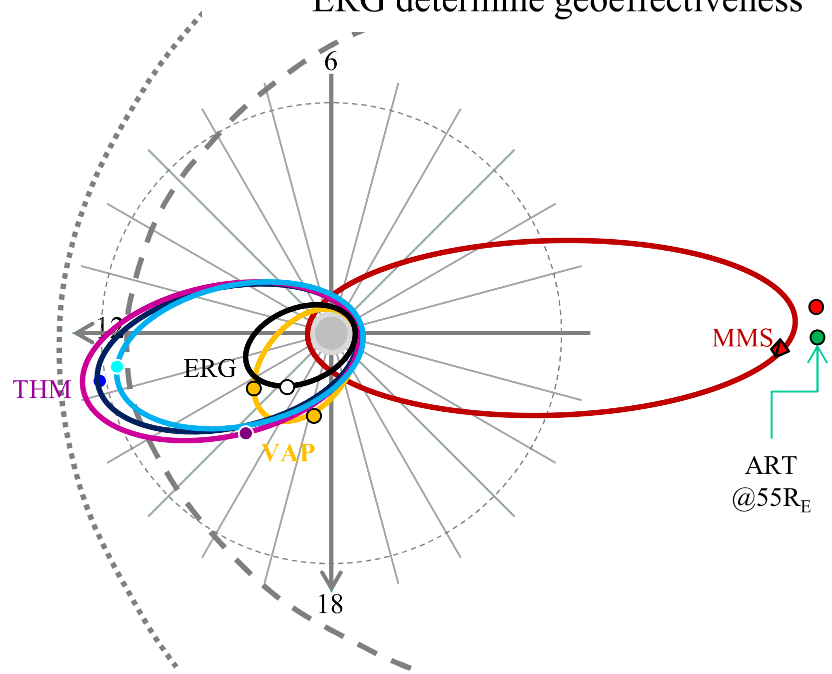
NASA's Heliophysics System Observatory (c. 2015-2024)

The HSO has provided a fuller understanding of space plasma processes, beyond ISTP. It is now studying how space weather fronts conspire to create space weather.

- New (multi-spacecraft) and legacy missions were combined in powerful new ways
- Ground based observatories now more abundantly available also started to contribute
- THEMIS/ARTEMIS optimized the HSO thanks to its fuel (**reconfigurability**).

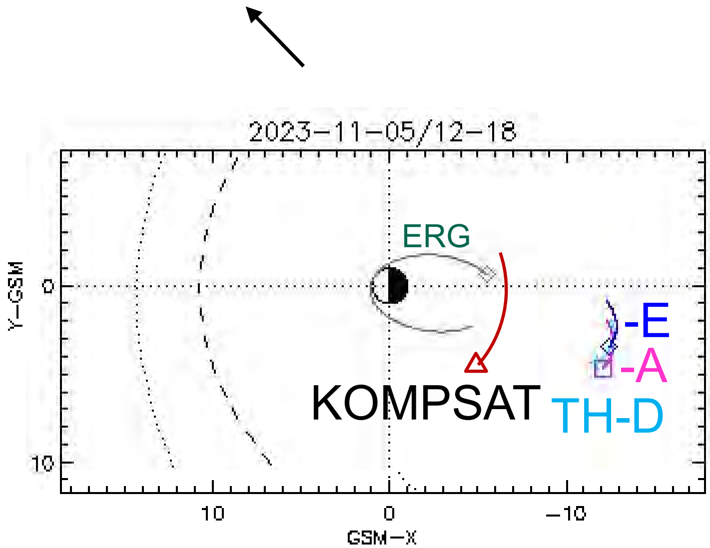


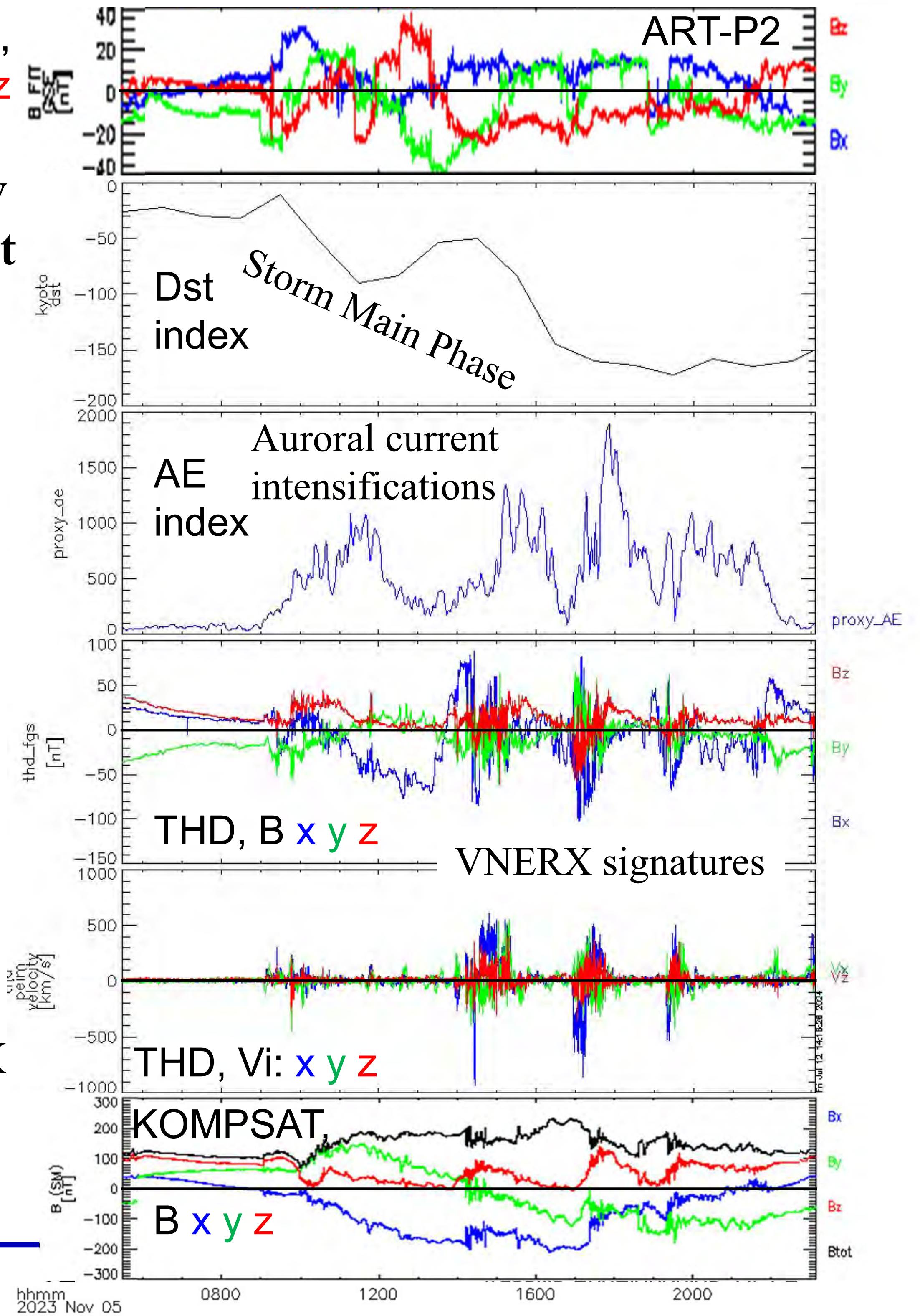
MMS Tail #2 (THM at dayside)
(MMS Phase 2B & Extended Phase)
THM and MMS study dayside and nightside Rx simultaneously; VAP and ERG determine geoeffectiveness



Solar Wind,
B x y z

In the new solar cycle, recent HSO observations have revealed that very near-Earth reconnection (VNERX, at <13R_E distance) plays a key role in powering the main phase of storms!





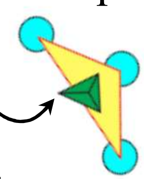
Like classical near-Earth RX during substorms (at ~25R_E), storm-time VNERX most common at pre-midnight.

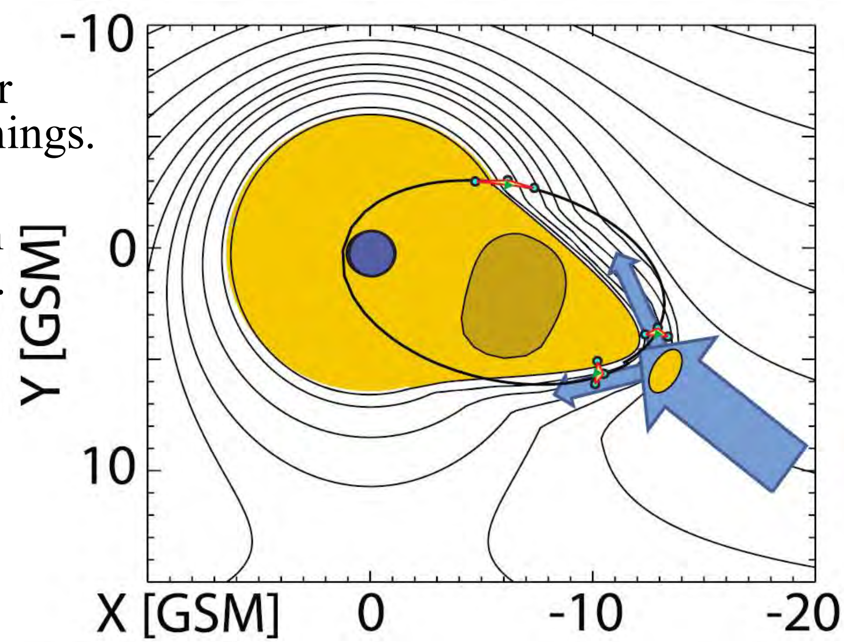
Beyene et al., 2024 *JGR in prep.*

New questions arise, to be addressed in the future: How is the magnetic energy in the magnetotail converted to heat and powers the ionosphere and storm-time ring current?

A <u>complete</u> resolution of this question requires measurements of vector quantities (**J**·**E**, **V**·∇P) with 4 satellites in tetrahedral formation, at a few 100km separation. This requires measuring the gradients of plasma and magnetic pressure, as well as the flow vorticity.

- ✓ Plasma Observatory a 7 satellite mission competing for ESA's M7 slot, strives to address this amongst other things.
- ✓ THEIA (a 5 satellite MIDEX mission proposal) shown embedded within THEMIS is focused on this question.
- ✓ MagCon (under study by the Decadal Survey) can also address some of these objectives using dozens of satellites.





Gabrielse et al., 2019

Questions:

- Kinetic energy → near-Earth plasma heating
  - ✓ Compare **J**·**E** with **V**·∇P and ∇·[($\rho V^2/2$)**V**]
- EM - thermal energy conversion (how is **J**·**E** >0 or **J**·**E** <0 produced)?
  - ✓ Compare **S**=**E**×**B**/μ_0 and **V**·∇P with **J**·**E**
- How is the field aligned current $J_{\|}$ generated?
  - ✓ Compare **S**=**E**×**B**/μ_0 and $J_{\|}$ with $\nabla_{\perp}P_M$, $\nabla_{\perp}P_B$ and vorticity $\Omega_{\|}$=**b**·($\nabla_{\perp}$×**B**)

Ideally, **large HPS constellations are needed** to address how localized reconnection-driven flows cause diverse space weather

A new generation of missions critical for advancing our understanding of Sun-Earth connections is needed *to: understand the interactions of plasmas within and across targeted regions: Magnetopause, near-Earth magnetotail, distant magnetotail – and how these result in modes of circulation*

1. **Space Weather Energy Coupler**

- **30-50 probes** on 4 equatorial orbits x 10 probes per petal, $\Delta V<100m/s$, $1.5x12R_E$.

Science objectives

- *Nightside*: interaction of bursts with *radiation belts*:
  Dayside: coupling of solar wind energy into the magnetosphere.

2. **Drivers and Consequences of Reconnection Explorer**

- **40 probes**, 4 petals x 10 probes / petal, $\Delta V\sim1000m/s$, $3 \times 24R_E$.

Science objectives: Global drivers and consequences of near-Earth reconnection.

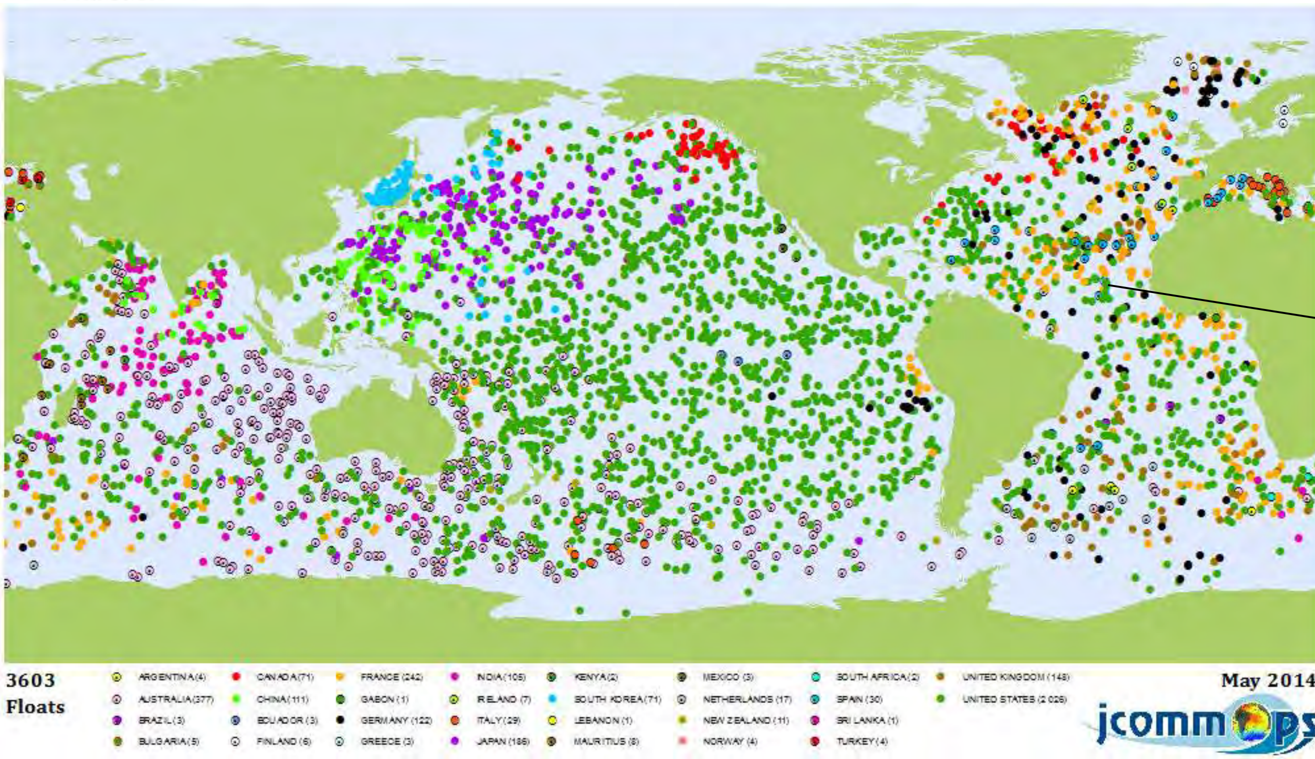
3. **Global drivers of magnetotail circulation**

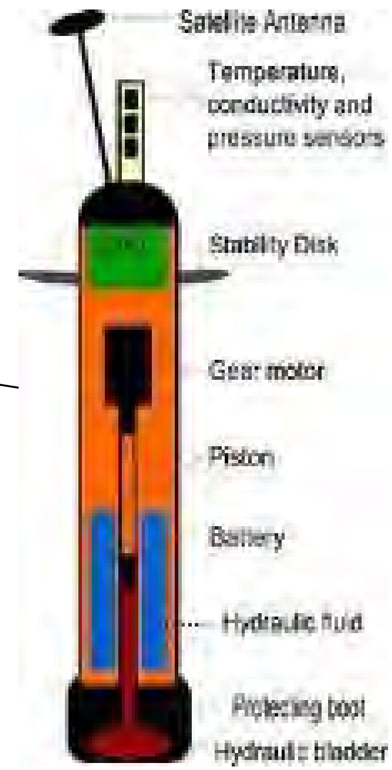
- **50-100 equatorial probes**, $4 \times 65R_E$ orbits, always in tail using solar sails for station-keeping

Science objectives: Quantitative understanding, and prediction energy input and release.

Beyond 2030: Coordinated constellations are needed to explore physics of various components of space weather

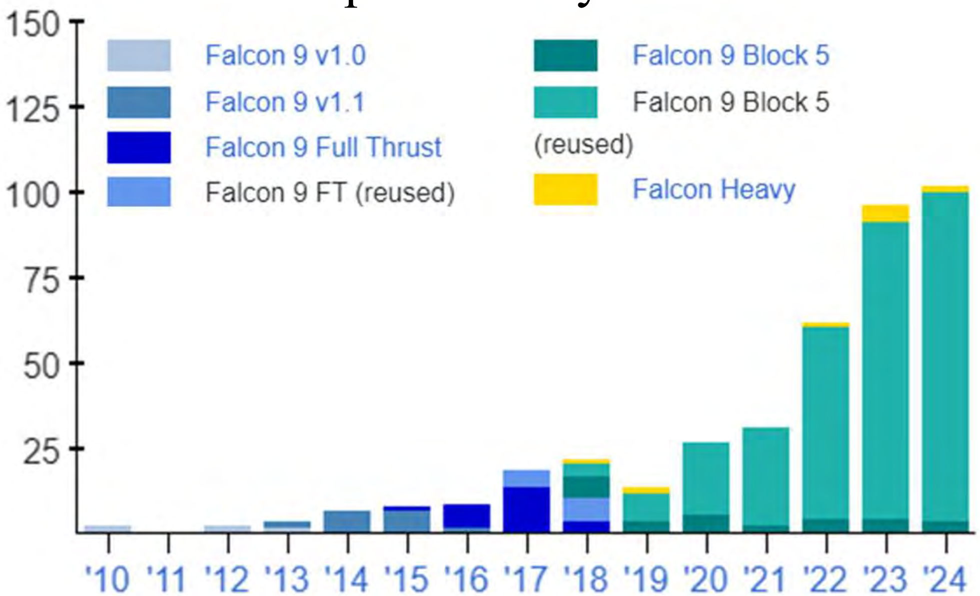
Example: how oceanography deals with a large complex system.
A multi-national network of buoys that adhere to a set of standards



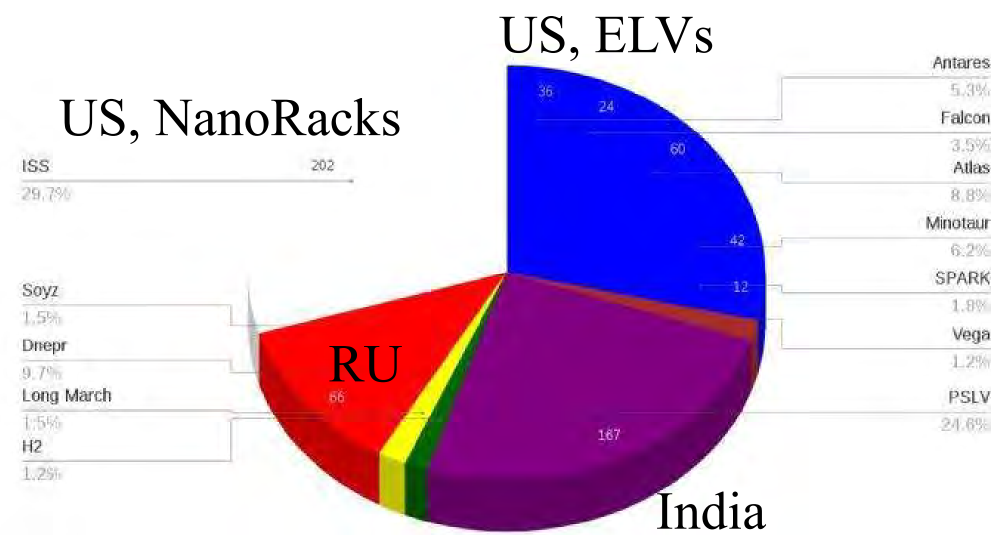


The small-sat revolution can facilitate this scientifically driven desire for constellation class missions

Space X only



Satellite launches, c. 2017



Attributes allowing exponential growth of small-sat launches:

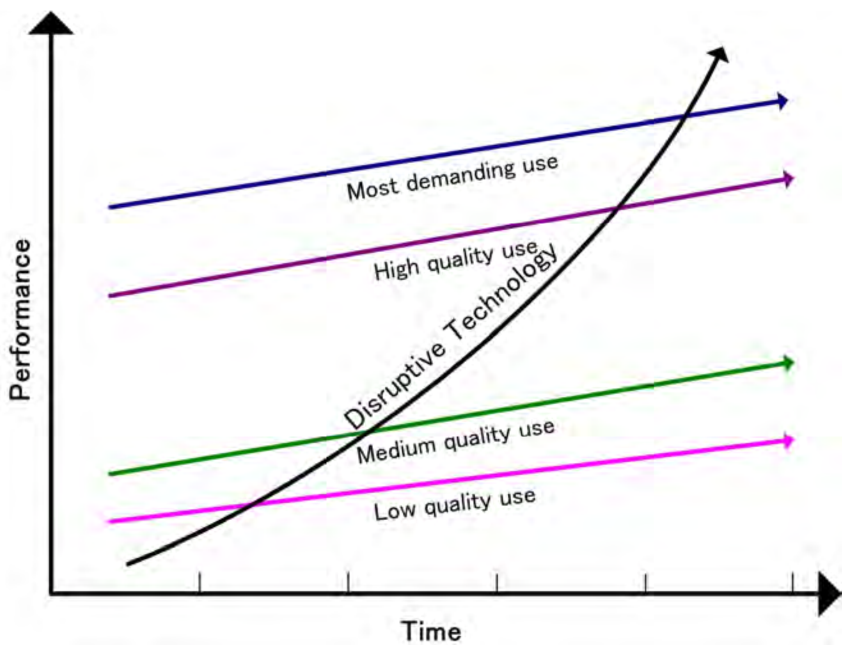
- Standardizing interfaces [P-POD] (CalPoly SLO + Boeing)
- Under-writing by government agencies [NSF, NASA]
- Large available throw-weight on LVs [e.g., Falcon 9, Falcon Heavy]
- Small size of CubeSats/SmallSats [1-10kg]
- New opportunities for business and education [e.g., Nanoracks/ISS]
- Multiple orbits attainable from single release orbit using, e.g. SHERPAs →
- They spur innovation and testing of unproven components
- Enable new business opportunities, allow risk taking, rapid re-testing …


"SHERPA"

Small-sats are a disruptive technology

Disruptive (as opposed to evolutionary) innovations [C. M. Christensen]:

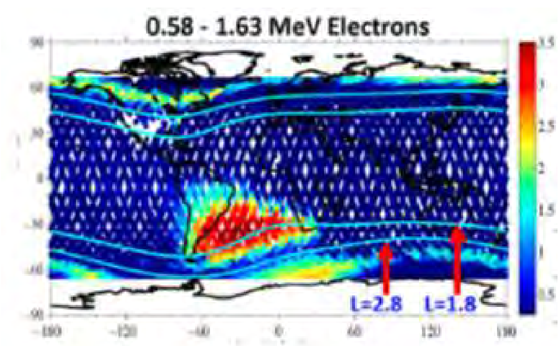
- Create a new market and value network
- Eventually displace market leading firms, products and alliances.
- At early stages they have attributes preventing mainstream entry
  - Lack refinement
  - Have no proven practical application
  - Limited customer base
  - Have performance problems
- Once capability exceeds low-end customer needs, they gain wider market share
- Market foot-hold, expanding customer base, and wide range of attributes disrupt.



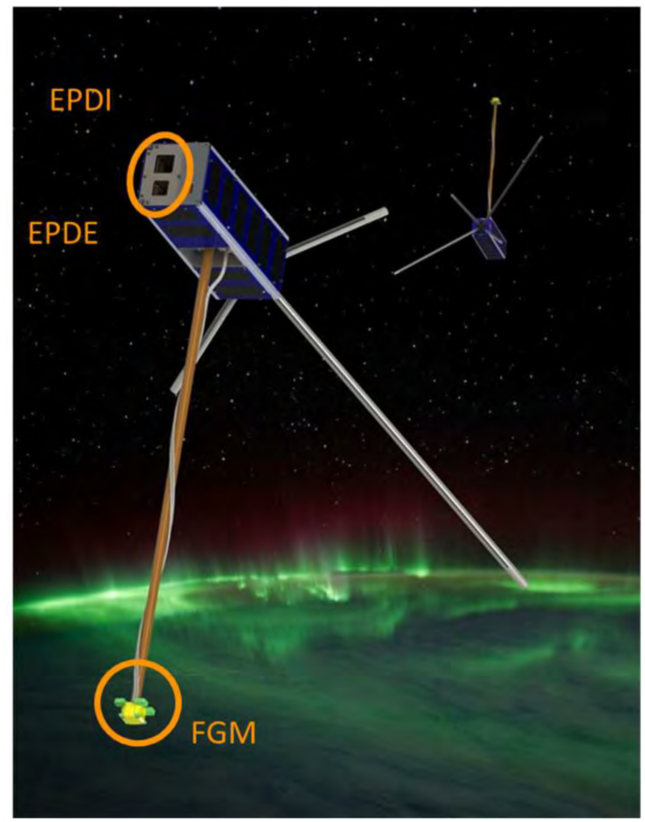
	Disruptive	Evolutionary
Automotive:	Production Line [Model-T]	Combustion engine
Academia:	Online Searches	Encyclopedias
	(Google/Wikipedia)	*(e.g., Britannica)*
Computers:	PCs	Mainframes
	(IBM, Apple, ...)	*(DEC, Sun, ...)*
Displays:	LCD	CRTs
Lighting:	LED	Lightbulbs
Medical imaging:	Ultrasound	X-Ray
Photography:	Digital	Chemical
	(Nikon/Canon)	*(Kodak/Agfa/Fuji)*

Small-sats advancing cutting-edge space weather science, can also help test HPS technologies and train the workforce of the future.

CSSWE by *CU/LASP* (2012-2014)
Studied energetic ion/electron precipitation
>20 publications, including one in Nature.



ELFIN by *UCLA* (2018-2022)
Pitch-angle resolved spectra of i^+, e^-.
Studied wave scattering of relativistic e^-.
Legacy: >45 pub's, many HSO conjunctions



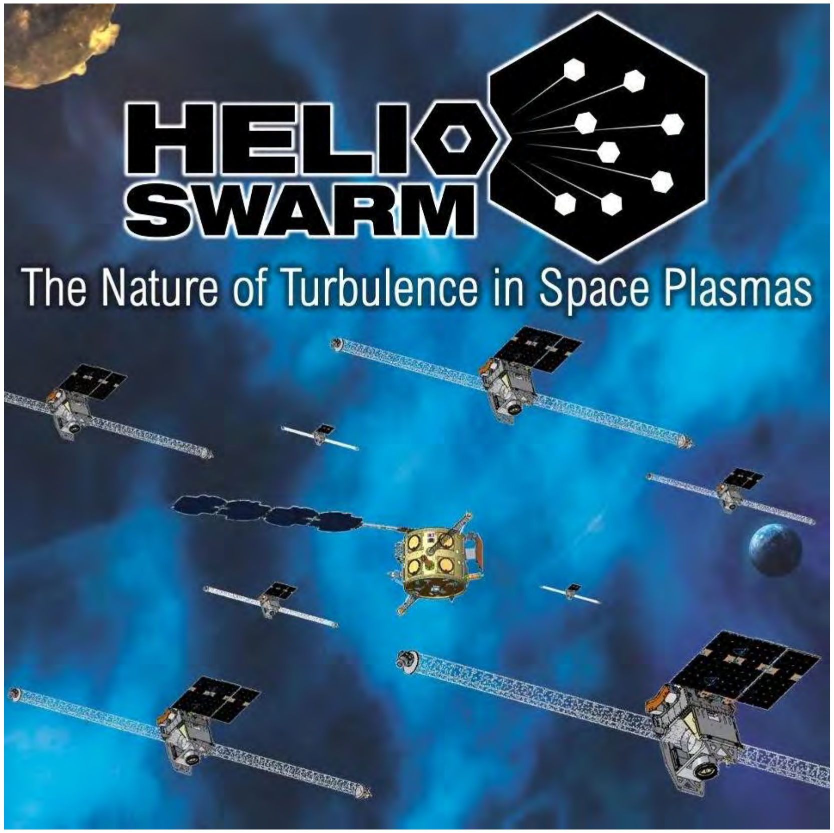
FIREBIRD by *MSU/UNH* (2015-2023)
JGR Highlight on electron microbursts
Legacy: Conjunctions with Van Allen Probes

NASA constellations, enabling new science are becoming mainstream
They promise to revolutionize our understanding of near-Earth space

CYGNSS (Cyclone Global Navigation Satellite System) [*UMich+SwRI*]
8 micro-sats on a dedicated NASA LV
$157M, Launch: Nov. 2016

CINEMA [*Dartmough + APL, SMEX in Phase-A study]*
9 CubeSats to study the magnetosphere and its connection to the aurora from LEO, $150M, L: 2028

HelioSWARM [*UNH + SwRI, MIDEX*]
8 micro-sats and a hub on an ESPA ring to study solar wind turbulence
$250M, Launch: Nov. 2026



Conclusions

The magnetospheric community has made tremendous progress in the last 15 years thanks to a series of multipoint missions that have revealed how space weather fronts power substorms and storms.

Substorms occur as a series of reconnection impulses at ~25 R_E sending flows to the tail-dipole transition region at 10-12 R_E, where pre-onset auroras lie, initiating onset.

Reconnection initiates energy conversion that can power the inner magnetosphere and accelerate radiation belt particles leading to the space weather phenomena we know.

Substorm-like processes, manifested as Very Near-Earth Reconnection, VNERX, also occur during the storm main phase.

Magnetic energy conversion to thermal and kinetic energy and field-aligned currents occur in the near-Earth region during both substorms and storms. **The kinetic aspects of that energy conversion require investigation by future missions in tetrahedral formation.**

Low altitude CubeSats can become the first in a series of heliophysics constellations that can help address the field's most pressing questions related to the localized nature of reconnection and energy conversion.

CubeSats can help in that regard by becoming the testing ground for new technologies and the training ground for future space explorers.

Backup Slides

What causes the poleward motion of aurorals, the substorm expansion?

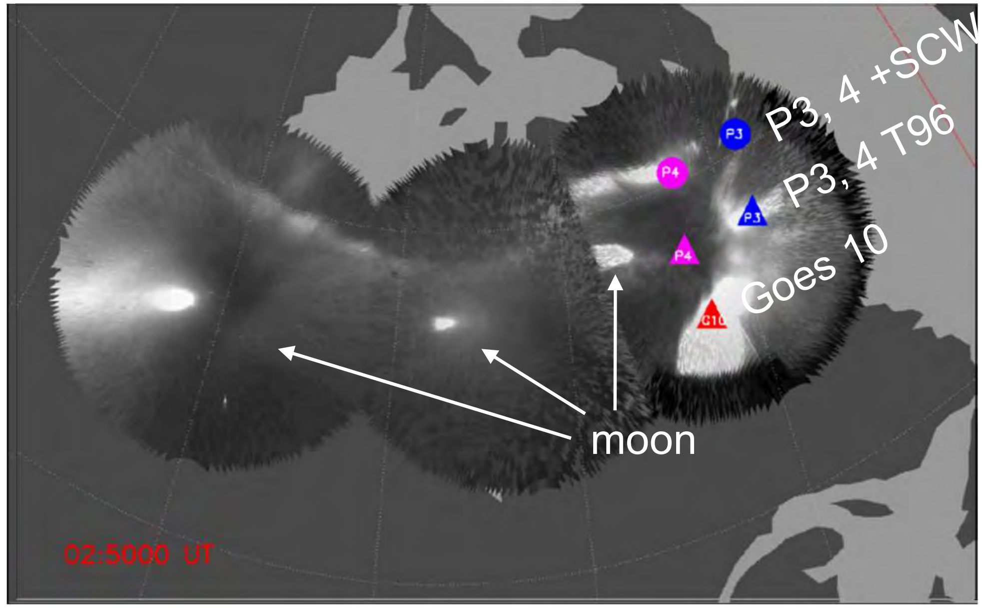
Ans.: The mapping distortion by flow bursts / dipolarizing flux bundles depositing their flux near Earth!

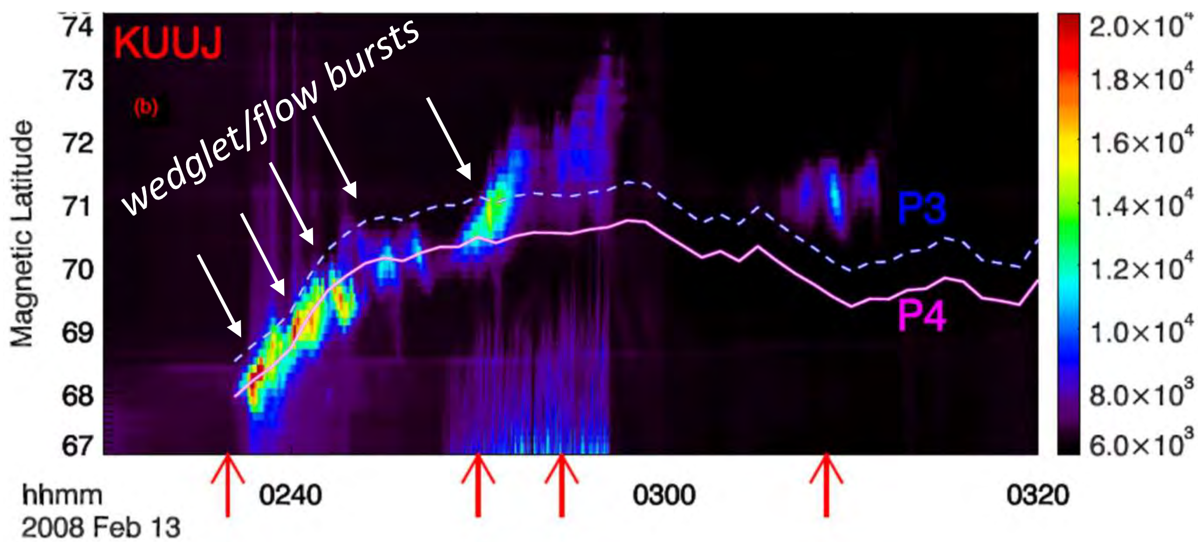
Xiangning Chu McPherron, et al., 2014

Mapping including substorm currents

P3, P4 are in the tail around 8-10 R_E

Also confirmed by: Nikolaev et al. 2015





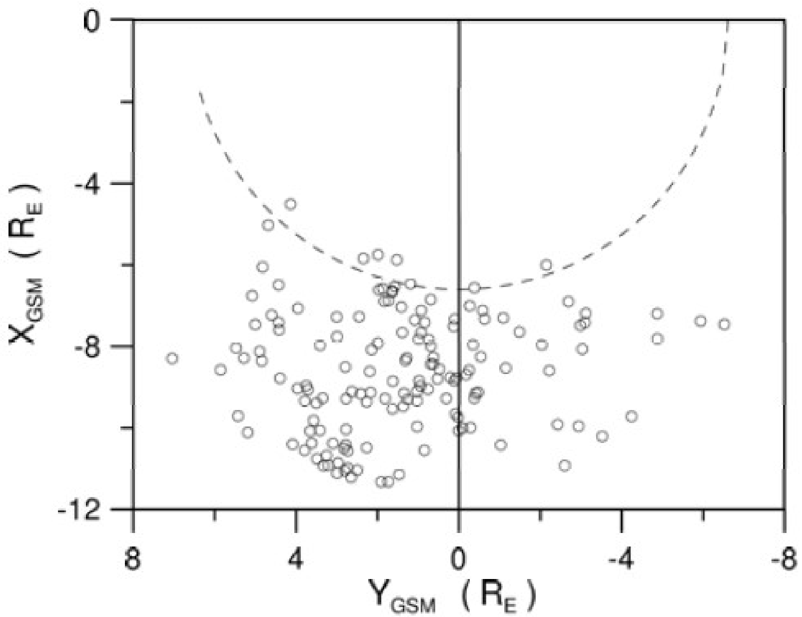
Which DFBs make it to inner magnetosphere?

Dubyagin et al., JGR 2010, GRL 2011

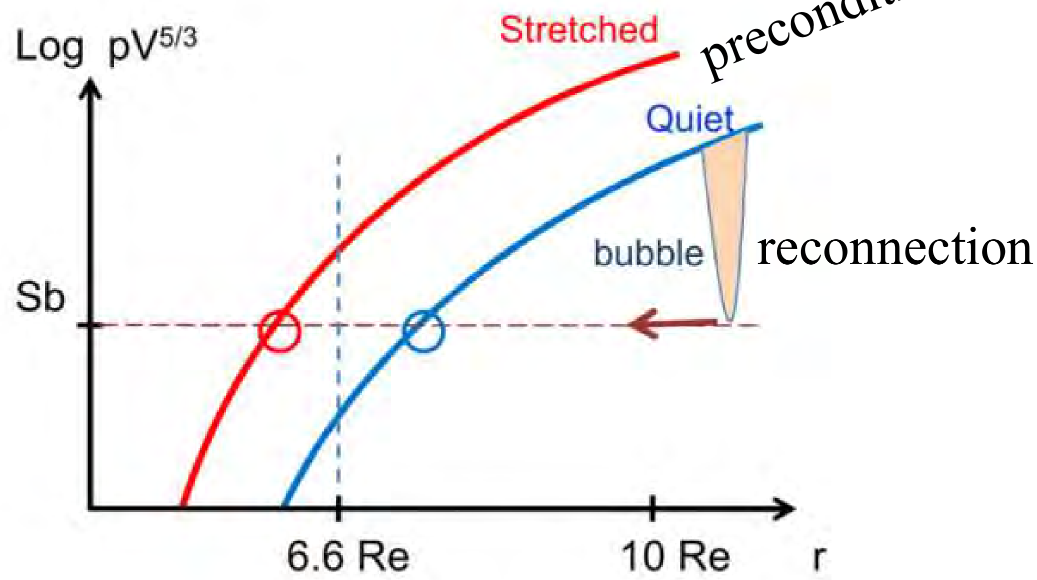
Ratio of $S=PV^{\gamma}$ within the bundle (S_{DIP}) to pre-DFB (S_0) conditions is <1.

– Only low entropy flow bursts make it to satellite location

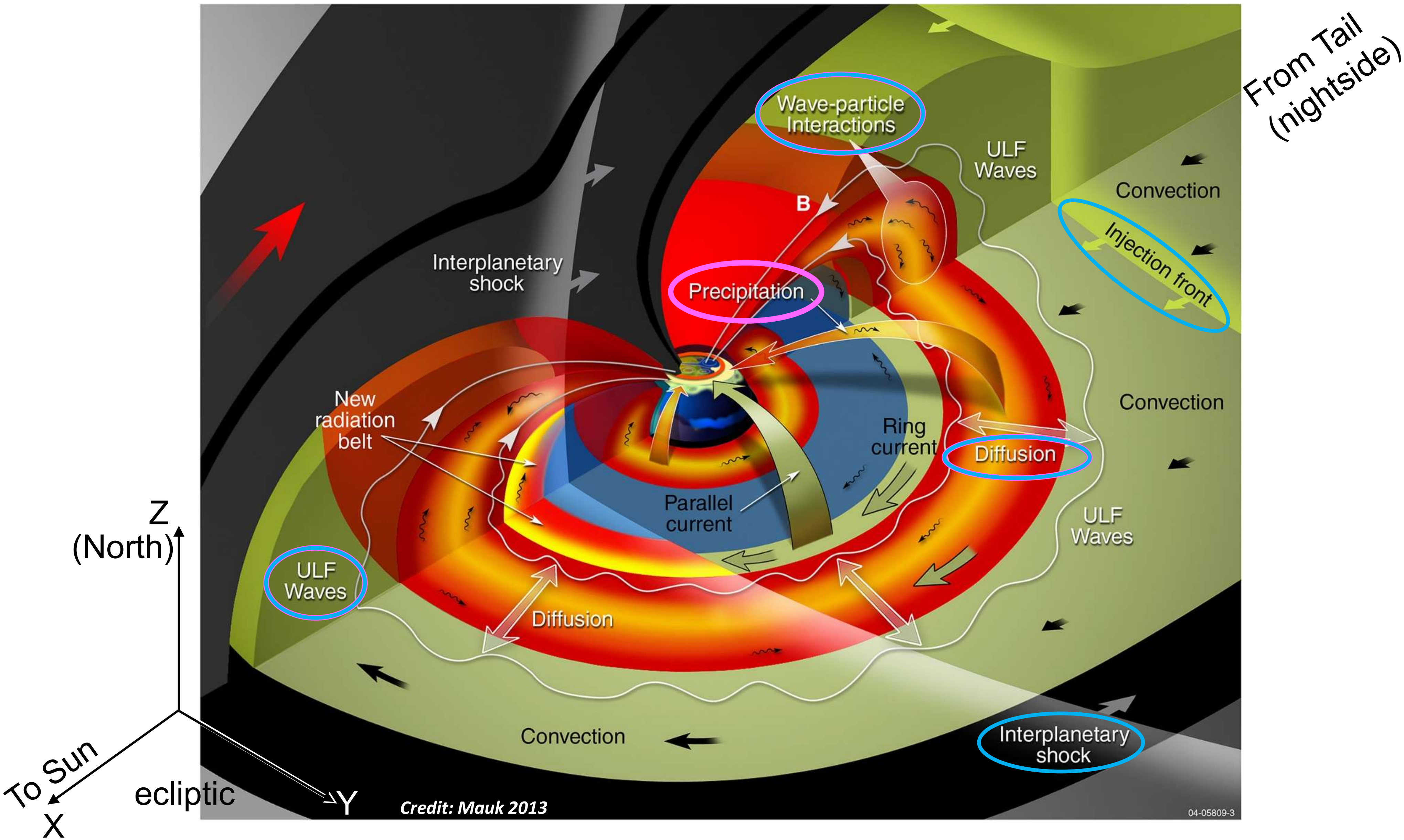
– Ratio increases with proximity to Earth, as fewer bubbles make it there.



Sergeev et al., 2012



Monitoring Earth's Dynamic Inner Magnetosphere from the Ionosphere

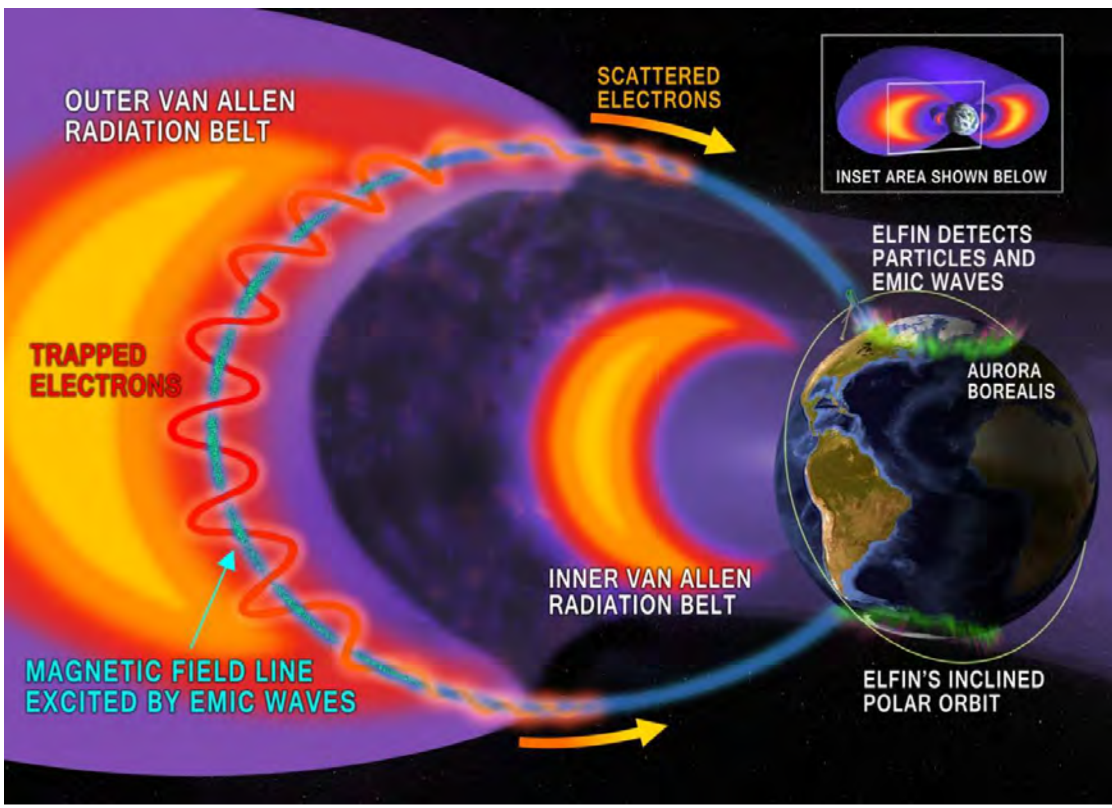


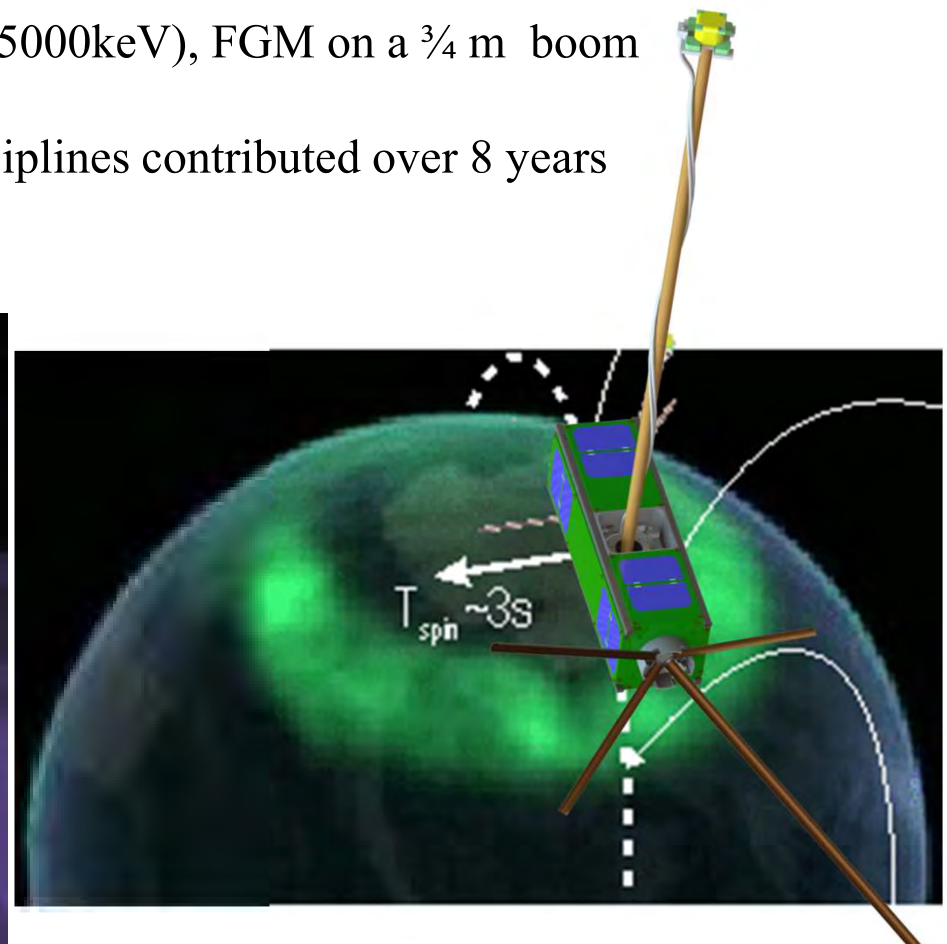
Small-sat contributions to cutting edge space weather science: ELFIN

ELFIN (Electron Losses and Fields INvestigation with Spatio-Temporal Ambiguity Resolution) [*UCLA, in partnership with the Aerospace Corporation*]
Launch: September 2018. Goal: to resolve if relativistic electron loss is caused by EMIC waves or other processes (a focused investigation).

3U packs: i^+, e^- detectors (50-5000keV), FGM on a ¾ m boom

>350 students from many disciplines contributed over 8 years



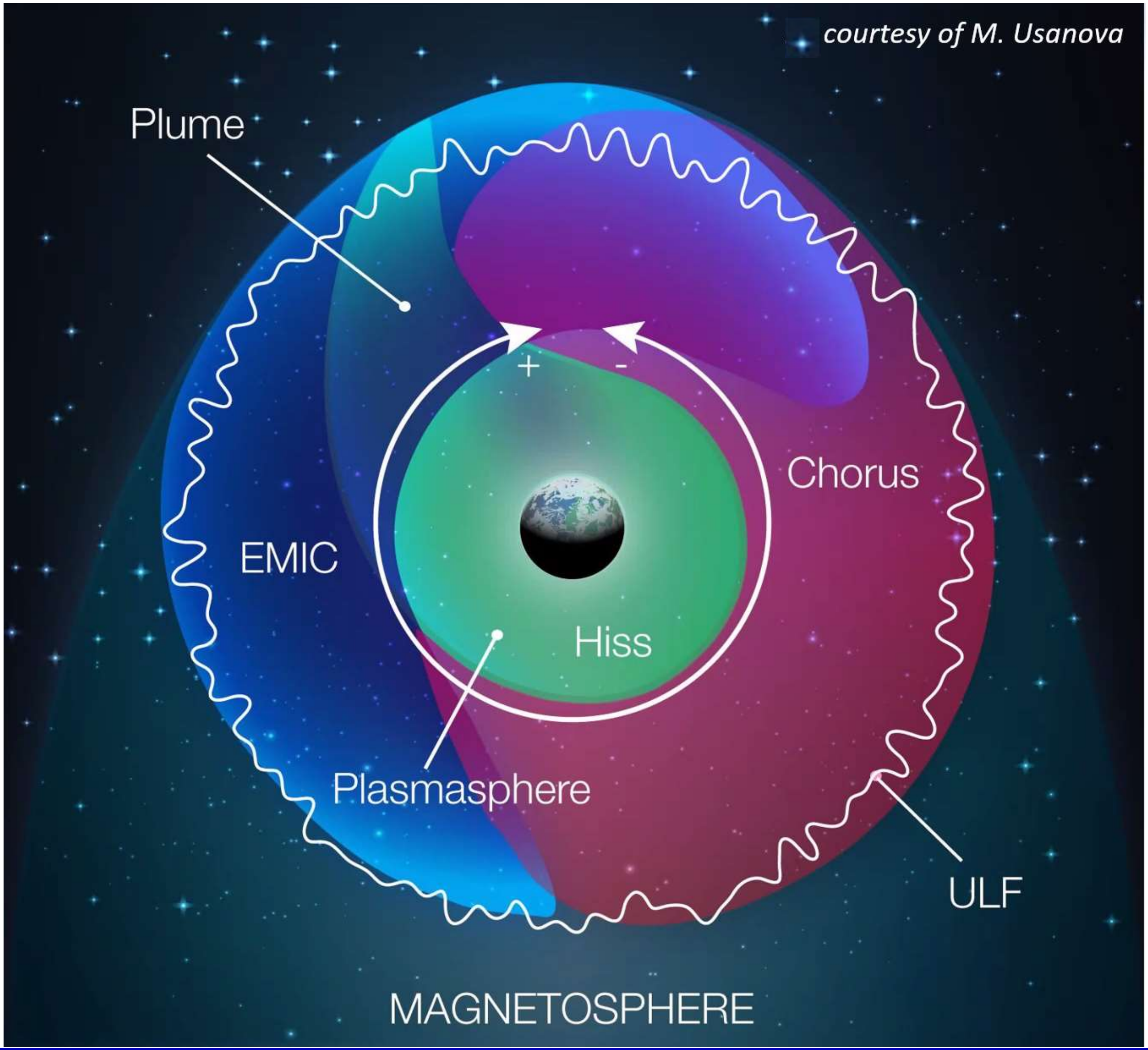


Vassilis Angelopoulos, UCLA

Radiation Belt Sources are due to Reconnection, Losses due to Waves

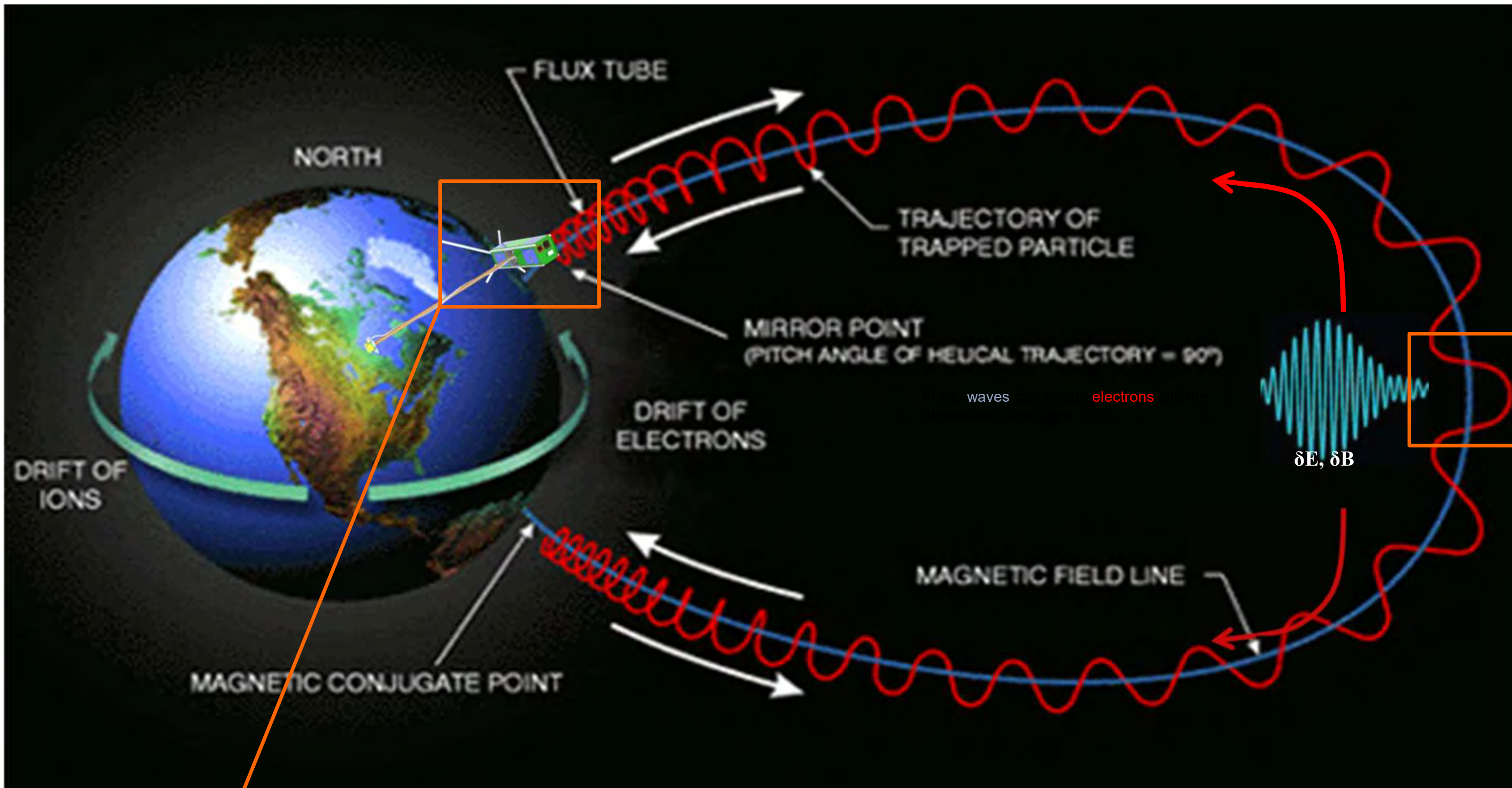
Electromagnetic Ion Cyclotron (EMIC) waves can scatter MeV electrons to atmosphere
- losses are hard to study from magnetosphere, easy to study from ionosphere, had not been done before

Top-down view of wave types in equatorial outer radiation belt



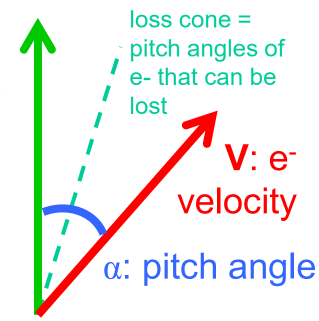
Radiation belt losses can be studied well from LEO, provided the electron flux can be measured as a function of energy, pitch-angle

- From equator, losses are difficult to detect, because pitch angles of electrons that make it to ionosphere are ~1^{o}.
- ELFIN was the first mission to produce e^- pitch angle and energy distributions of 50keV – 5MeV at low altitude.
- Ratios of fluxes along and perpendicular to the B-field are the most accurate measurement of loss rate.



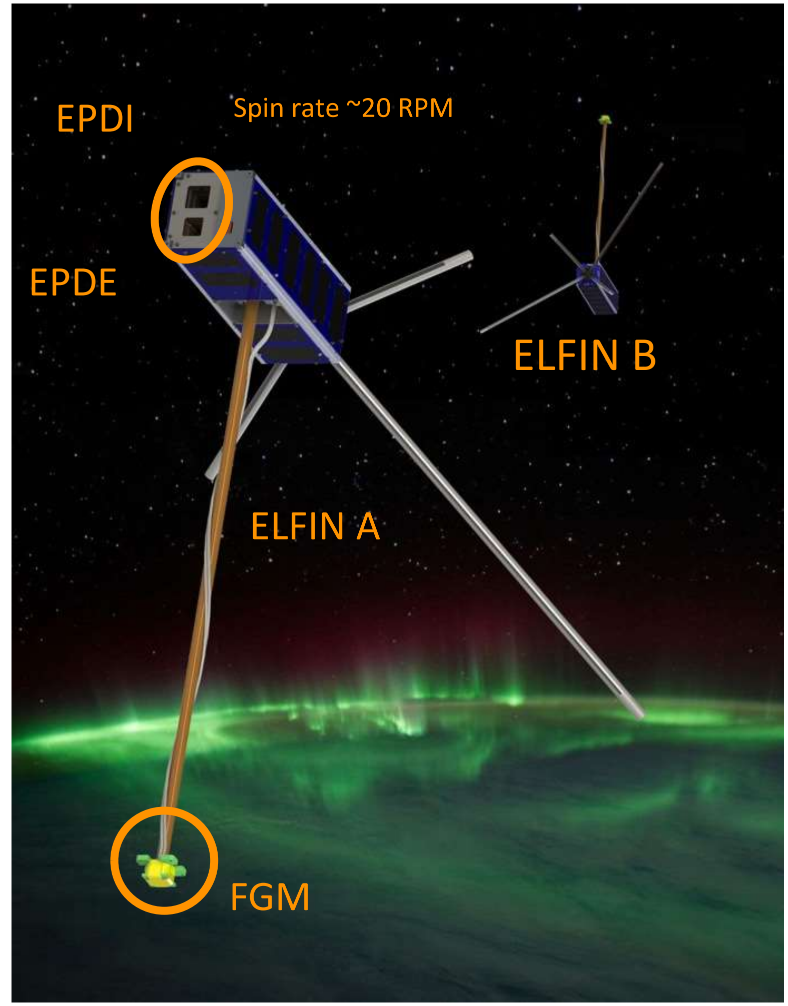
Van Allen Probes, MMS or THEMIS measure sources but not losses

ELFIN at LEO easily measures losses (what comes down).

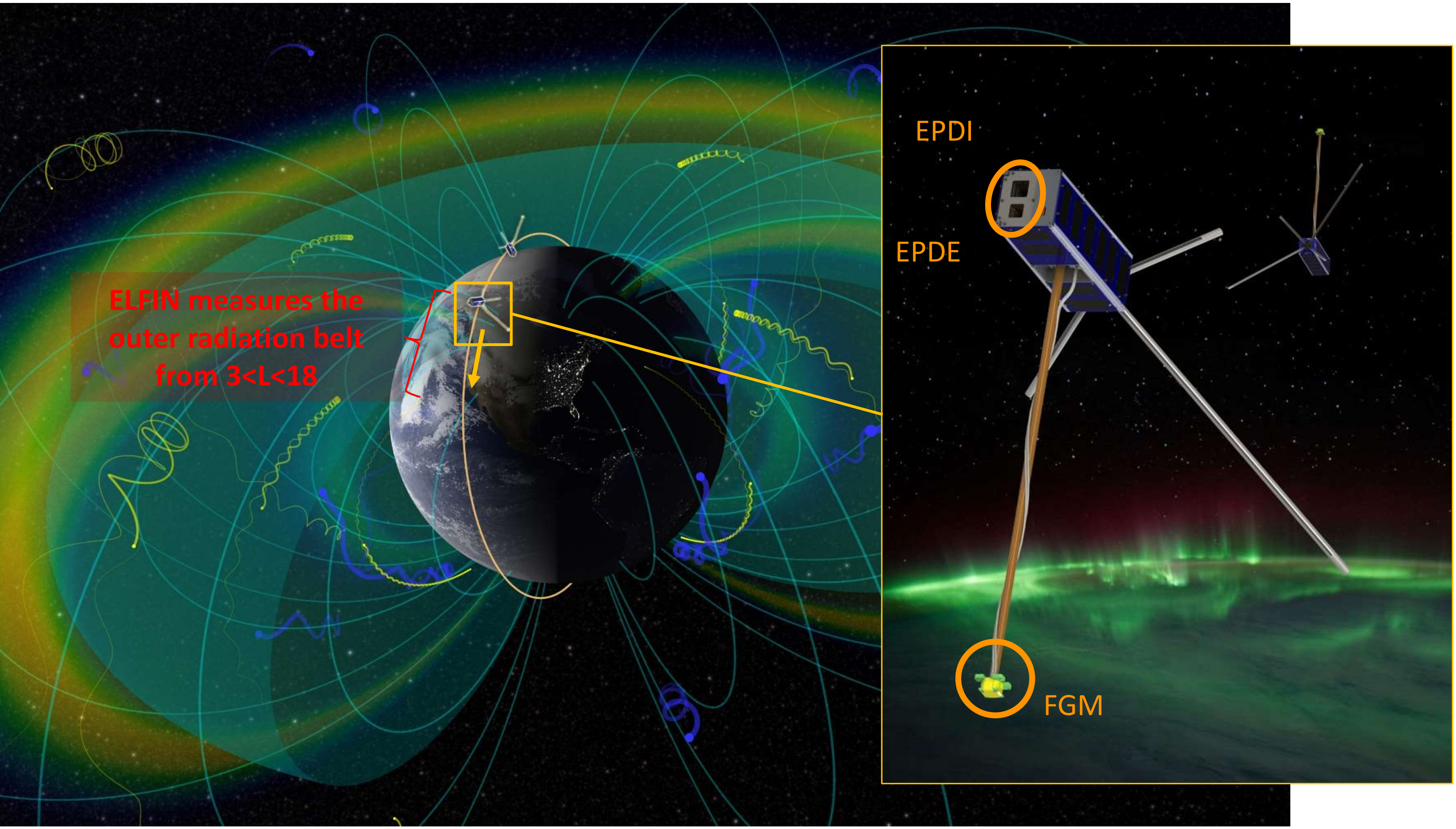


Electron **L**osses and **F**ields **In**vestigation, ELFIN

- Developed between 2014 – 2018 by UCLA
  - two 3U CubeSats, funded by NSF + NASA
  - avionics boards (& technical support): the Aerospace Corp.
  - everything else: built in-house or purchased (c. 2014)
- Launched in Sept 2018, deorbited in Sept 2022
- Carried 3 instruments built in-house at UCLA:
  - EPD-Electrons (EPDE), EPD-Ions (EPDI), Fluxgate Magnetometer
  - EPD Measured full pitch angle energy distribution of **50 keV – 5 MeV** over 16 energy channels
- Spinning at ~20 RPM; FOV=22.5 deg, 16 sectors per spin, **can resolve the loss cone**
- 350+ Undergraduate students:
  - Designed, developed, and built ELFIN, ground assets, build, then refactored mission operations, science processing pipeline
  - Operated ELFIN for 4 years, up-scoped its capabilities in-orbit
- 4 successful years on orbit:
  - Year 1: Commission/calibration
  - Year 2: Learned lots of lessons, refactored operations paradigm
  - Year 3-4: Collected prime science + bonus science
- Has resulted in >40 publications

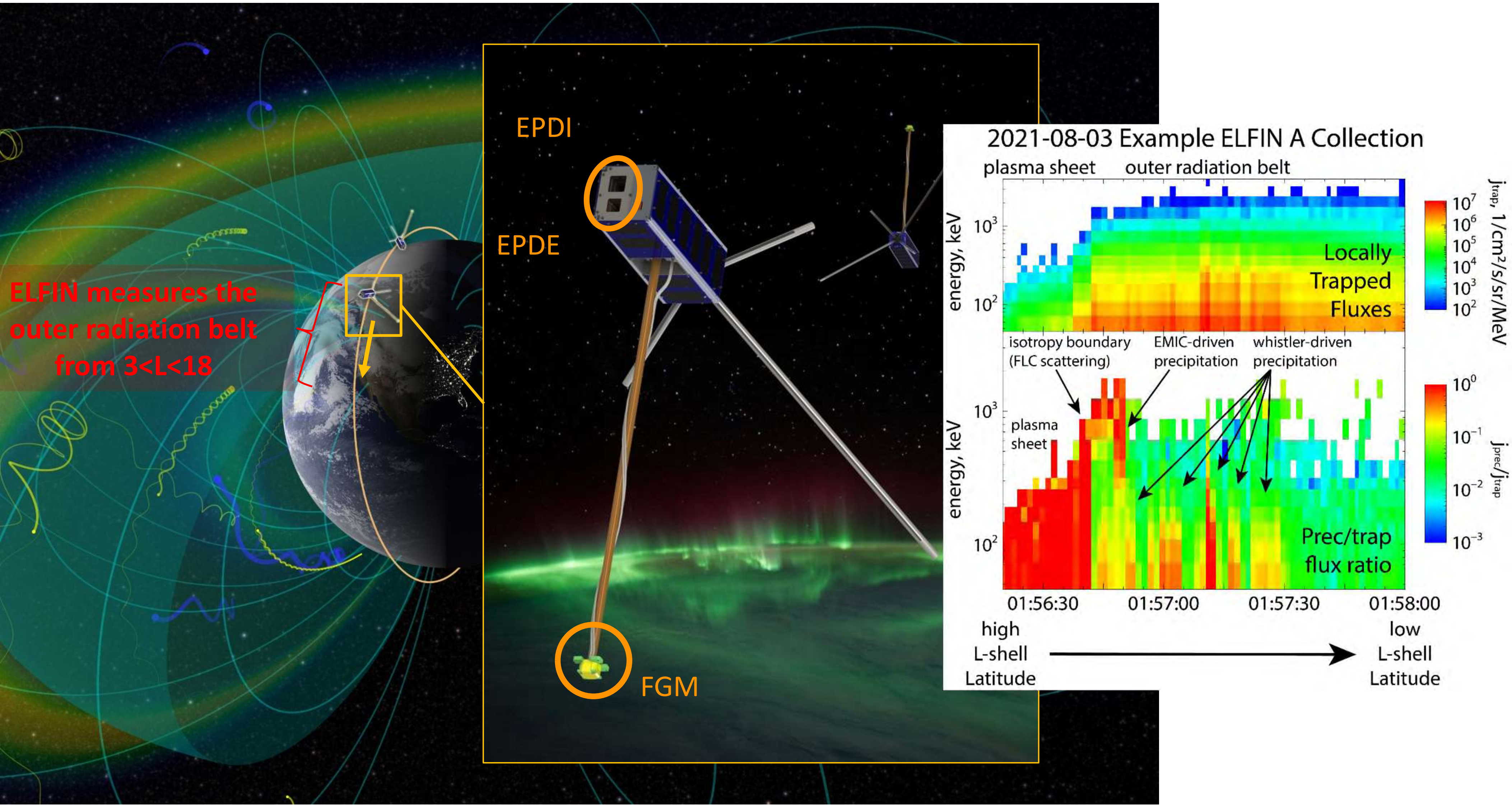


What do the data look like?

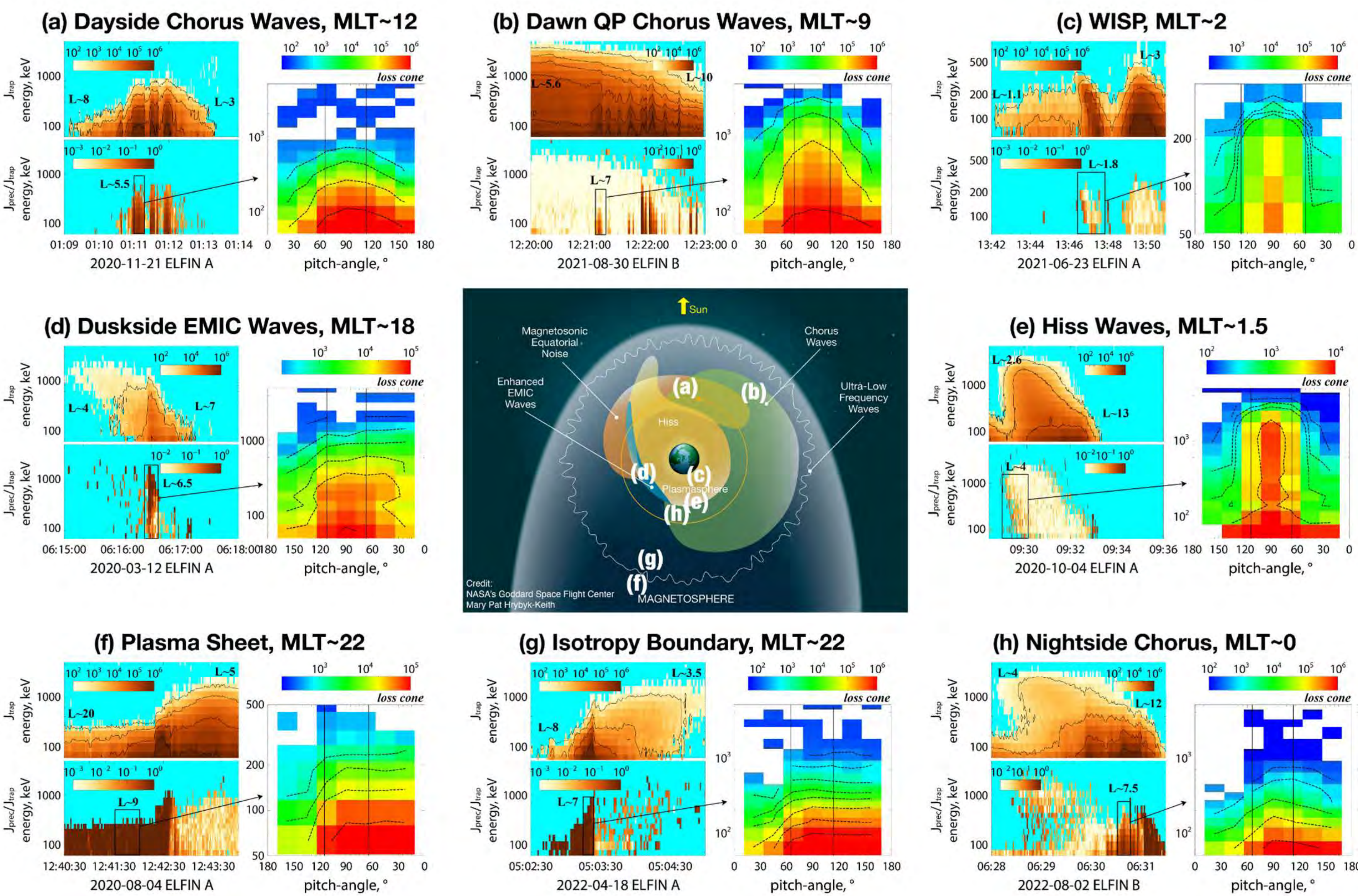


What do the data look like?

Energy spectrograms of precipitating flux and precipitating-to-trapped flux ratio = clear view of equatorial processes



Each scattering process, MLT, and activity level has a distinct fingerprint at ELFIN. These processes can be resolved & quantified from LEO!



Possible first step for HPS Constellations: An Ionospheric Constellation

Magnetosphere-ionosphere coupling constellation

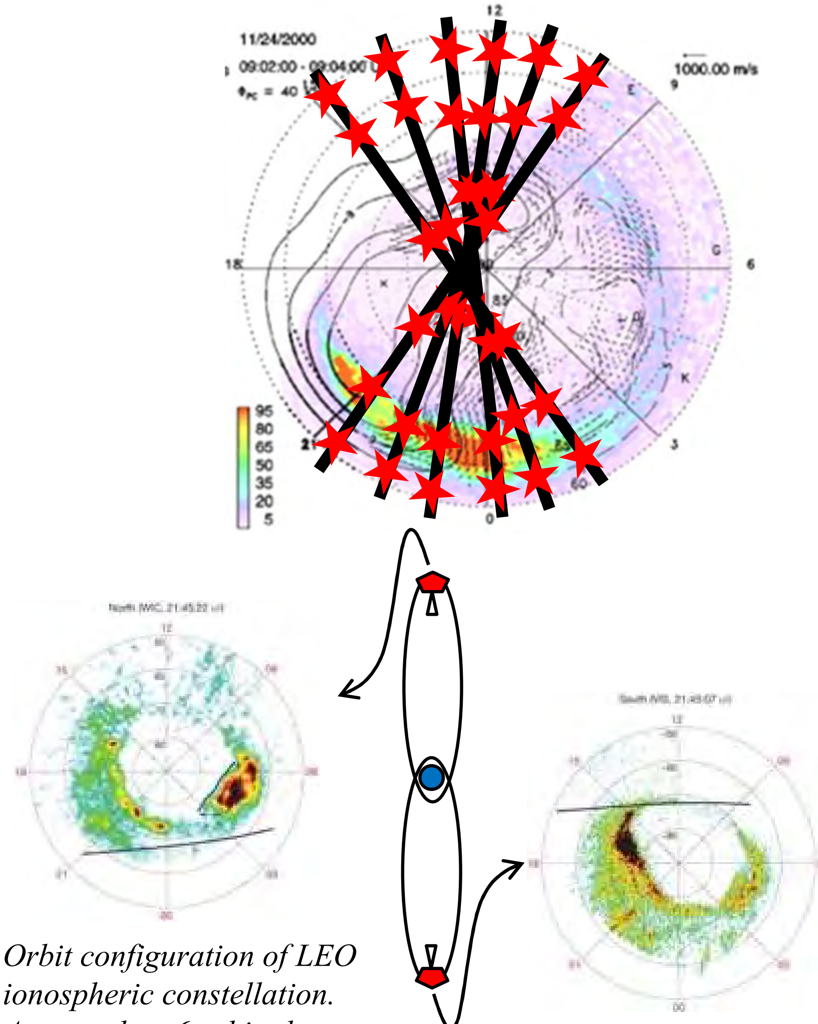
Science objective:
Derive global models of magnetospheric-ionospheric coupling.

Mission implementation:
60 LEO (600km) probes, 6 polar orbits (10-min. resolution) of the global current system.

A reconfigurable constellation (ΔV~100m/s) enables trades between spatial, temporal and local time resolution.

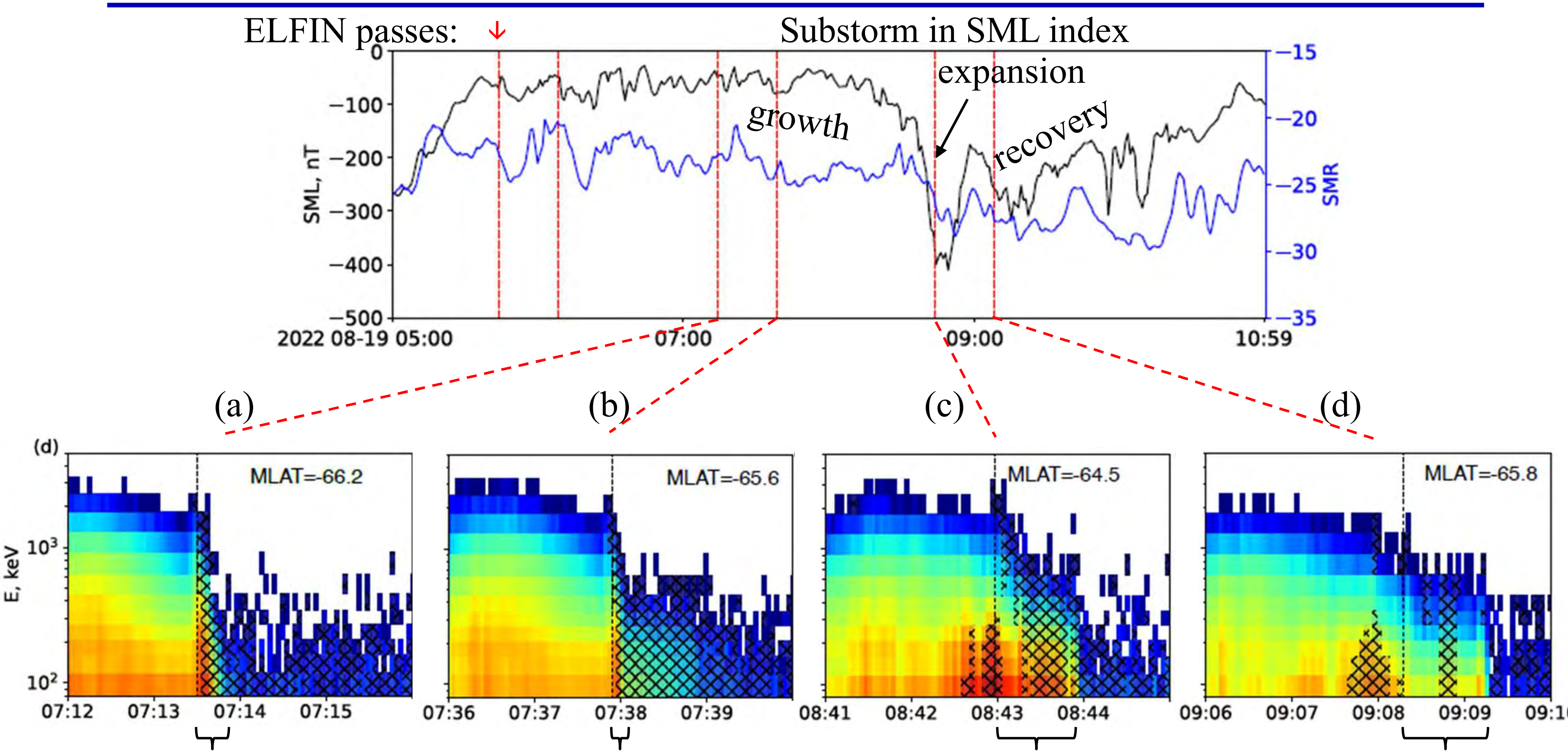
FUV imaging of both auroral ovals from two satellites on two highly eccentric polar orbits (one north, one south) explores hemispheric asymmetries.

How can we get there?



Orbit configuration of LEO ionospheric constellation. Arranged on 6 orbit planes round 0-12MLT it establishes intensity, location, and localization of strongest field aligned currents during storms. It is superimposed on a Super-DARN ionospheric convection map. High-altitude imagers provide global conductivity information.

Substorm evolution tracked in consecutive ELFIN passes: (a)-(d) below



X. Shi et al. 2024, in Space Weather

Tail-dipole transition region: ⌴
moves equatorward and thins during growth phase: (a) → (b),
then expands poleward and becomes hotter during expansion phase: (c),
then cools down during recovery phase: (d) and the cycle begins again… validating magnetic models

ELFIN's success could be replicated using the following recipes

1: Empowering students while challenging them.

2: A rigorous validation and verification program.

3: Self-imposed reviews reinforcing responsibility and task ownership.

4: Strategic view: advance design prior to mission start (2008-2014).

5: Capitalize on symbiotic relationship with nearby industry and academia.

6: Cultivate a University commitment & local, skilled staff mentors

7: Groom a tightly-integrated science & engineering team

8: Embrace an open data policy, easy data access