Diagnosing Geospace Dynamics with Magnetometer Arrays

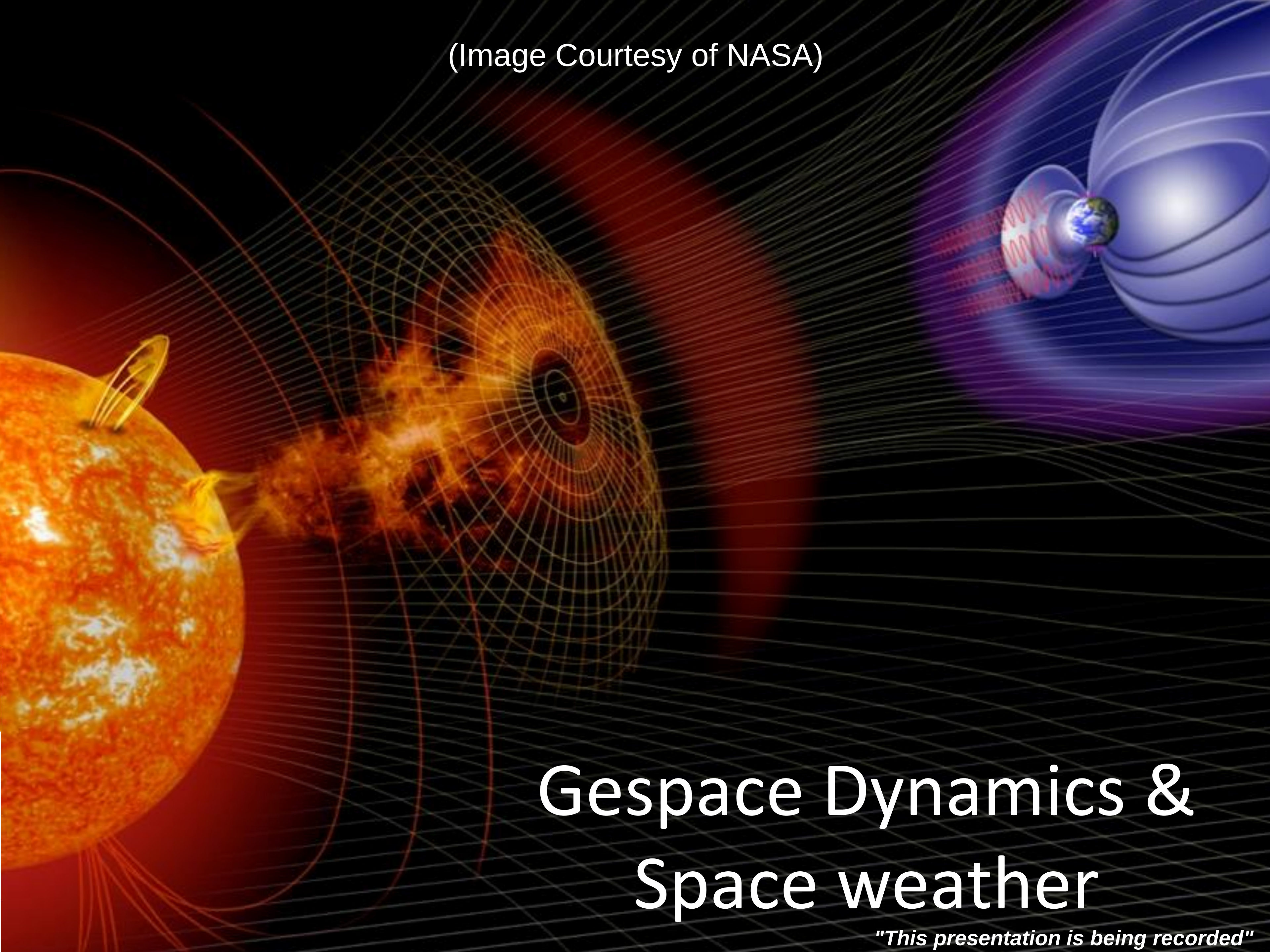
Prof. Ian R. Mann

Department of Physics
University of Alberta

ian.mann@ualberta.ca

Institute for Space Science, Exploration and Technology
University of Alberta

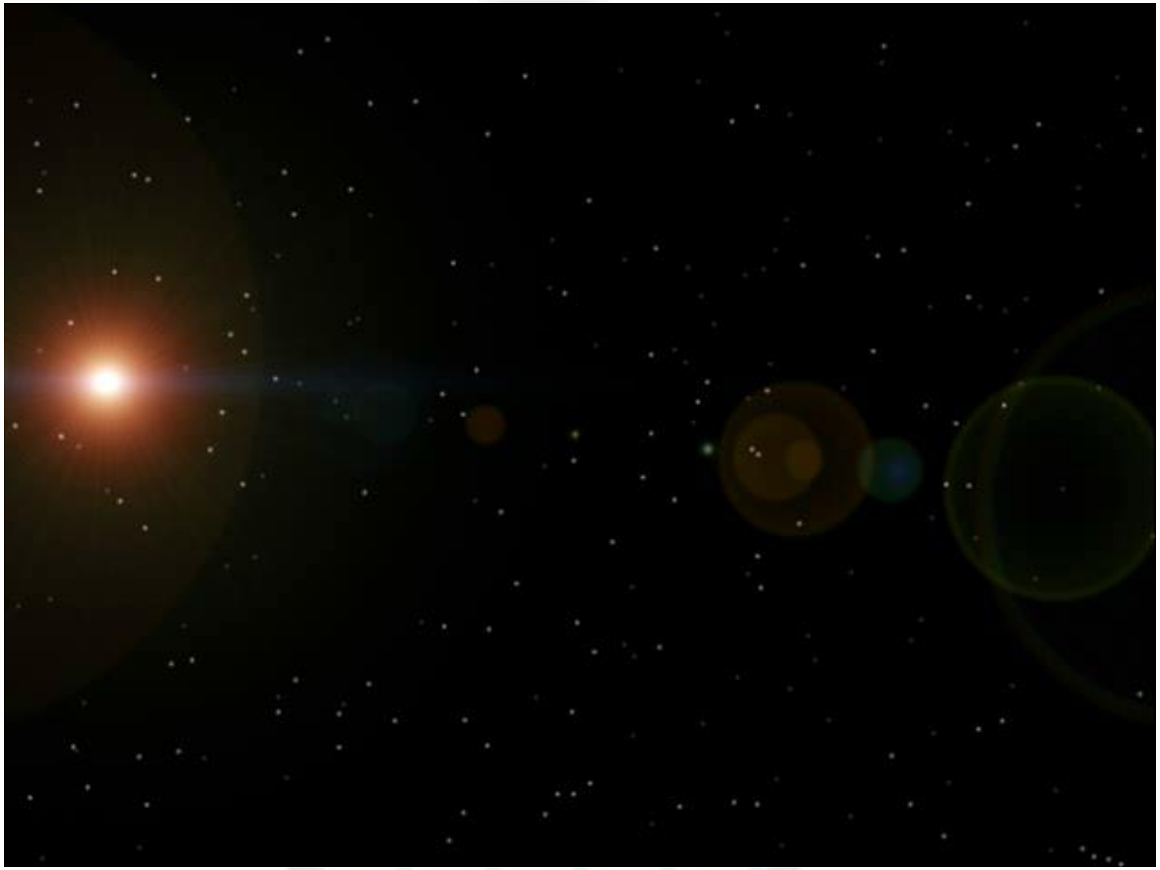
"This presentation is being recorded"


(Image Courtesy of NASA)
Gespace Dynamics &
Space weather
"This presentation is being recorded"

The Challenge: Characterise Global Geospace Dynamics

[redacted]

Sparse In-situ Satellite Data



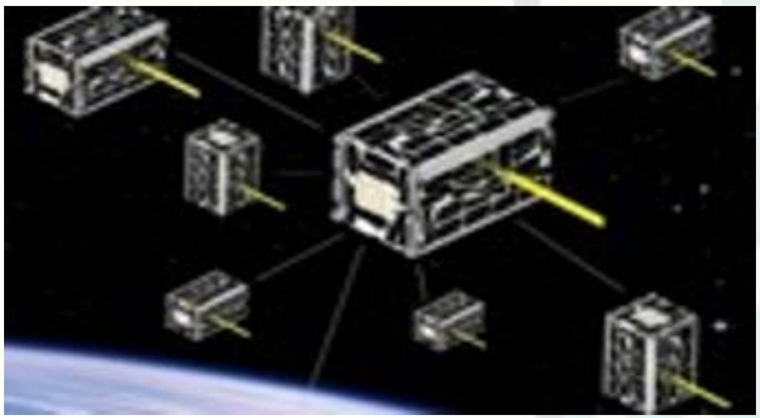
One of the major scientific opportunities for ground-based magnetometer data is in support of satellite missions.

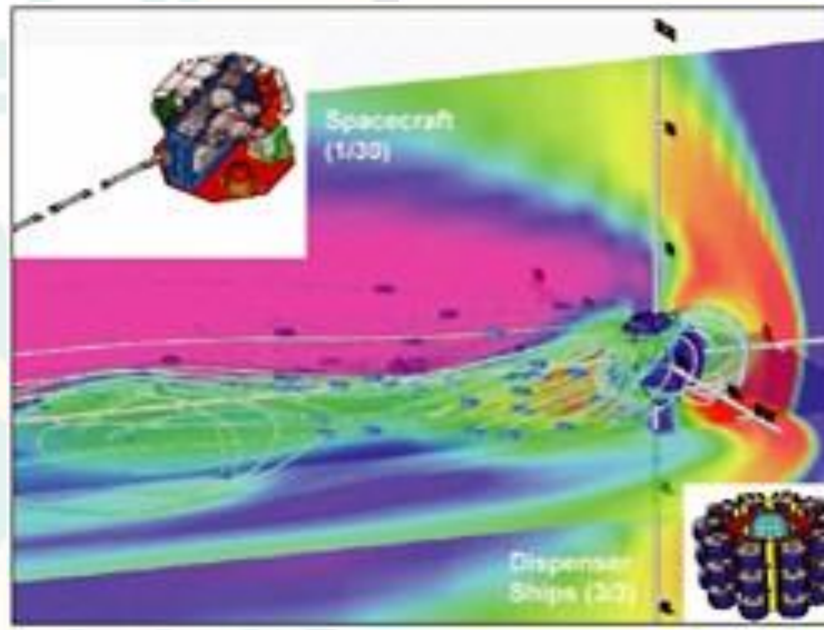
Examples from THEMIS and Van Allen Probes.

Institute for Space Science, Exploration and Technology
University of Alberta

"This presentation is being recorded"

Future Magnetospheric Constellation Mission (MagCon)?





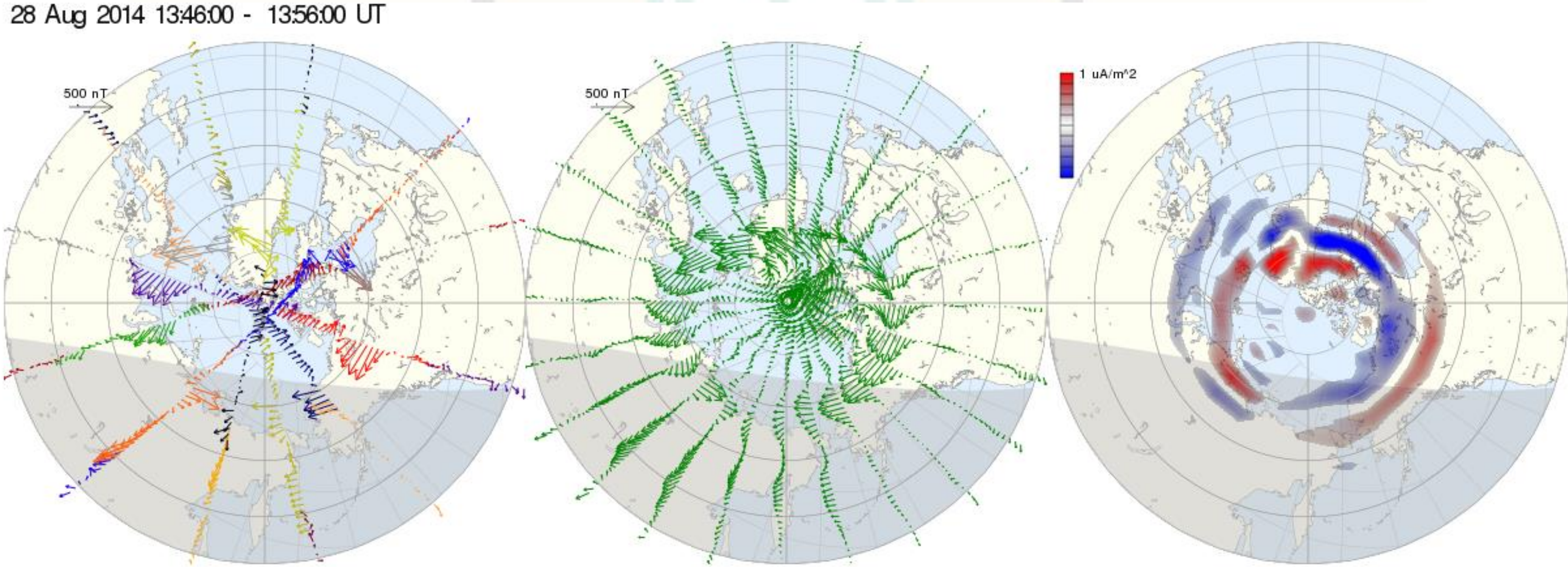
Cubesats?

MagCon Mission?

Institute for Space Science, Exploration and Technology
University of Alberta

"This presentation is being recorded"

Low-Earth Orbit Constellation: AMPERE



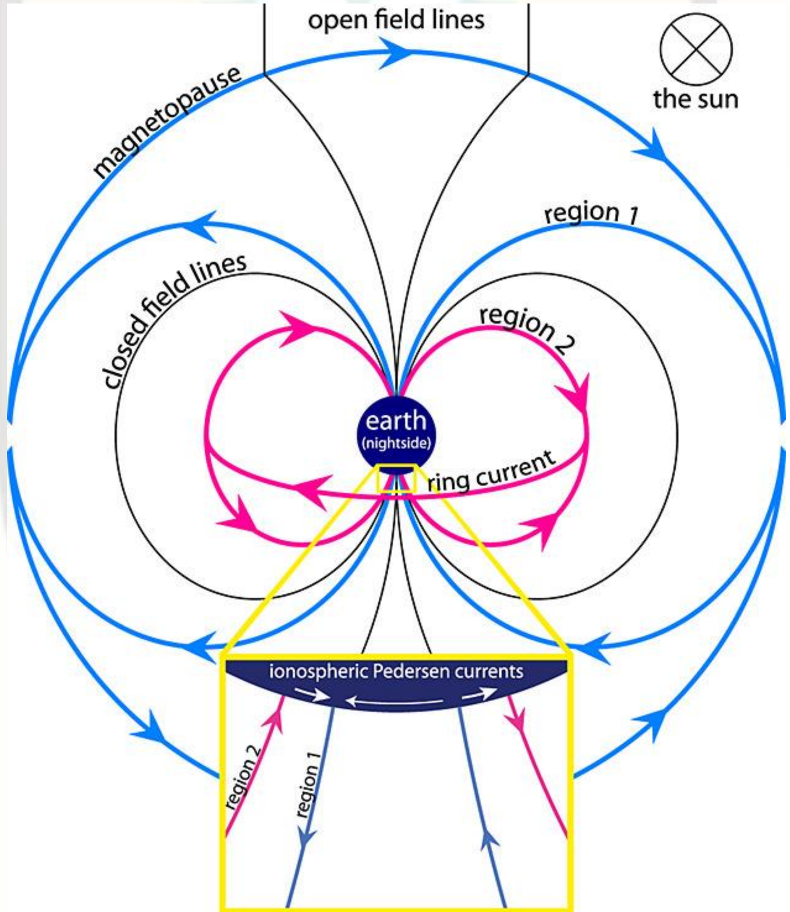
- Using ADCS magnetometer measurements from Iridium constellation (resolution ~30 nT).
- E.g., Anderson et al. JGR (2000).

Institute for Space Science, Exploration and Technology
University of Alberta

"This presentation is being recorded"

Dungey Cycle and Field-Aligned Current Closure

ULF waves transport energy in the global system, and Alfven waves are required to establish or change FAC.



Recent work with Swarm: Pakhotin et al. (2018, 2020), Mann et al. (2019).

From Coxon et al., JGR, (2014).

Institute for Space Science, Exploration and Technology
University of Alberta

"This presentation is being recorded"

Global Scale View Possible with Ground-Magnetometer Arrays

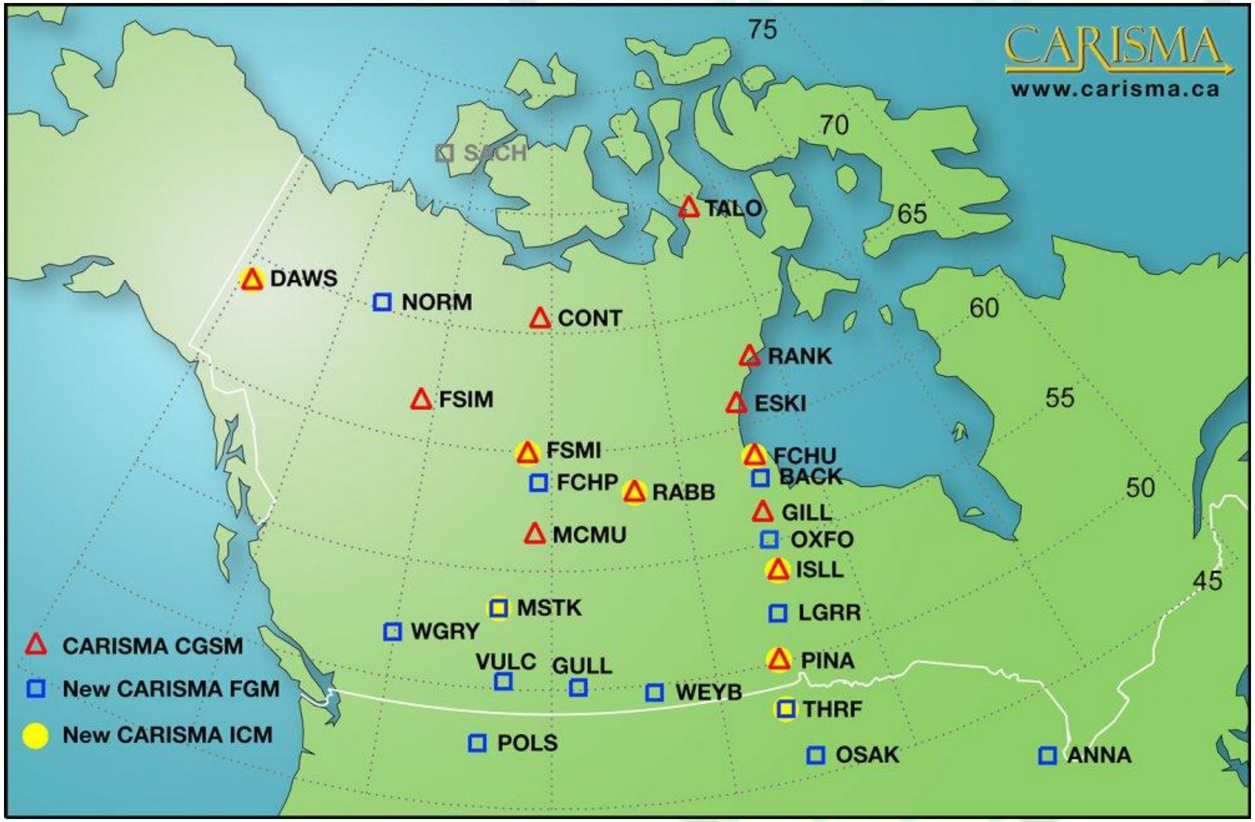
SuperMAG: http://supermag.jhuapl.edu/
(PI: Jesper Gjerloev; Jesper.Gjerloev@jhuapl.edu)

Institute for Space Science, Exploration and Technology
University of Alberta

Global Coordination promoted by Ultra-Large Terrestrial International Magnetometer Array (ULTIMA)
Current Chair: Peter Chi (pchi@igpp.ucla.edu)

"This presentation is being recorded"

Meso-Scale View Possible with Dense Arrays



Fluxgate magnetometers (CGSM and FGM)
Resolution < 0.1 nT
Raw 8 sps;
standard 1 or 2 sps.

Induction Coil Magnetometers (ICM).
Resolution in pT.
100 sps.

Institute for Space Science, Exploration and Technology
University of Alberta

Canadian Array for Real-time Investigations of Magnetic Activity (PI: Mann; PM: Milling)
www.carisma.ca

Diagnosing Geospace Dynamics With Magnetometer Arrays

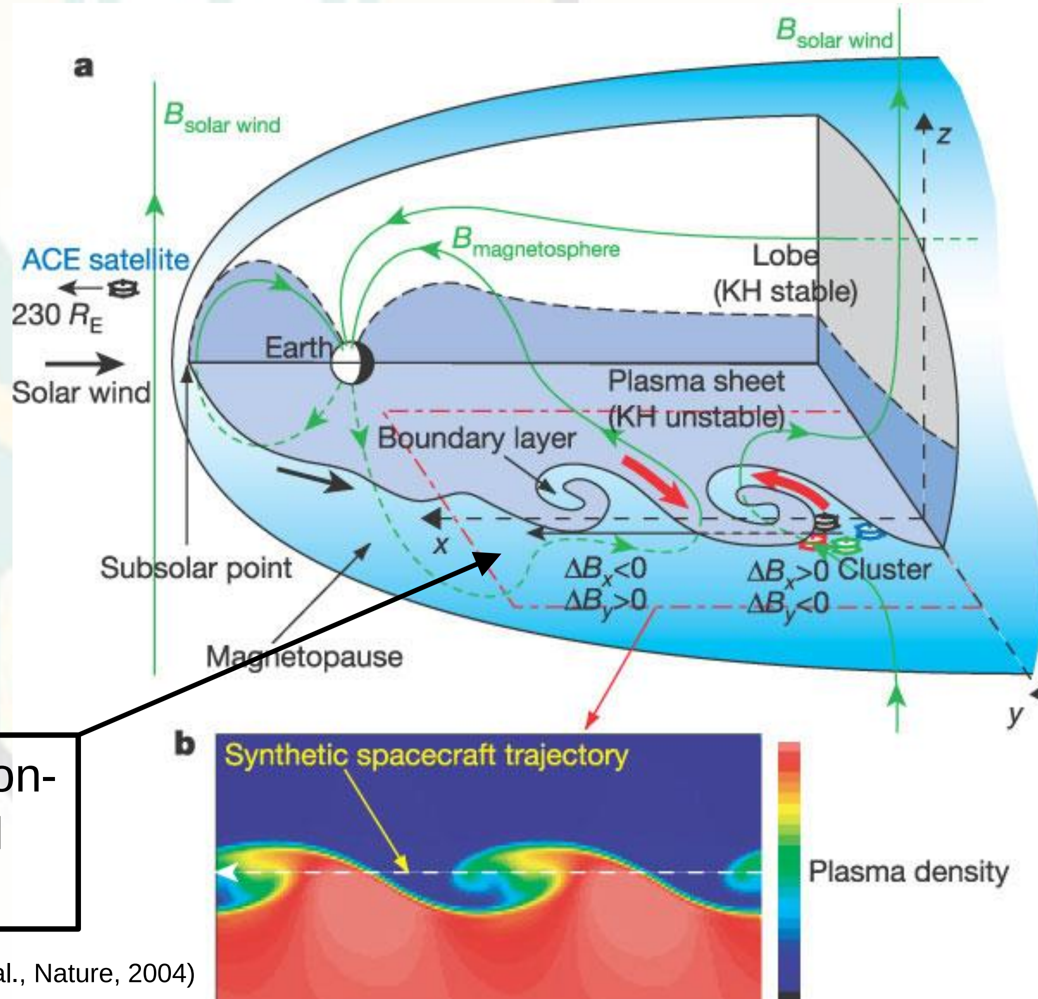
- Energy input into the geospace system – focus on ULF wave/disturbances here.
- Characterising magnetospheric substorms - especially onset and early expansion phase
- Magnetic Storm dynamics: Radiation Belt and Ring Current Wave-Particle Interactions
- Magnetospheric magneto-seismology.

Institute for Space Science, Exploration and Technology
University of Alberta

"This presentation is being recorded"

Kelvin-Helmholtz Instability at the Magnetopause

- Observed at flanks of magnetised planetary magnetospheres.
  - Earth (e.g., Fairfield and Otto, 2000; Hasegawa et al., Nature, 2004; Taylor et al., 2008)
  - Saturn (e.g, Masters et al., 2009), etc

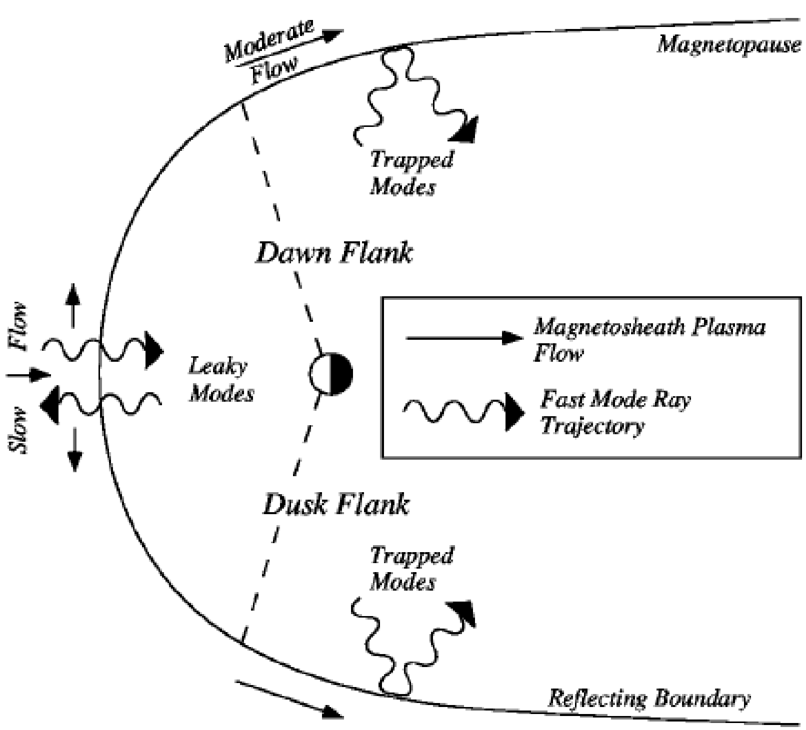


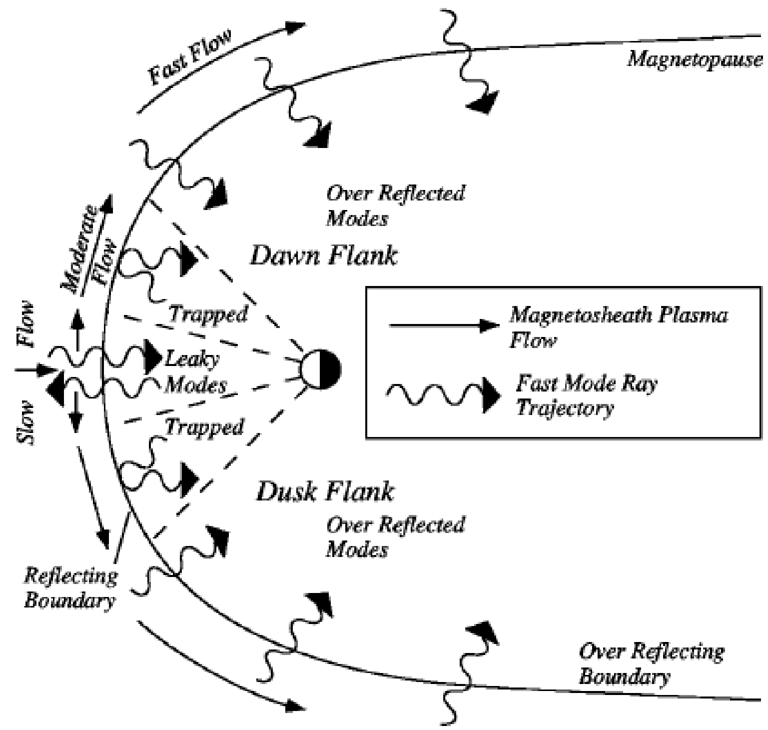
Wrapped non-linear KH vortices

(Hasegawa et al., Nature, 2004)

"This presentation is being recorded"

Excitation of Waveguide Modes





SLOW SOLAR WIND

FAST SOLAR WIND

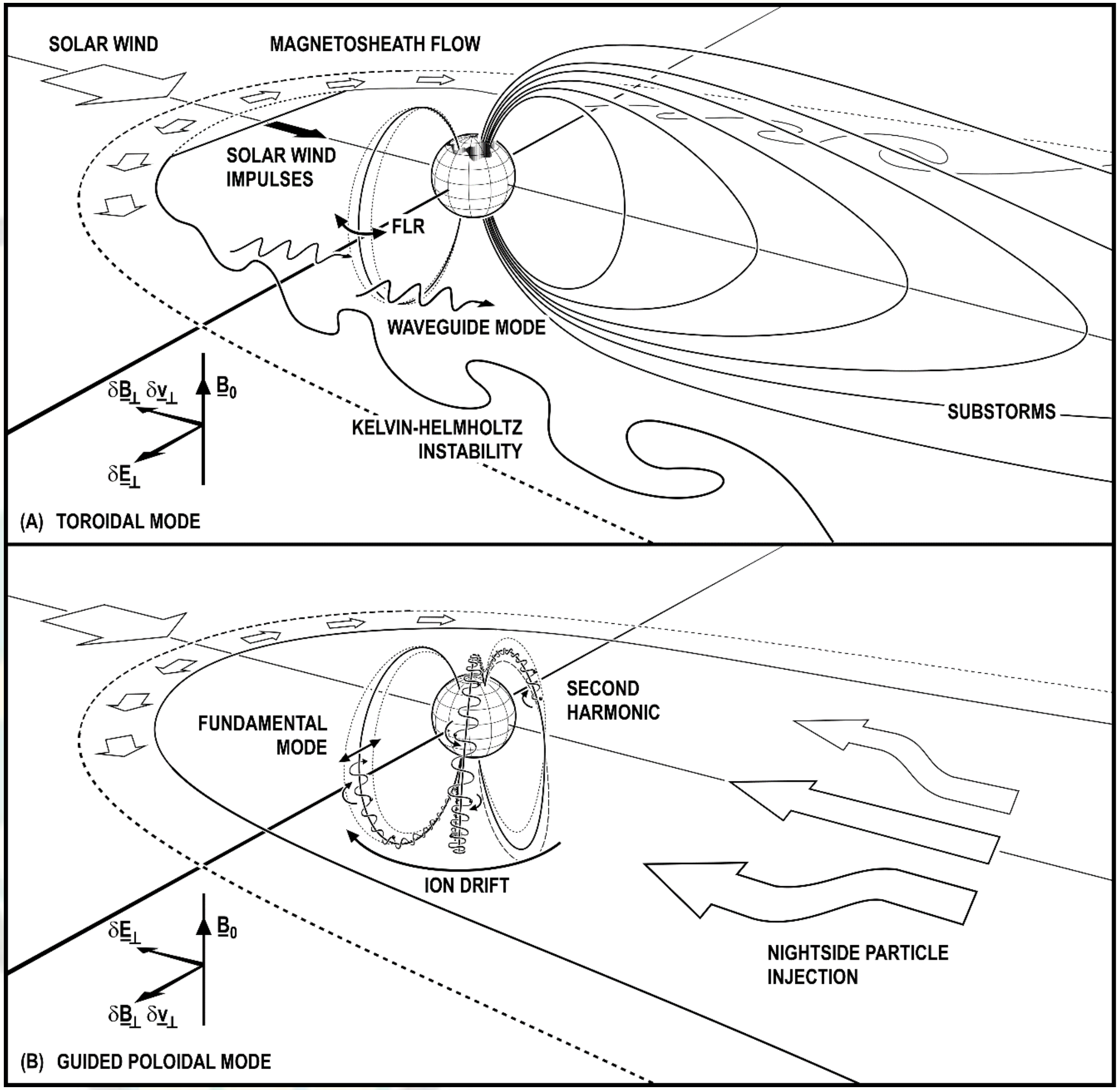
Institute for Space Science, Exploration and Technology
University of Alberta

Cavity/waveguide mode excitation by solar wind impulses or by magnetopause shear flow/KHI. (Mann and Wright, 1999)

"This presentation is being recorded"

Transport of Energy via Ultra-Low Frequency (ULF) Waves

Rae et al. 2007 estimate total ULF wave energy into ionosphere via Joule heating may actually be >30% of that in a substorm cycle.

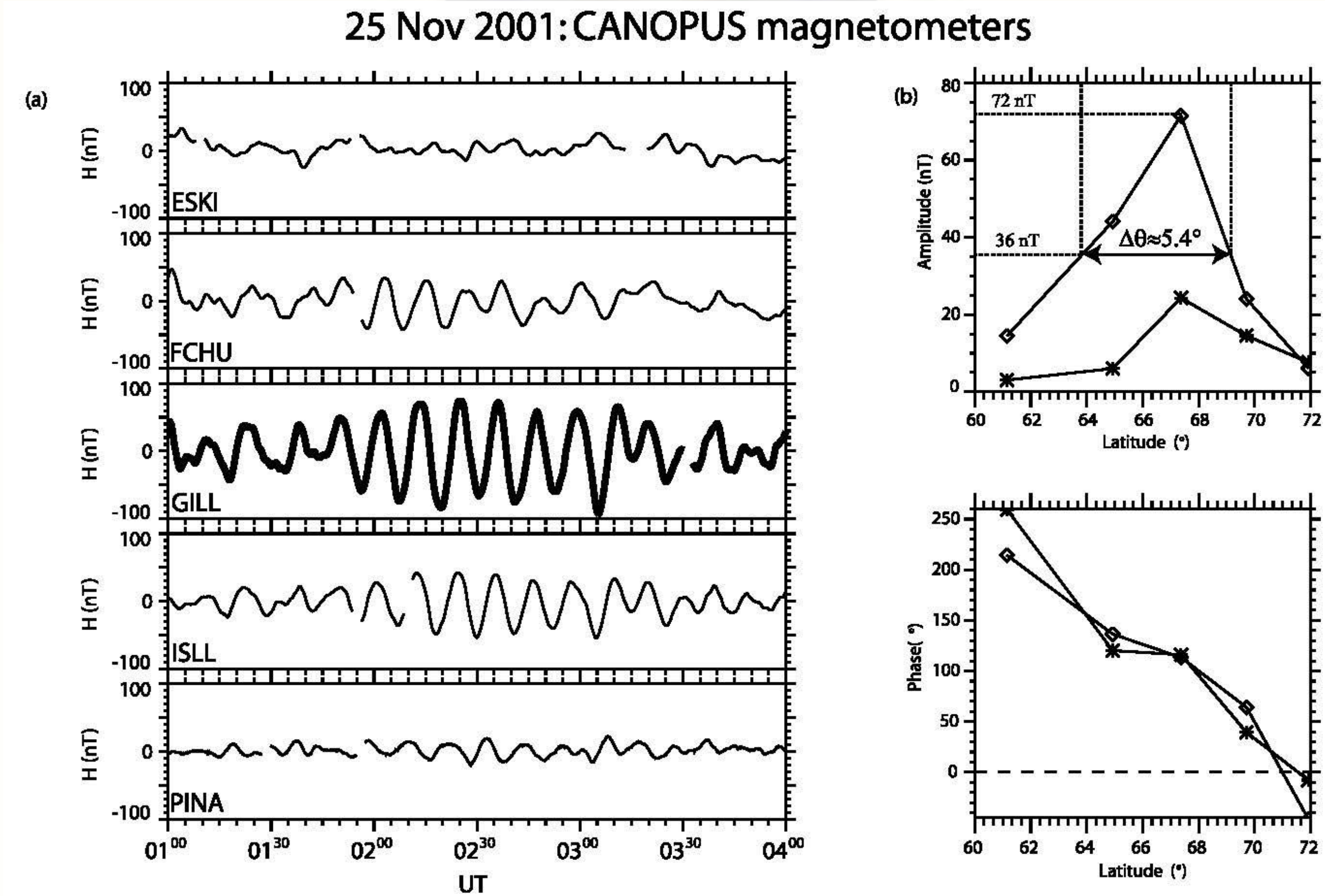


Institute for Space Science, Exploration and Technology
University of Alberta

From Mann (2019); in Geomagnetism, Aeronomy and Space Weather: A Journey from the Earth's Core to the Sun, Mandea, Korte, Yau, and Petrovsky (eds.). CUP, (2019).

"This presentation is being recorded"

Driven Field Line Resonance



Ozeke et al., JGR, 2009

Institute for Space Science, Exploration and Technology
University of Alberta

"This presentation is being recorded"

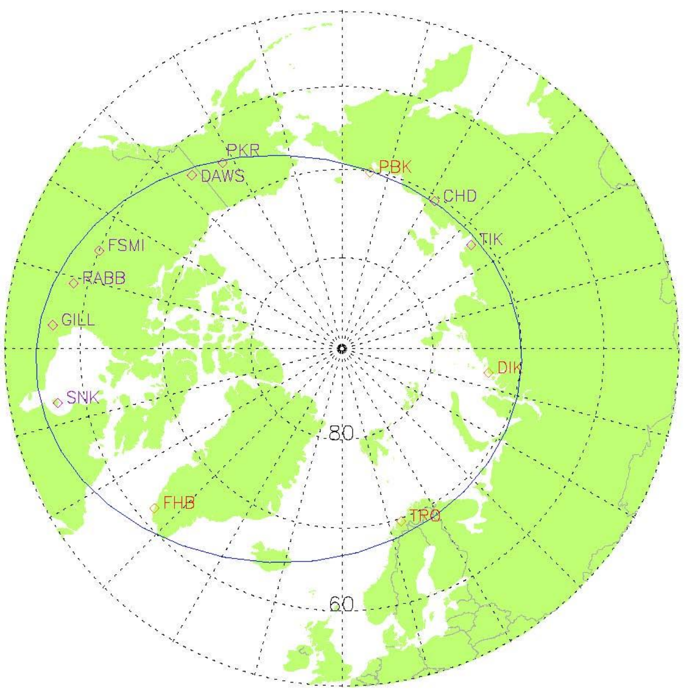
Flank ULF Interactions?

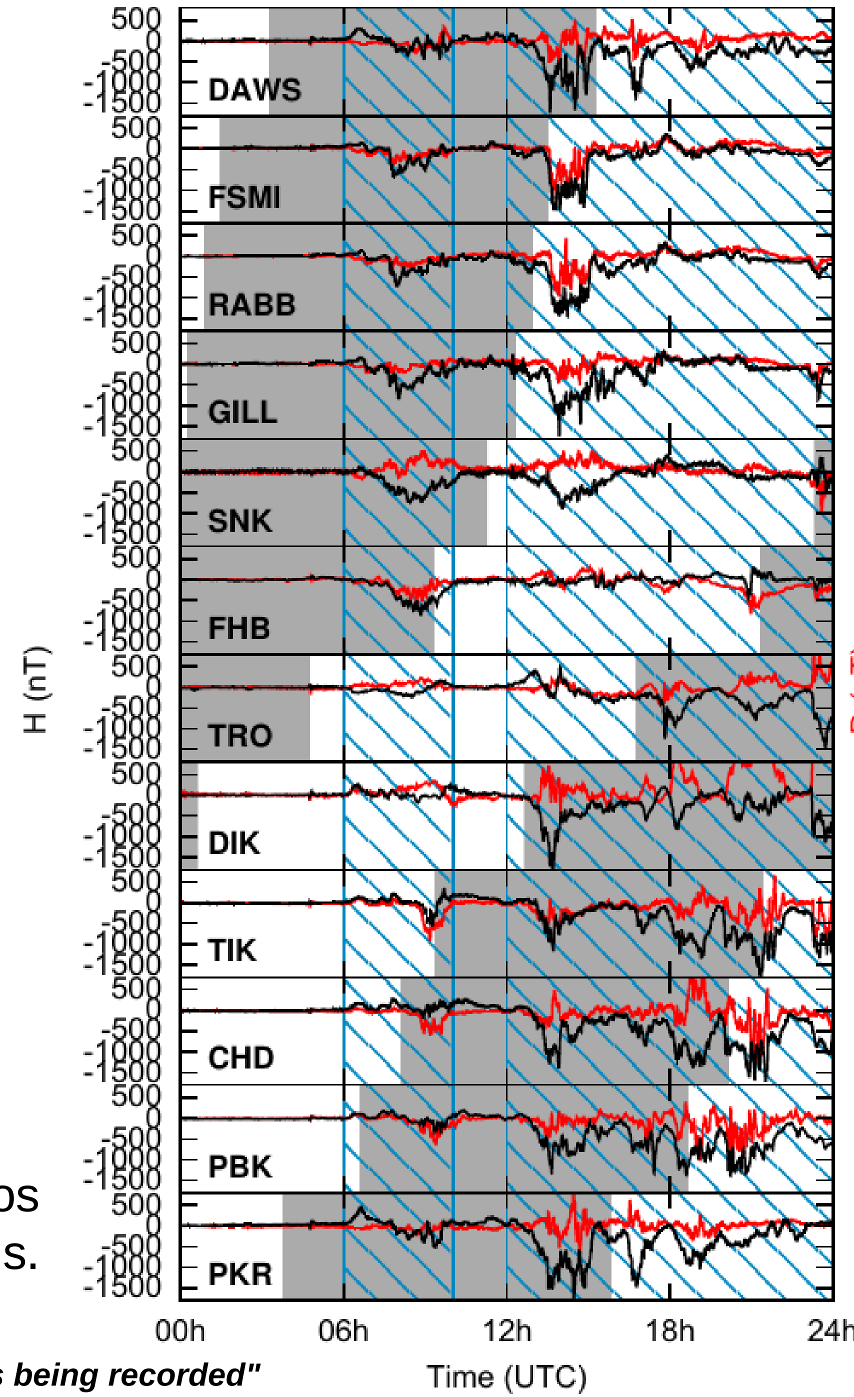
- Large scale dB/dt is also related to the risk of geomagnetically induced currents (GICs) in the electric power grid.
- Recent statistical analysis of U.K. ground-based magnetometer data show the largest dB/dt occur on the flanks due to convection and not at local midnight due to substorms (Freeman et al., Space Weather, 2019).
- New research (Dimitrakoudis et al., in prep., 2020) reveal some new and unexpected flank magnetic dynamics.

ISSET
Institute for Space Science, Exploration and Technology
University of Alberta

UNIVERSITY OF ALBERTA
QUAECUMQUE VERA

Flank dB/dt: March 2015

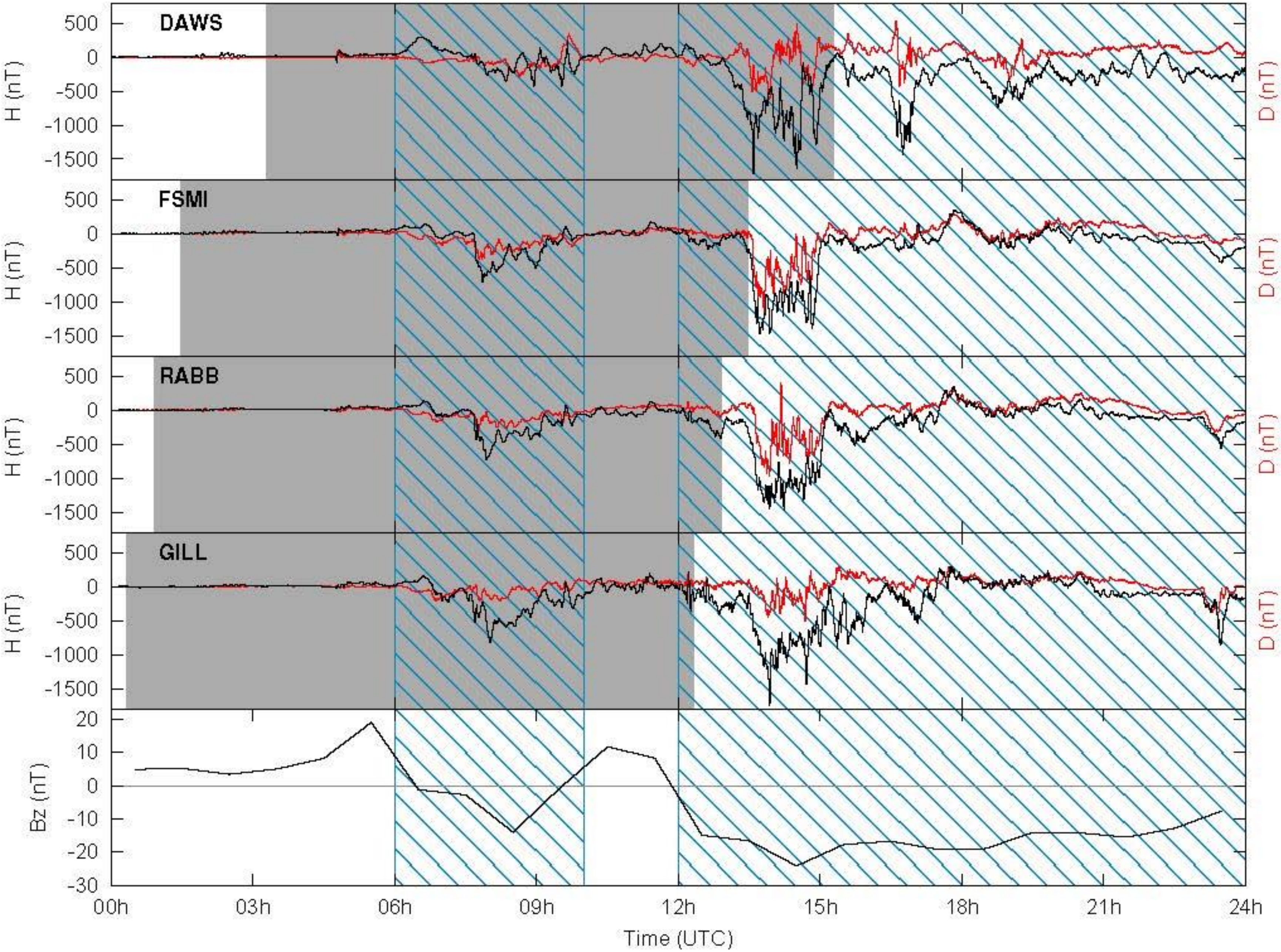




Courtesy of Stavros Dimitrakoudis.

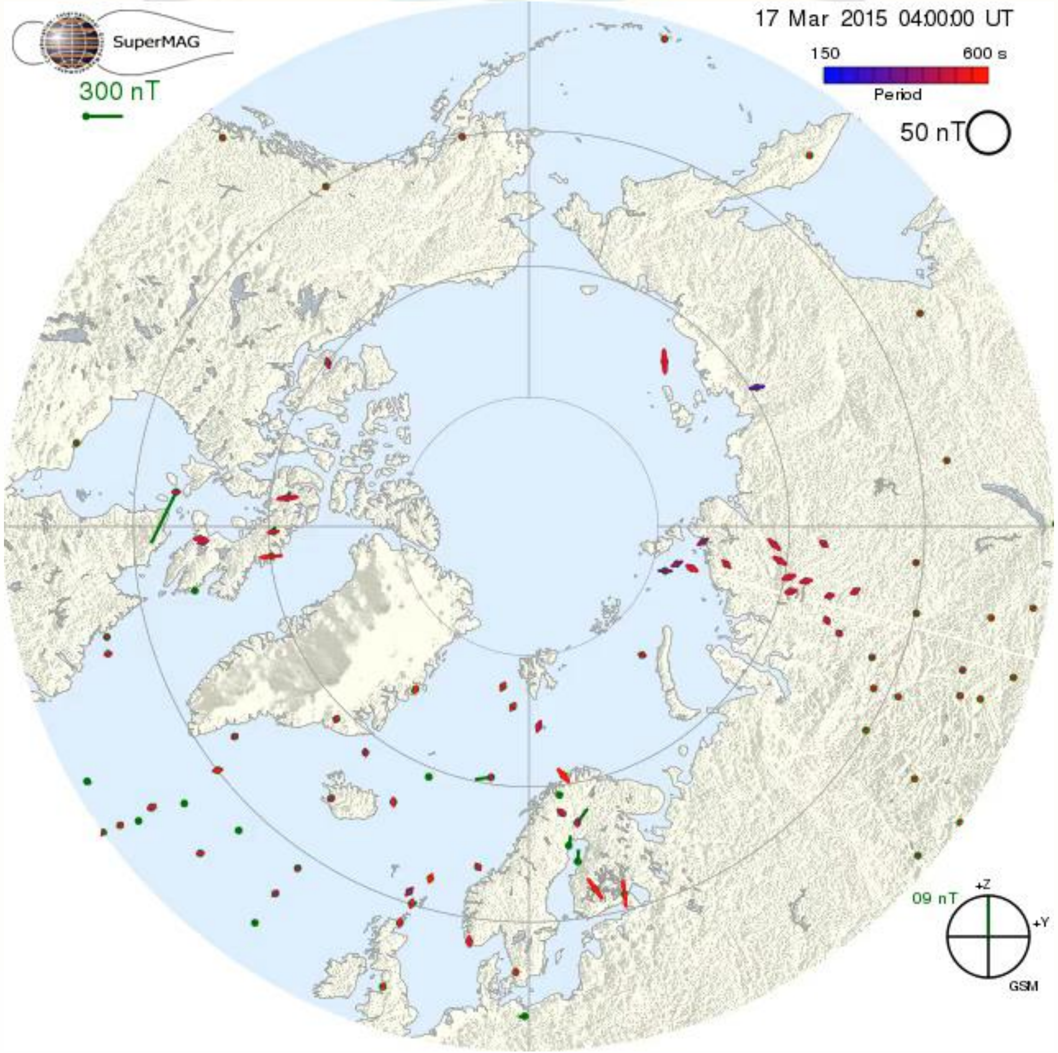
Institute for Space Science, Exploration and Technology
University of Alberta

"This presentation is being recorded"



"This presentation is being recorded"

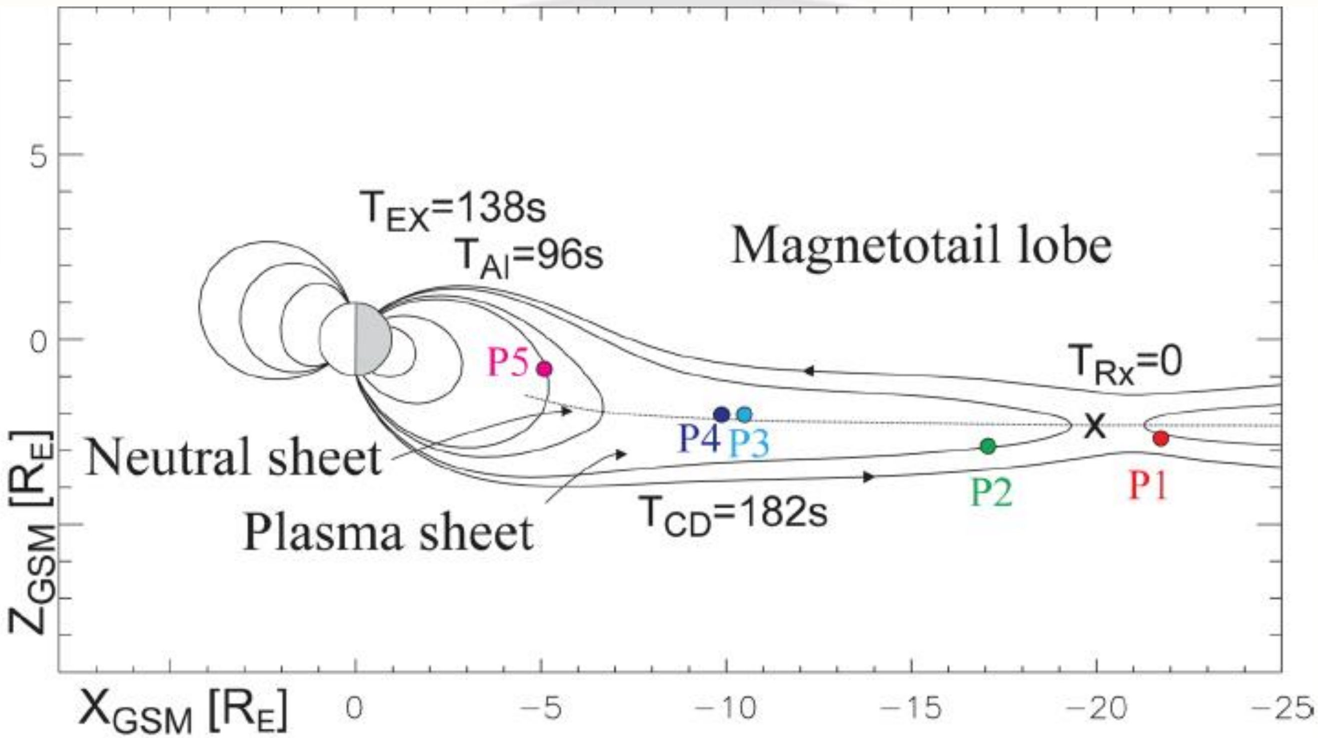
MARCH 2015 STORM



Courtesy of SuperMAG.

"This presentation is being recorded"

Magnetospheric Substorm



Angelopoulos et al. (2008), *Science*

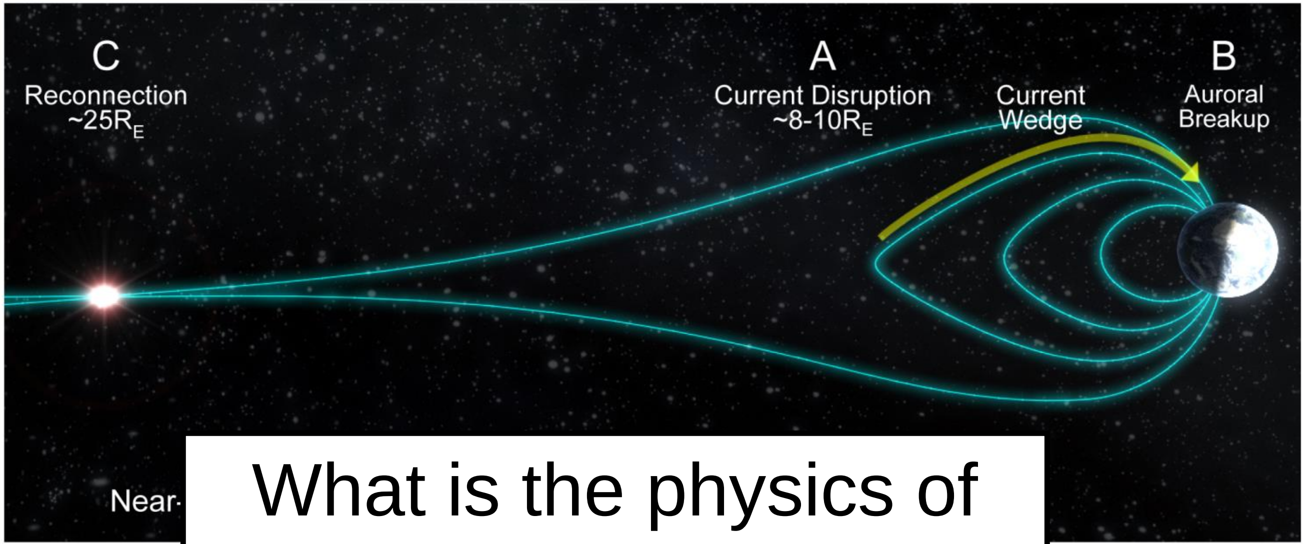
Substorm growth, expansion and recovery phases (e.g., McPherron et al. 1973).

Institute for Space Science, Exploration and Technology
University of Alberta

"This presentation is being recorded"

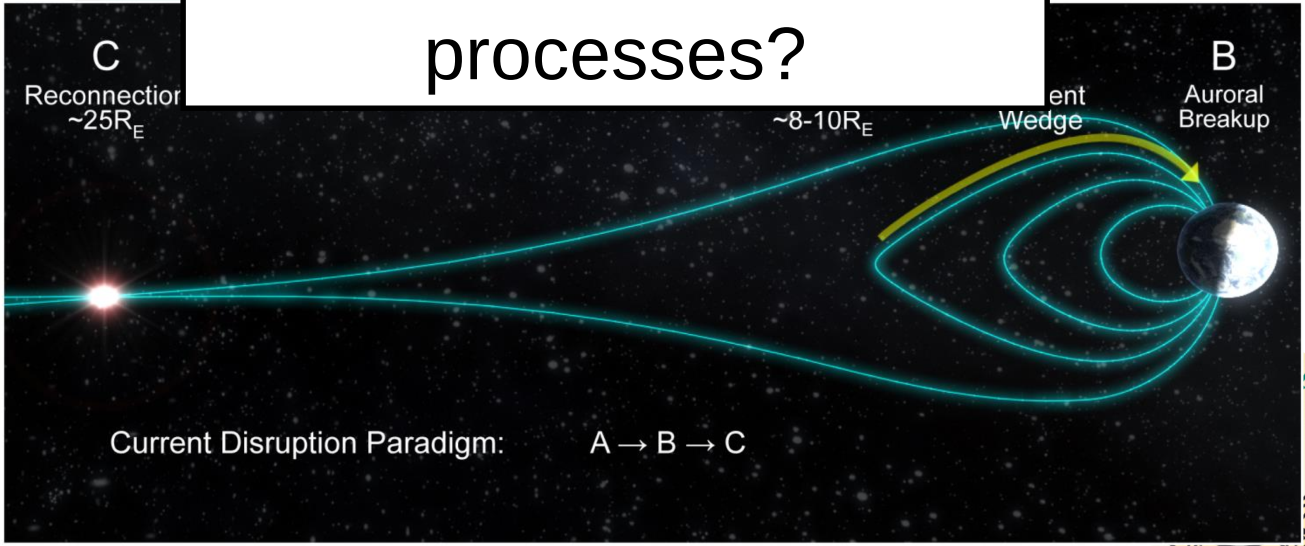
Magnetospheric Substorm

Outside
To
In



What is the physics of near-Earth Substorm processes?

Inside
To
Out



Institute for Space Science, Exploration and Technology
University of Alberta

"This presentation is being recorded"

What triggers the fast release of stored magnetic energy in reconnection driven magnetotails?

Courtesy of NASA THEMIS team.

Forecast GIC in electrical power grids?

Institute for Space Science, Exploration and Technology
University of Alberta

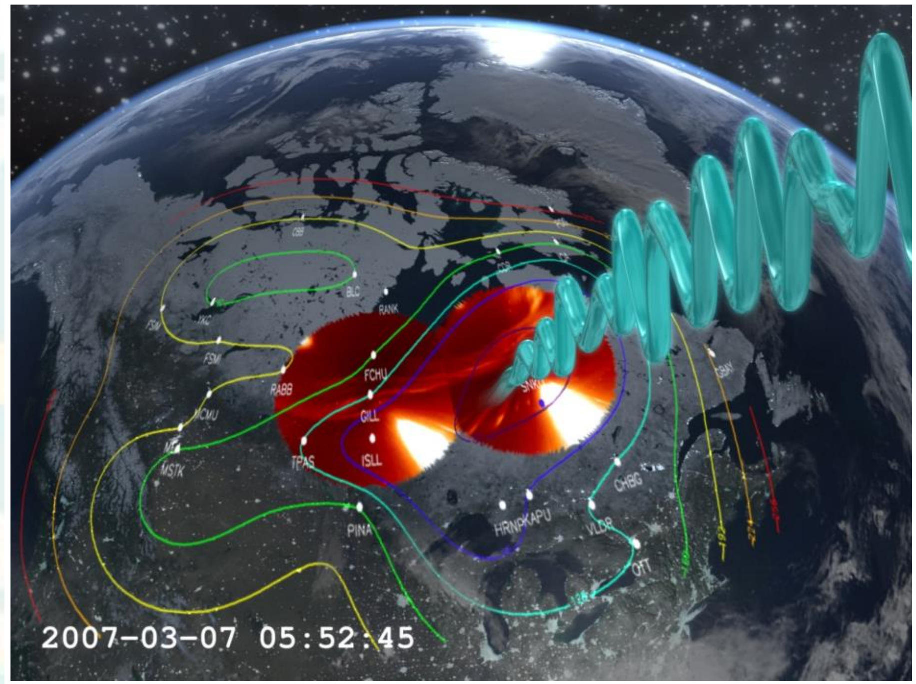
"This presentation is being recorded"

Ground-based Magnetic Substorm Diagnostics

- Expansion phase onset.
- Substorm onset magnetosphere-ionosphere coupling
- Development of substorm expansion phase: westward travelling surge, westward and poleward expansion, etc.

Pi2s: Timing Expansion Phase Onset

- Pi2s are irregular waves in the 40s – 150s period band (e.g., Jacobs et al., 1964).
- Can be used to time, and to some degree locate, expansion phase currents.
- Pi2 polarisation ellipses point to longitude of centre of the substorm current wedge (e.g., Lester et al., 1983).
- Pi2 timing, with ~2 minute uncertainty, can time substorm onset. Especially clear in mid-latitude stations in the sub-auroral zone.

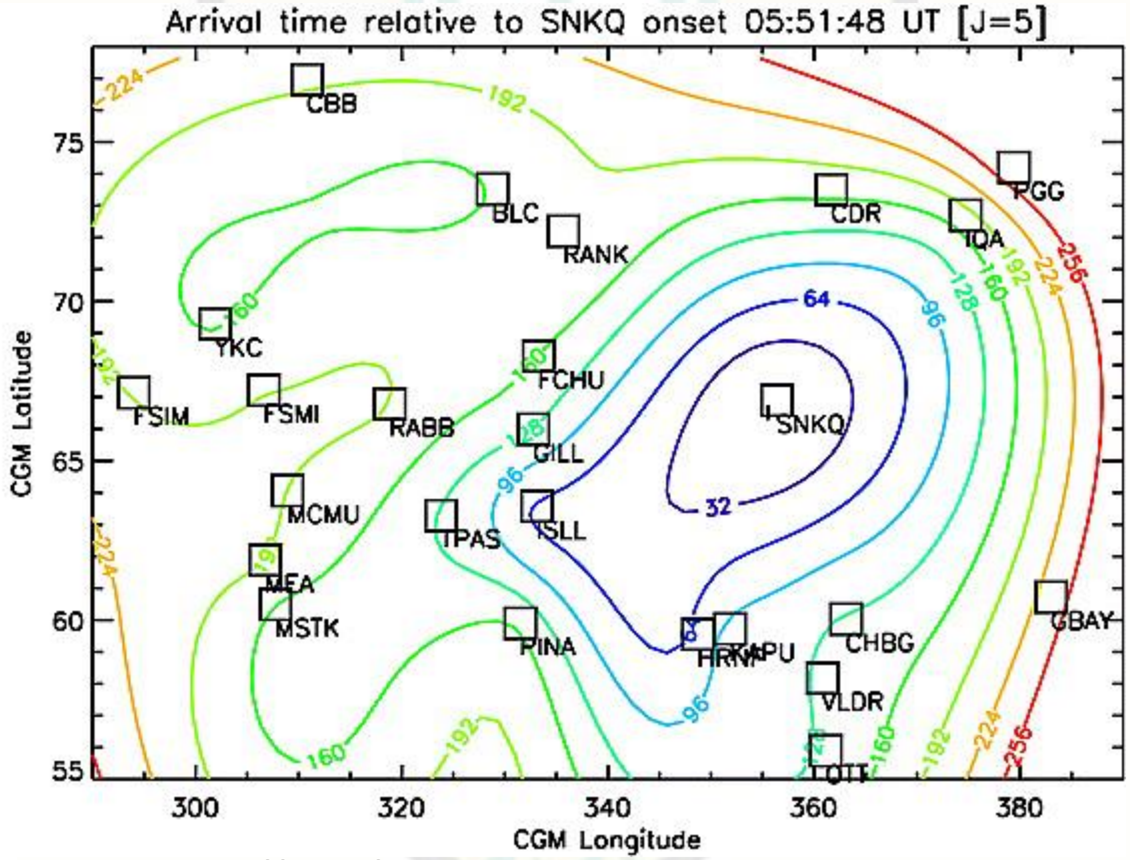


Institute for Space Science, Exploration and Technology
University of Alberta

"This presentation is being recorded"

Pi1, and Pi1-2s: Timing and Location of Expansion Phase Onset

24 - 96s period wavelet band.



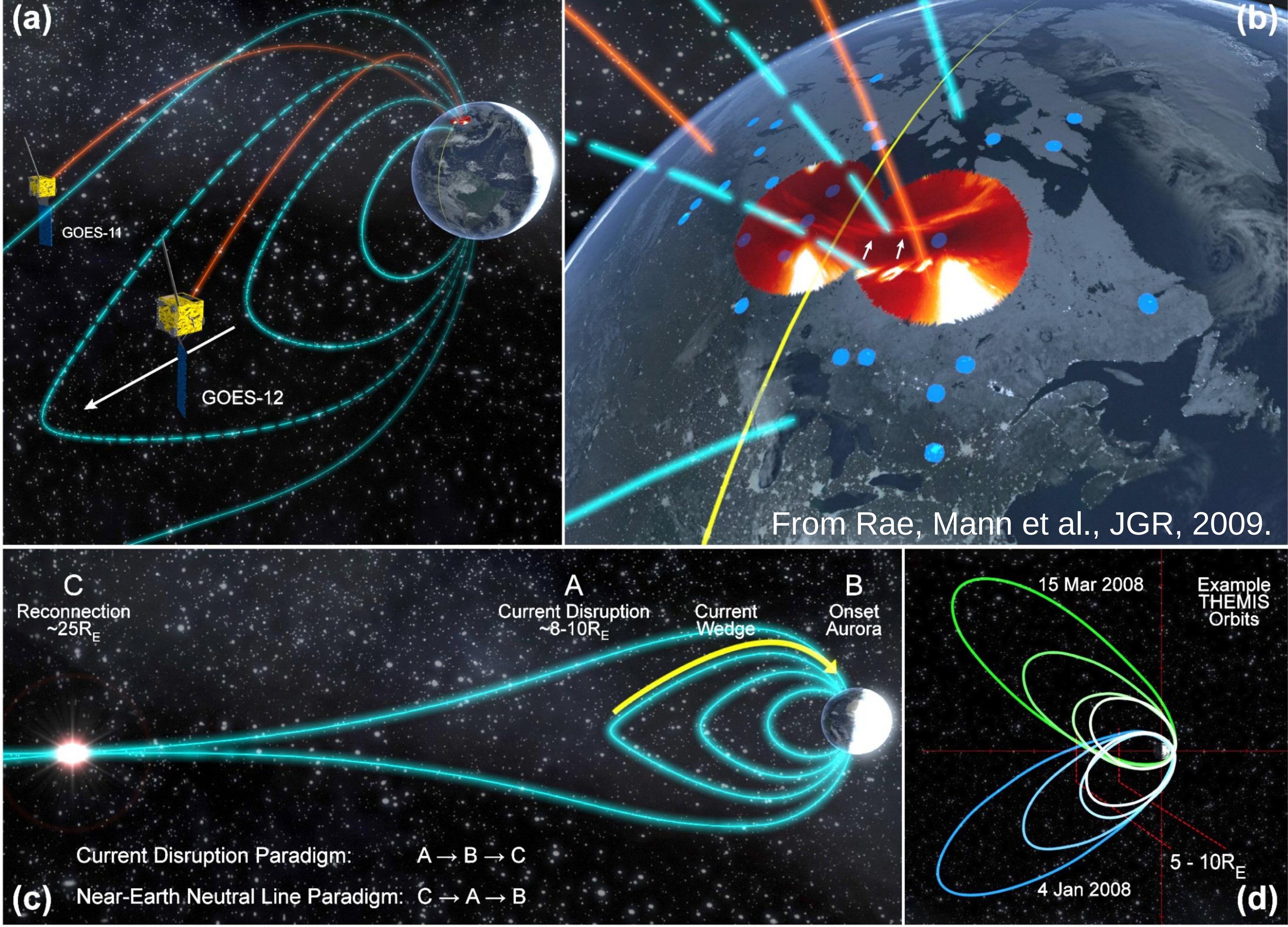
Rae, Mann, et al., JGR, 2009.

Wavelets: e.g., Milling et al., 2008; Rae et al., 2009; Murphy et al. 2009. Rae et al., 2017. Smith et al. 2020.

- Actually, the wave response is spatio-temporally inhomogeneous across the Pi1, Pi1-2, and Pi2 spectra.

Institute for Space Science, Exploration and Technology
University of Alberta

"This presentation is being recorded"


(a)
GOES-11
GOES-12
(b)
From Rae, Mann et al., JGR, 2009.
C
Reconnection
~25R$_E$
A
Current Disruption
~8-10R$_E$
Current
Wedge
B
Onset
Aurora
Current Disruption Paradigm: A → B → C
Near-Earth Neutral Line Paradigm: C → A → B
(c)
15 Mar 2008
Example
THEMIS
Orbits
5 - 10R$_E$
4 Jan 2008
(d)

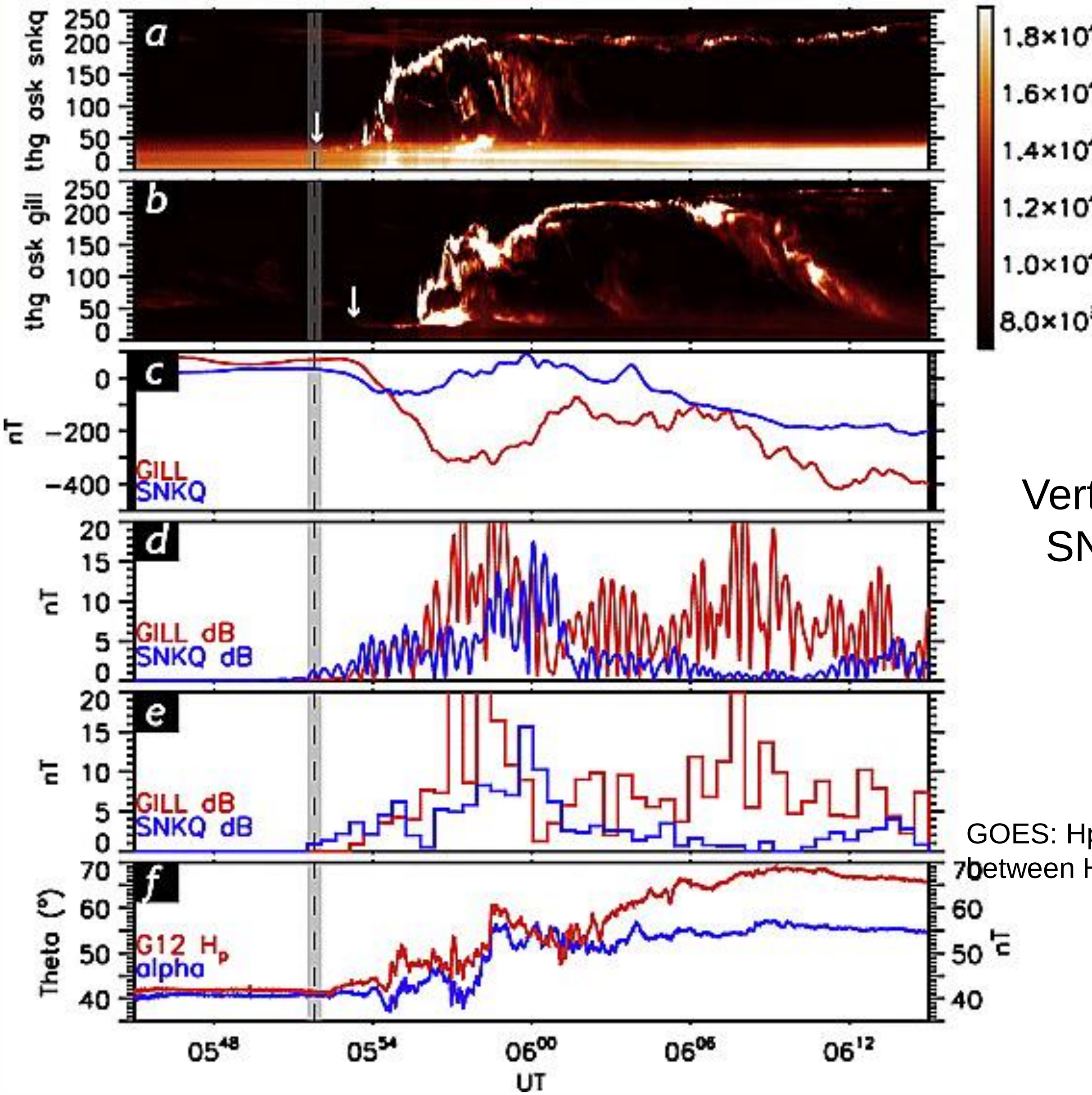
Rae, Mann et al. JGR (2009)

Keograms

Ground Substorm bays

Filtered dB

24-96s DWT



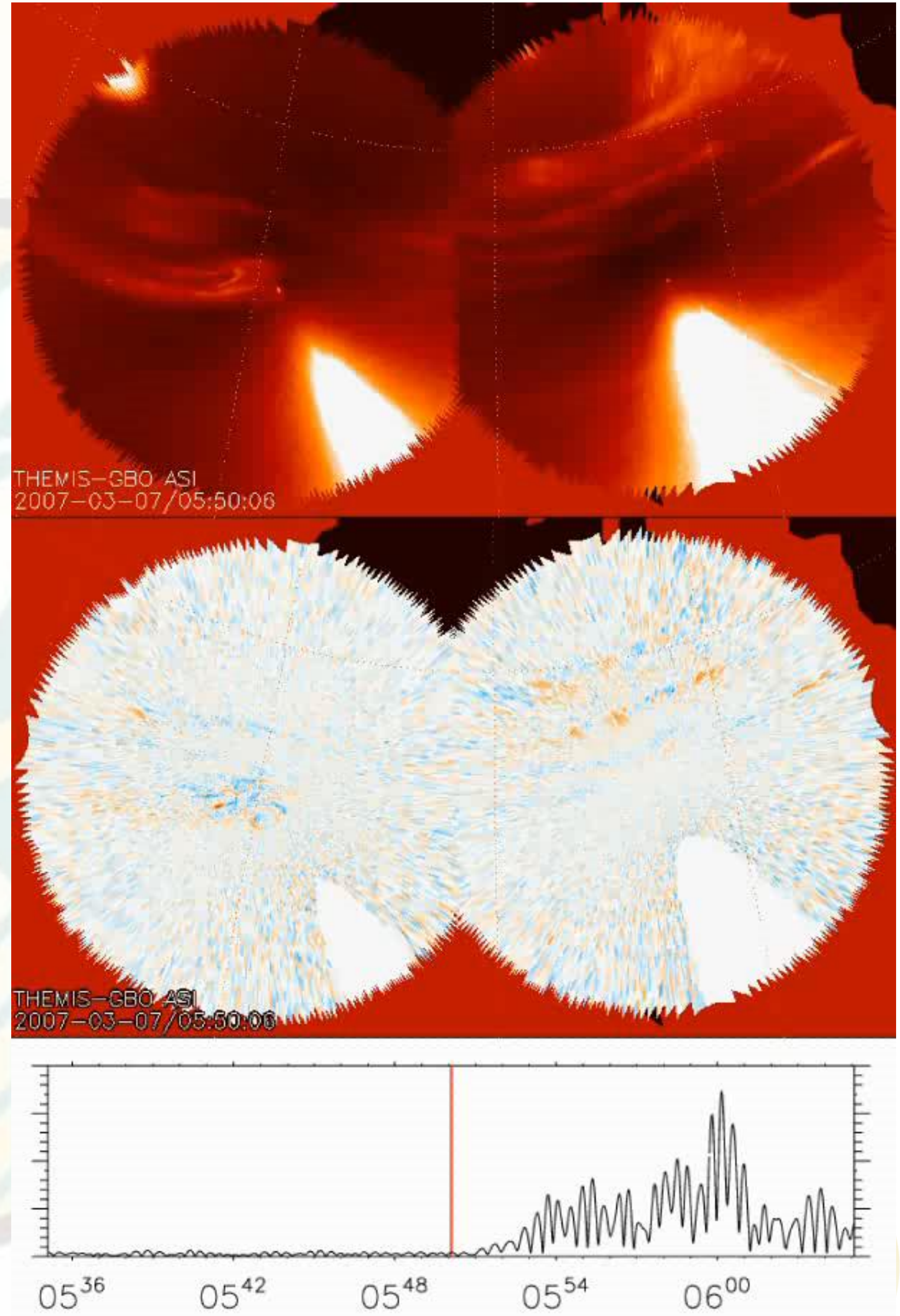
Vertical line is SNKQ onset in 24-96s band.

GOES: Hp, and angle between Hp, He.

Institute for Space Science, Exploration and Technology
University of Alberta

"This presentation is being recorded"

Relation between substorm onset auroral beads and Pi1-2



Supplementary Material from Rae, Mann, et al., JGR, 2009.

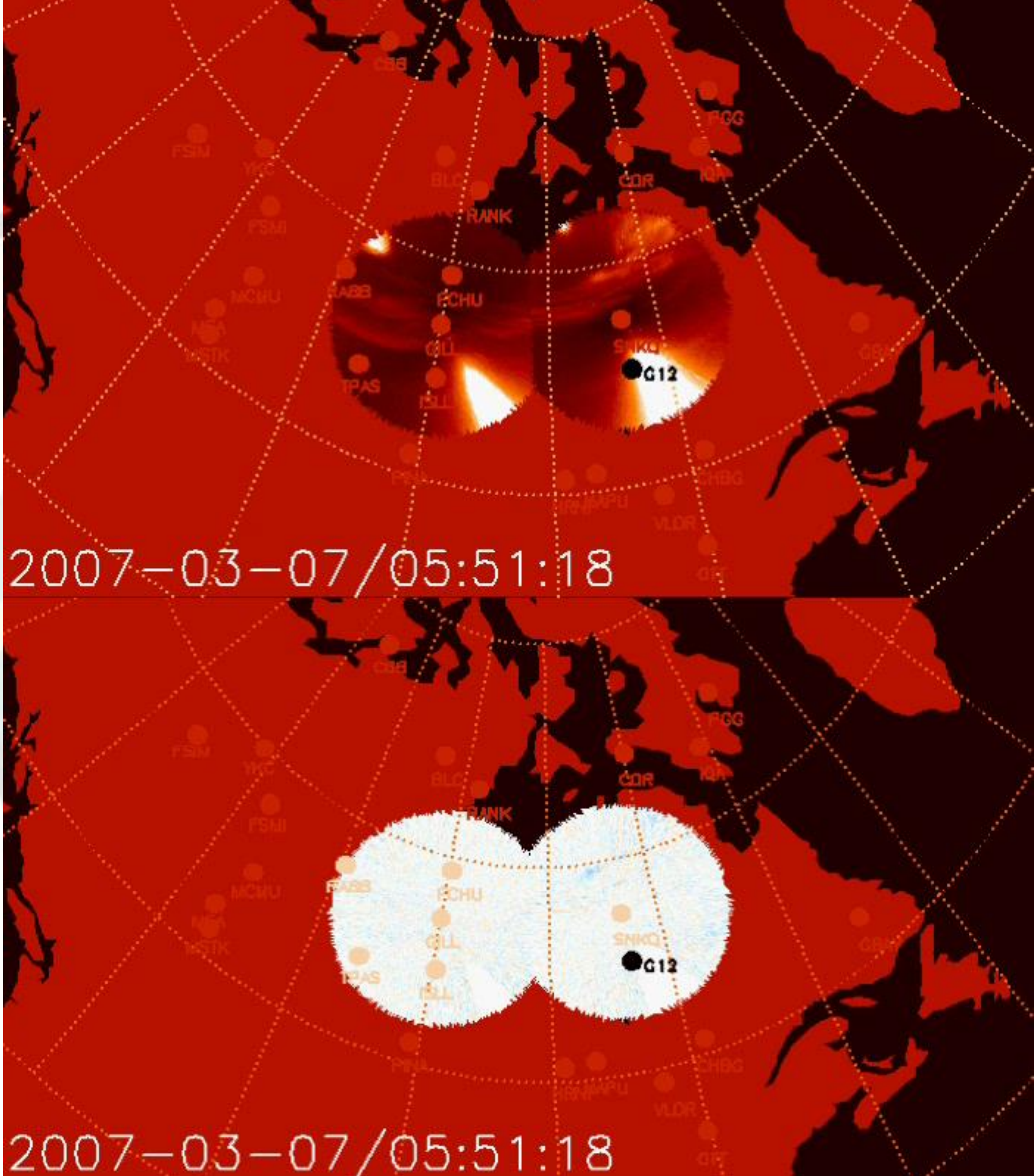
Institute for Space Science, Exploration and Technology
University of Alberta

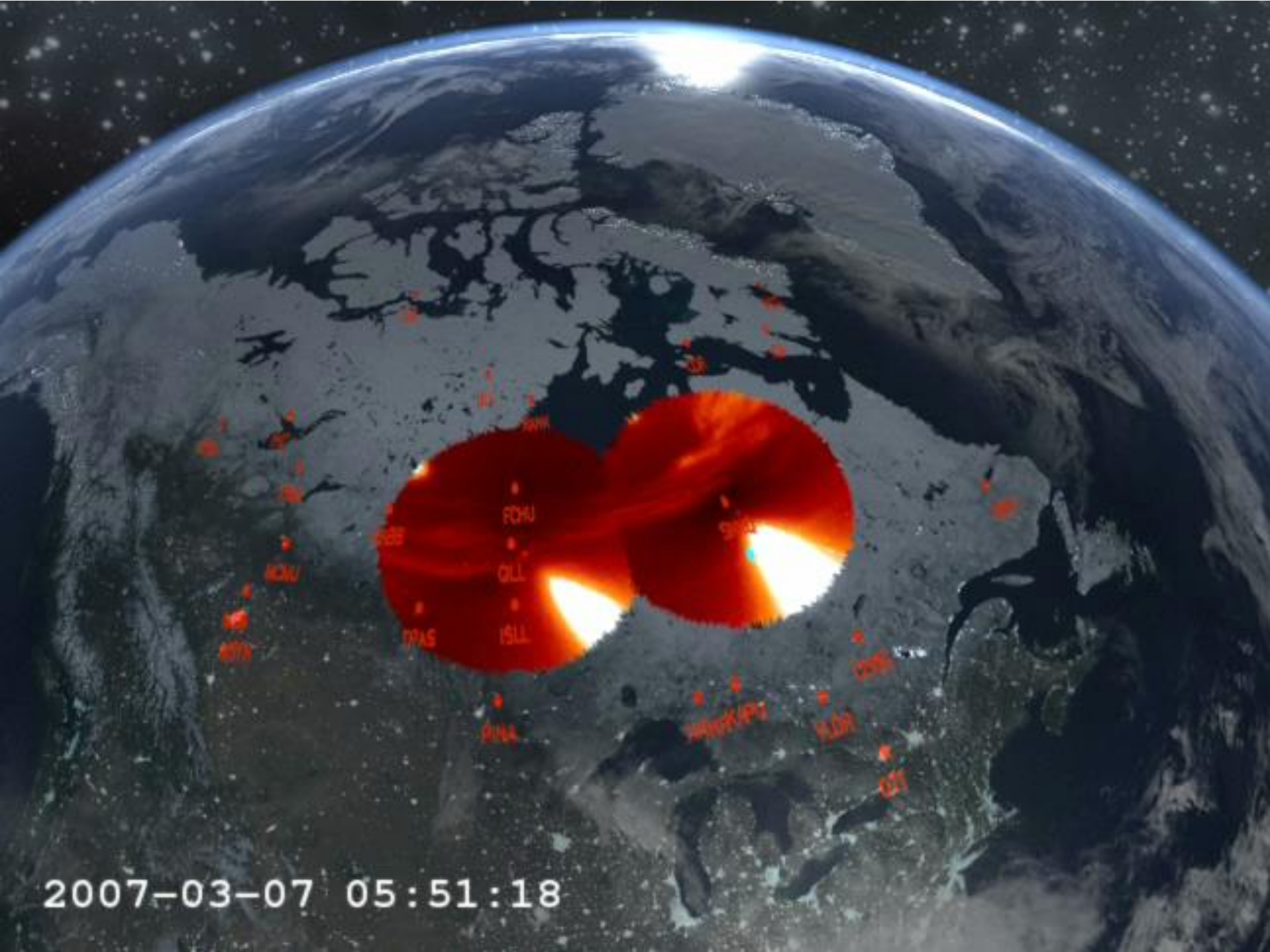
"This presentation is being recorded"

Movie courtesy of Jonathan Rae; (Rae, Mann et al. JGR, 2009).

"This presentation is being recorded"

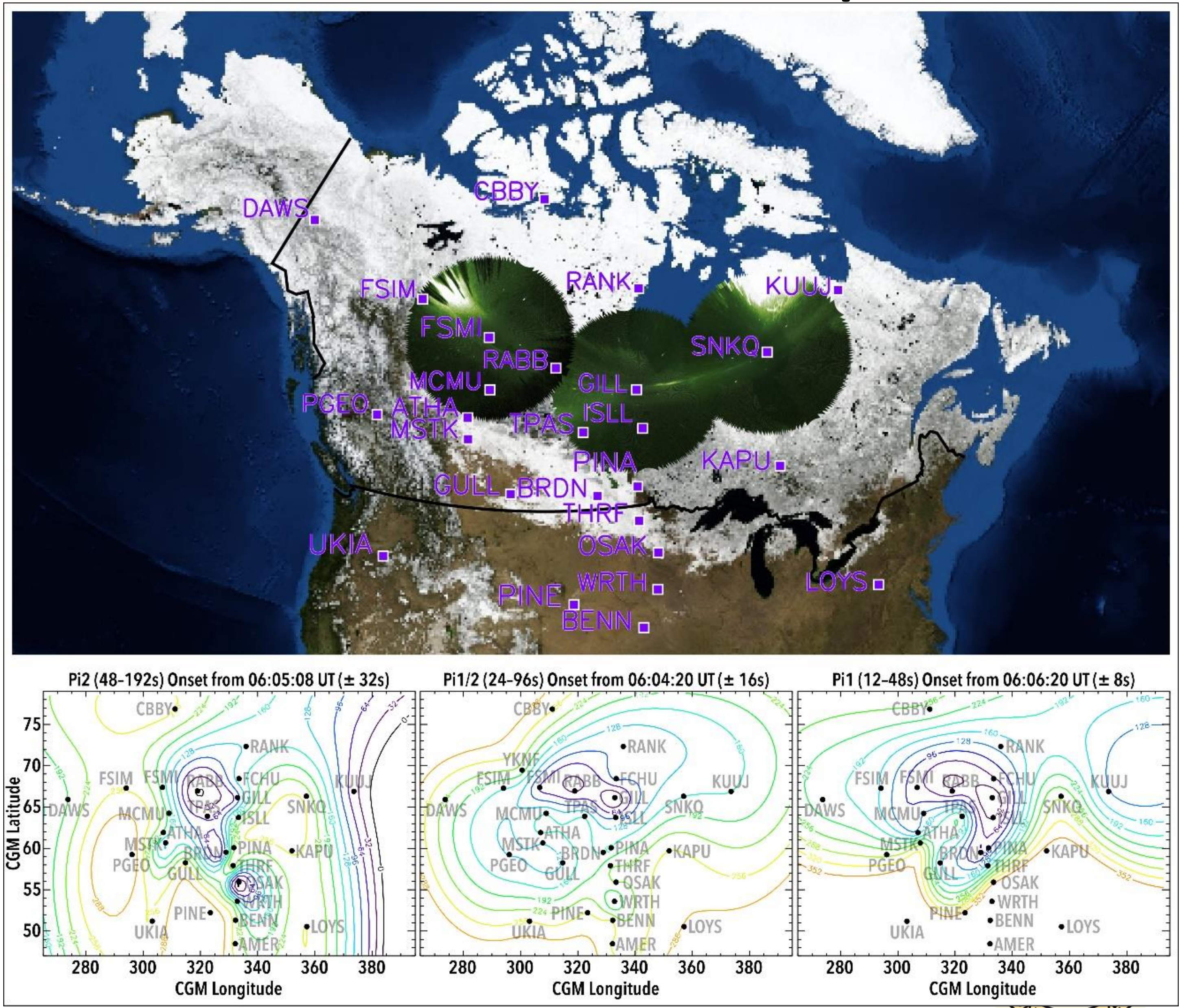
Institute for Space Science, Exploration and Technology
University of Alberta




FCHU
GILL
ISLL
TPAS
2007-03-07 05:51:18

Propagation is Waveband Dependent

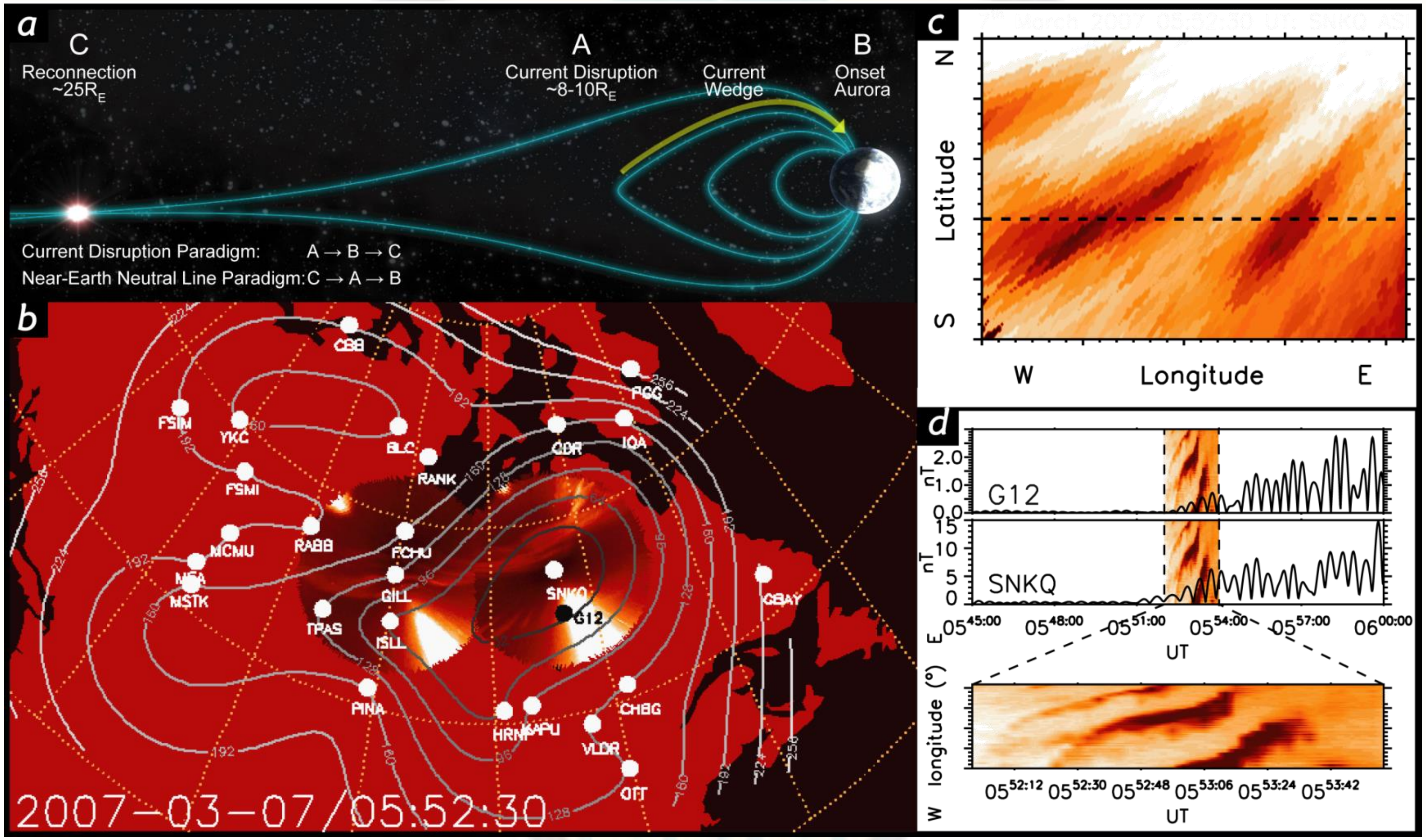
- Small substorm on 5th March 2008.
- From Mann et al. (2019); adapted from Figures 1 and 4 from Rae et al. (2017).



Institute for Space Science, Exploration and Technology
University of Alberta

"This presentation is being recorded"

Substorm Magnetosphere-Ionosphere Coupling



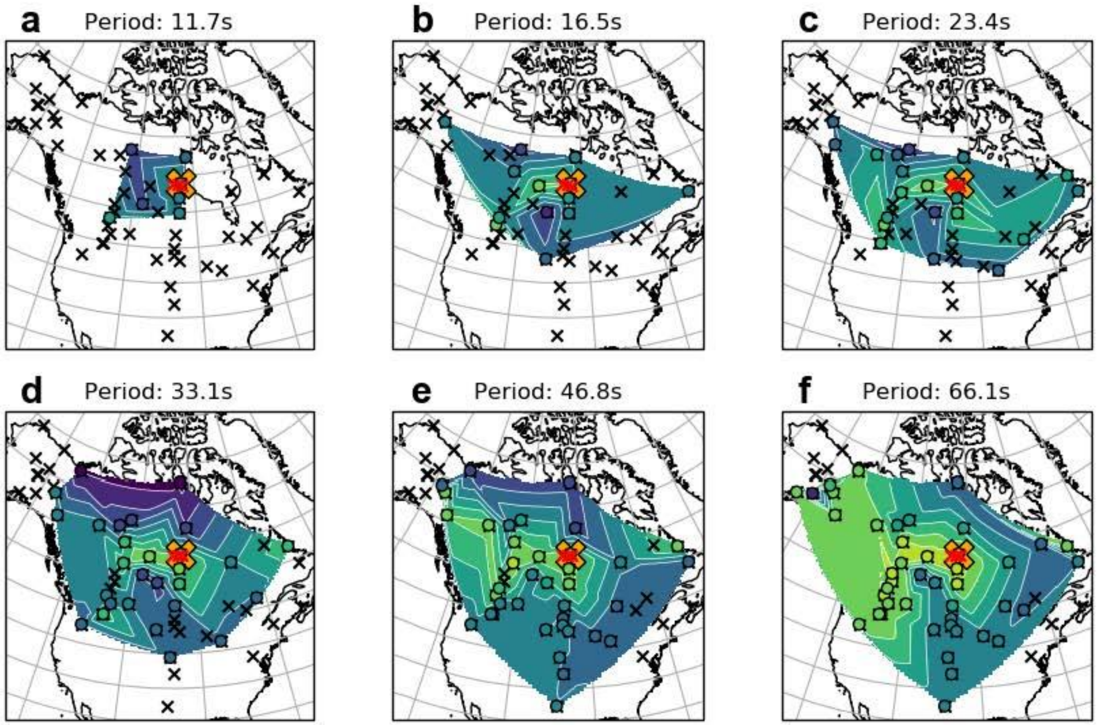
Pi1-2 activity also at GEO.

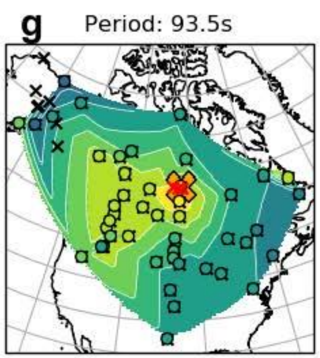
"This presentation is being recorded"

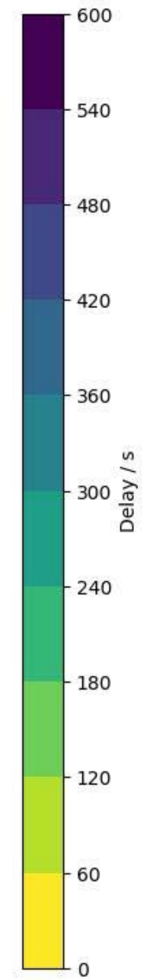
Delays THEMIS to Ground

From Smith et al., (2020b)

- Smith et al., (2020a, 2020b) examine THEMIS satellite to ground ULF wave delays, and relative powers.
- Examine period dependence of patio-temporal characteristics.
- Relative to GILL at 06:01:54 in the 93.5s band.







Wave paths connecting onset magnetosphere and ground are key to understanding.

Clear connection to onset processes in the near-tail.

Institute for Space Science, Exploration and Technology
University of Alberta

QUAECUMQUE VERA

"This presentation is being recorded"

ULF Wave Impacts on Radiation Belt Electron Dynamics

- Coherent ULF wave interactions (e.g., Mann et al., 2013; Claudepierre et al., 2013; Hartinger et al., 2020.)
- Data driven ULF wave radial diffusion (e.g., Mann et al., 2016; Ozeke et al., 2020)
- Electromagnetic ion cyclotron (EMIC) waves and related loss to the atmosphere (e.g., Usanova et al. 2015 and references therein).

Institute for Space Science, Exploration and Technology
University of Alberta

"This presentation is being recorded"

Power of the Combination of Ground and Satellite Data

Ultra-Low Frequency (ULF) Wave-Particle Interactions

[redacted]

University of Alberta

"This presentation is being recorded"

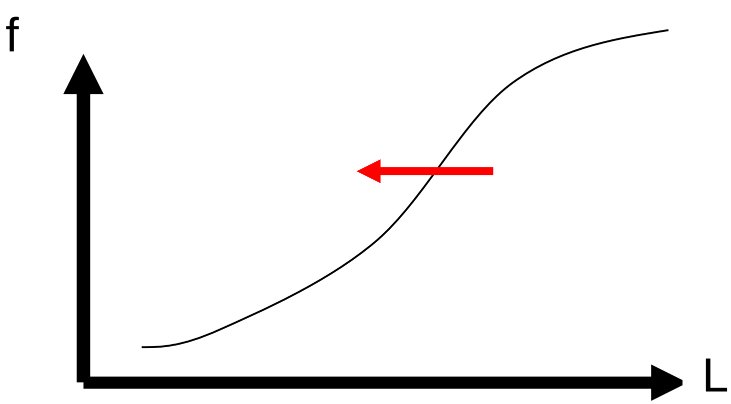
ULF Wave-MeV Electron Energy Exchange

- Rate of energy change due to ULF interactions:

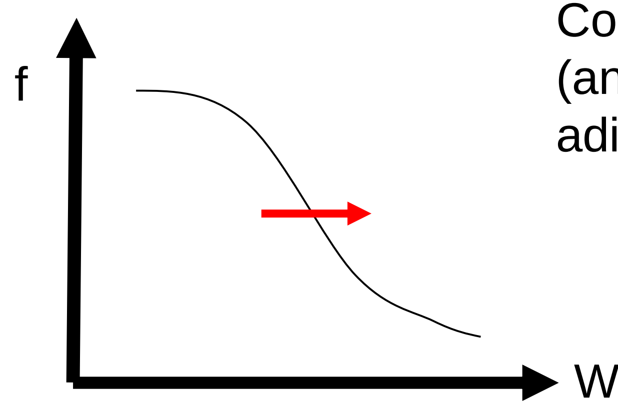
$$\boxed{\frac{dW}{dt} = q\mathbf{E} \bullet \mathbf{V}_d + \frac{M}{\gamma}\frac{\partial b}{\partial t}}$$

- Effect from electric field and compressional magnetic field; dominated by electric component (Ozeke et al., 2012).
- Can transport particles along phase space density gradients: inwards (energisation) or outwards (e.g., magnetopause loss; Loto'aniu et al., 2010; Turner et al., 2012).

Diffusion to lower L

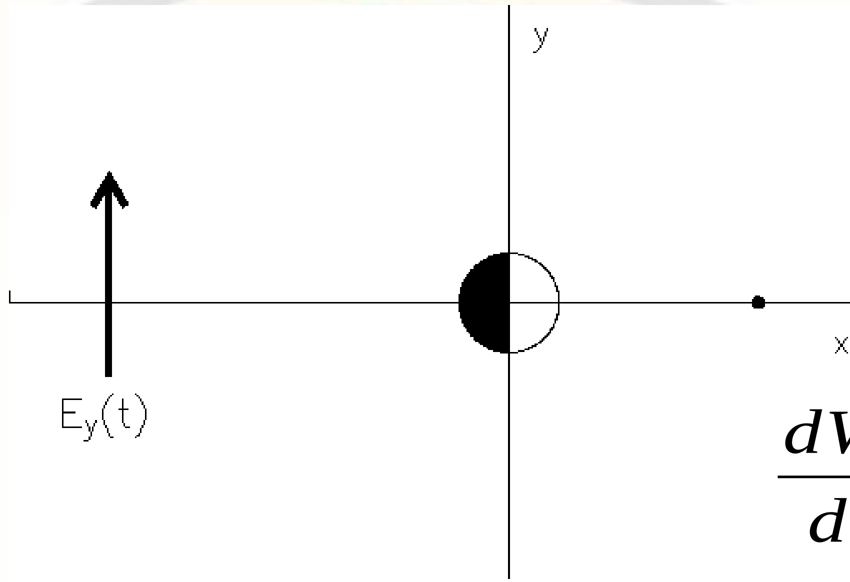


Diffusion to higher W

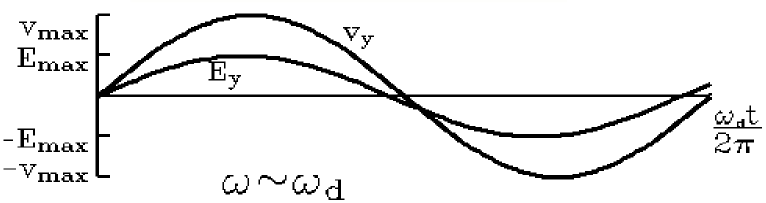


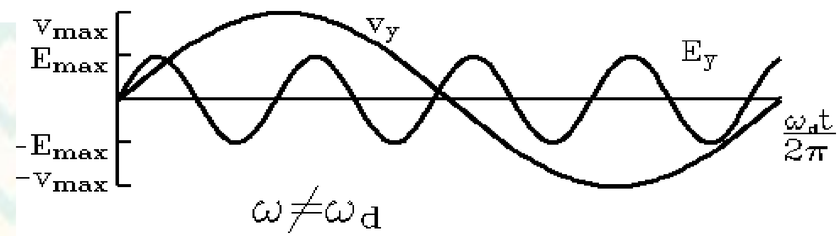
Conservation of first (and second) adiabatic invariant.

ULF Wave-Particle Drift Resonance

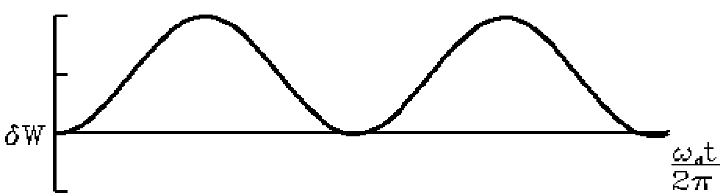


$$\frac{dW}{dt} = q\,\vec{v}_D \cdot \vec{E}$$

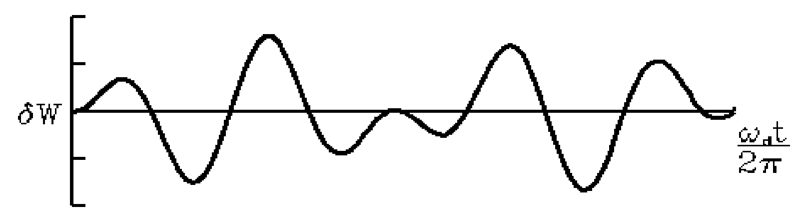




Images courtesy of Scot Elkington, LASP.



$\int v_y E_y \, dt > 0$



$\int v_y E_y \, dt \sim 0$

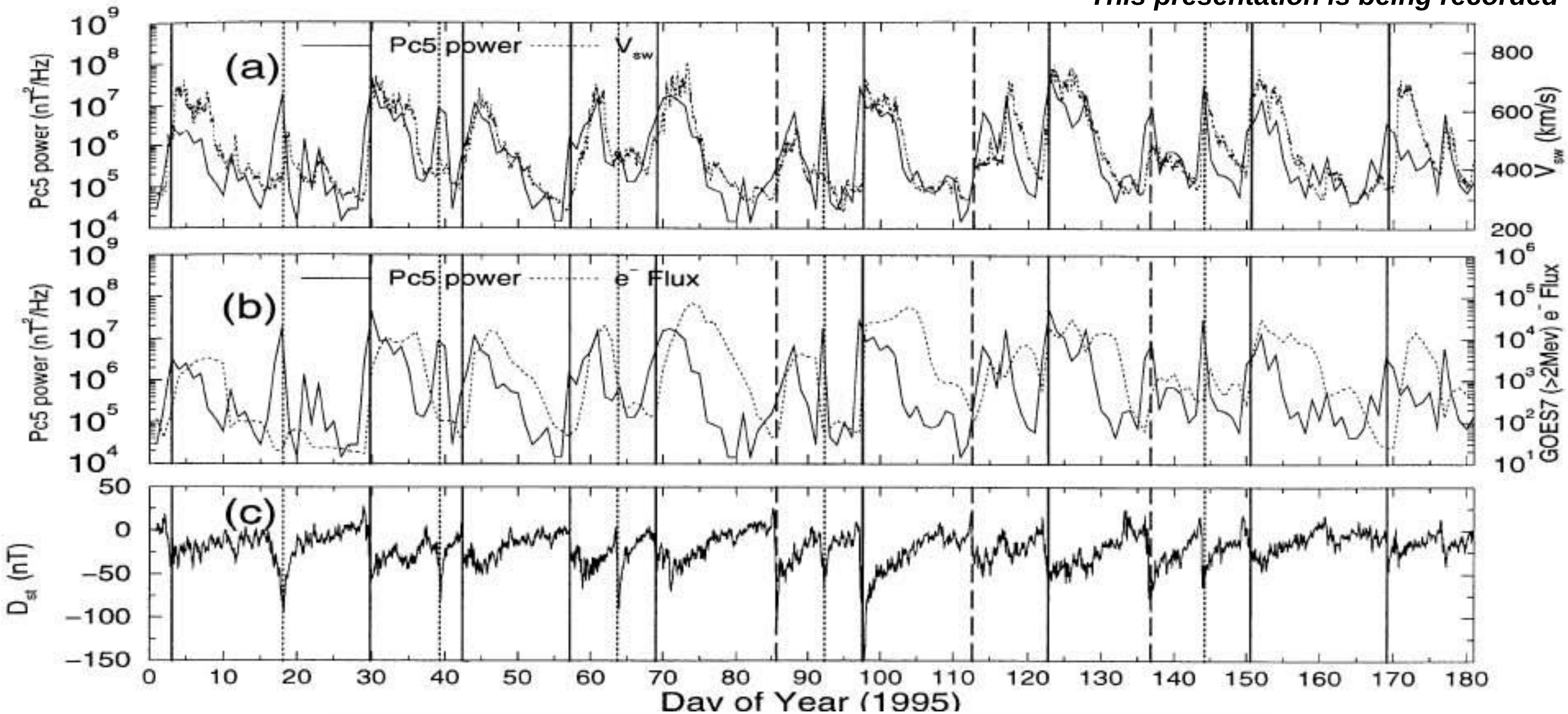
"This presentation is being recorded"

Strong Correlation Between Solar Wind, ULF waves, and Radiation Belt Electron Dynamics.

ULF Waves, Fast Solar Wind Streams and MeV Electrons at GEO

(From Mathie and Mann, GRL, 2000).

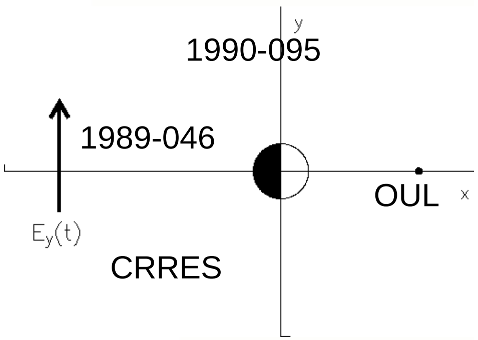
"This presentation is being recorded"

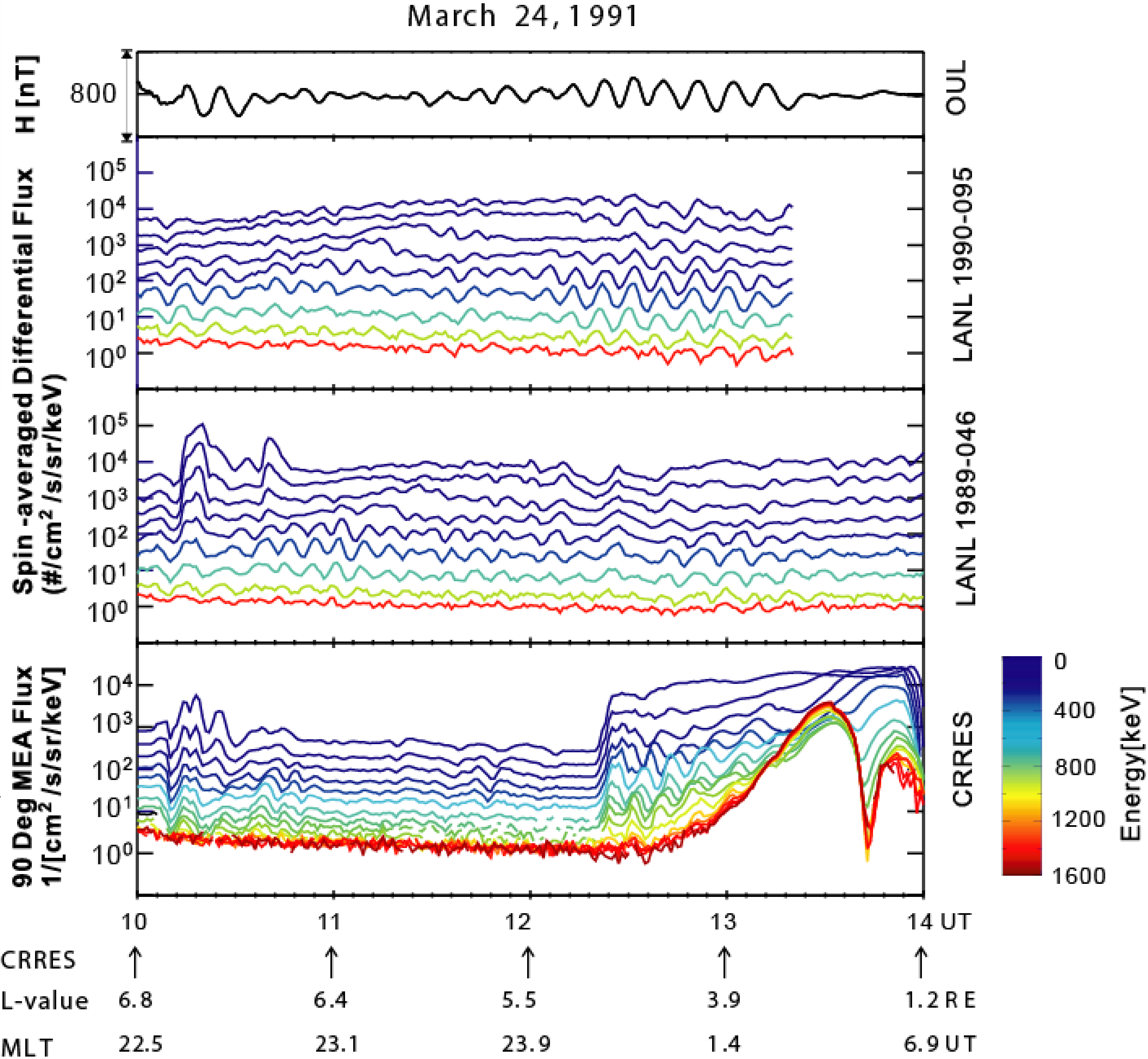


Coherent ULF Wave Interactions

From Mann et al., Nature Comm., 2013.

See also Hartinger et al. 2020.





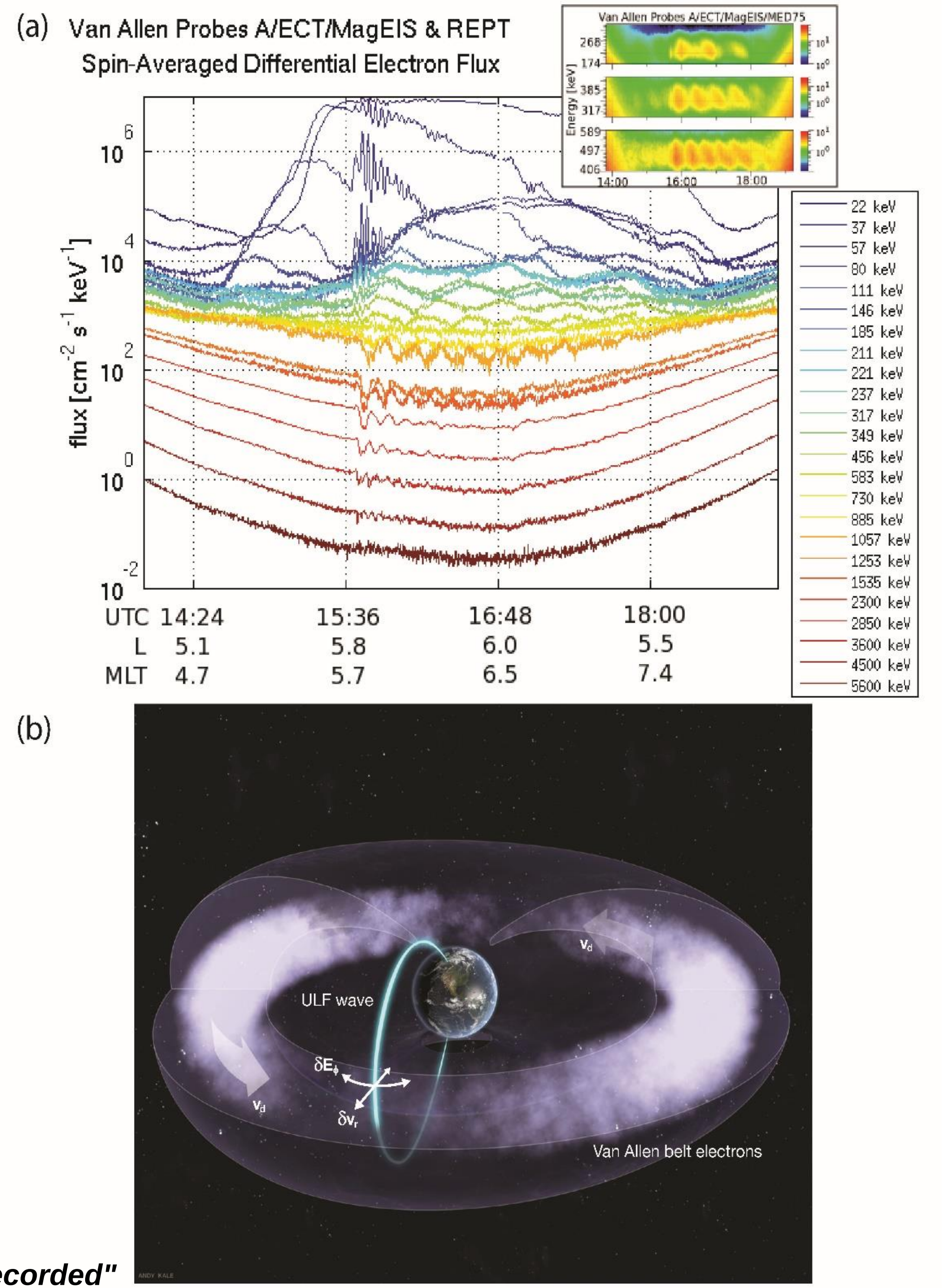
Thanks to LANL and CDAWeb for LANL and CRRES Data.

"This presentation is being recorded"

Institute for Space Science, Exploration and Technology
University of Alberta

Van Allen Probes

- Mann et al., Nature Comms., 2013; Claudepierre et al., GRL, 2013.



Institute for Space Science, Exploration and Technology
University of Alberta

"This presentation is being recorded"

ULF Wave Radial Diffusive Transport

Model (Brizard & Chan, Phys. Plasmas, 2004)

Loss term

$$\frac{df}{dt} = L^2 \frac{\partial}{\partial L}\left(\frac{1}{L^2} D_{LL} \frac{\partial f}{\partial L}\right) - \boxed{\frac{f}{\tau}}$$

"MAGNETIC"

"ELECTRIC"

$$D_{LL}^{m} = \frac{1}{8}\left(\frac{M}{q\gamma B_0 R_E^2}\right)^2 \cdot L^4 \cdot \sum_m m^2 P_m^B(L, m\omega_D)$$

$$D_{LL}^{E} = \frac{1}{8 B_0^2 R_E^2} \cdot L^6 \cdot \sum_m P_m^E(L, m\omega_D)$$

Compressional Magnetic Field Power

Energy dependence

Azimuthal Electric Field Power

These two terms can be derived in space empirically. But electric dominates – allows DLL characterization from ground.

Ozeke et al., 2012, 2013, 2014

Institute for Space Science, Exploration and Technology
University of Alberta

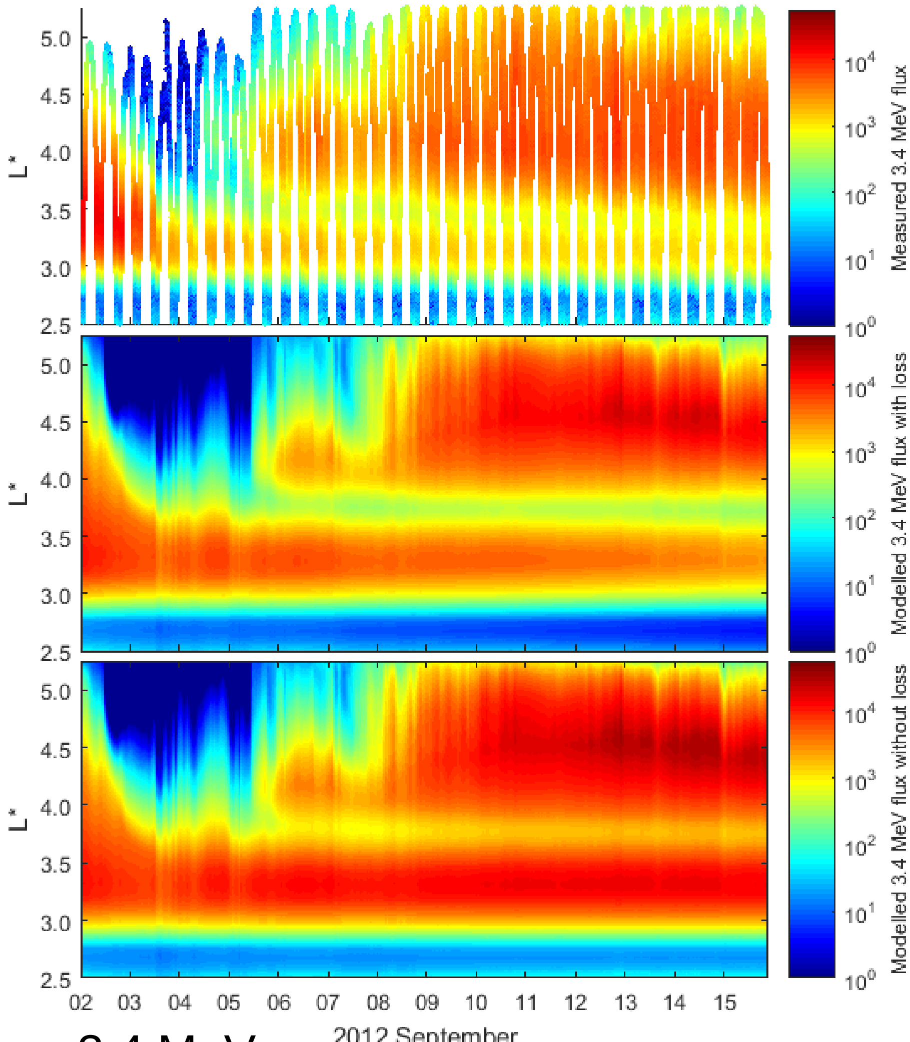
"This presentation is being recorded"

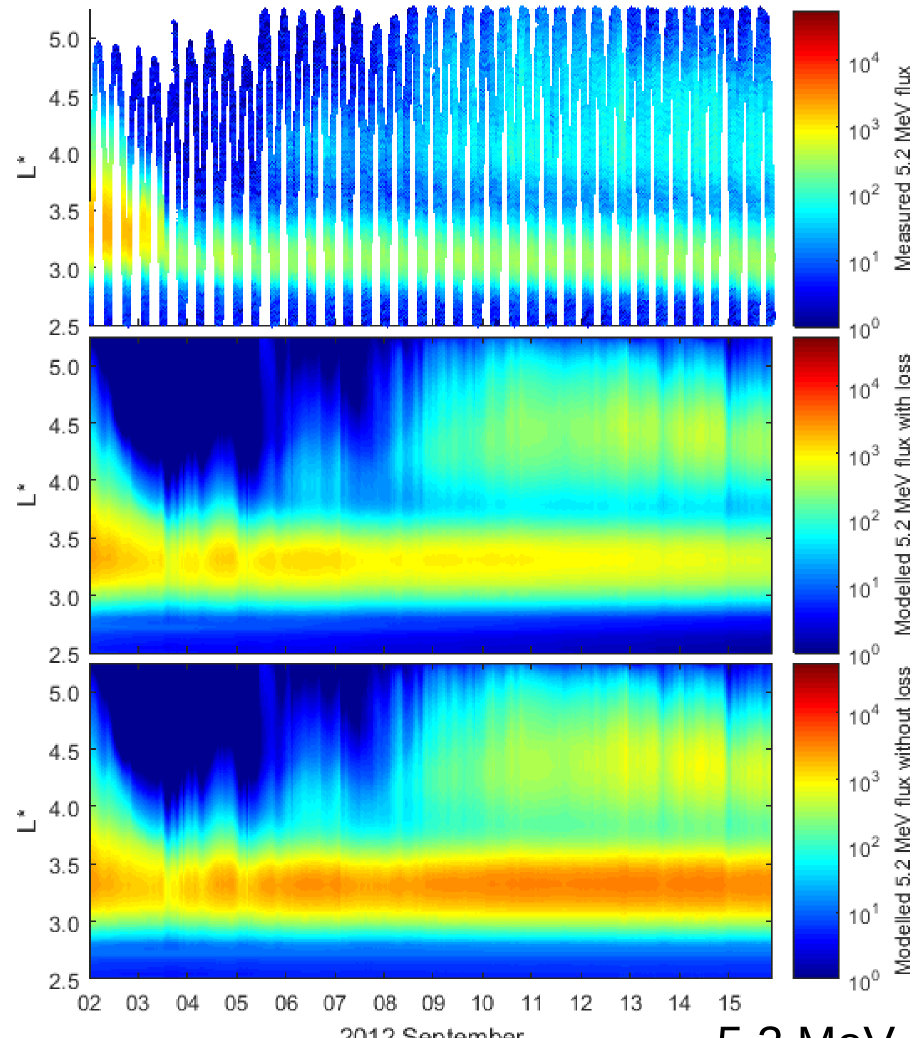
Third Radiation Belt

(this also required L* mapping)

Driven by observed ULF waves.

Mann et al., Nature Physics, 2016.



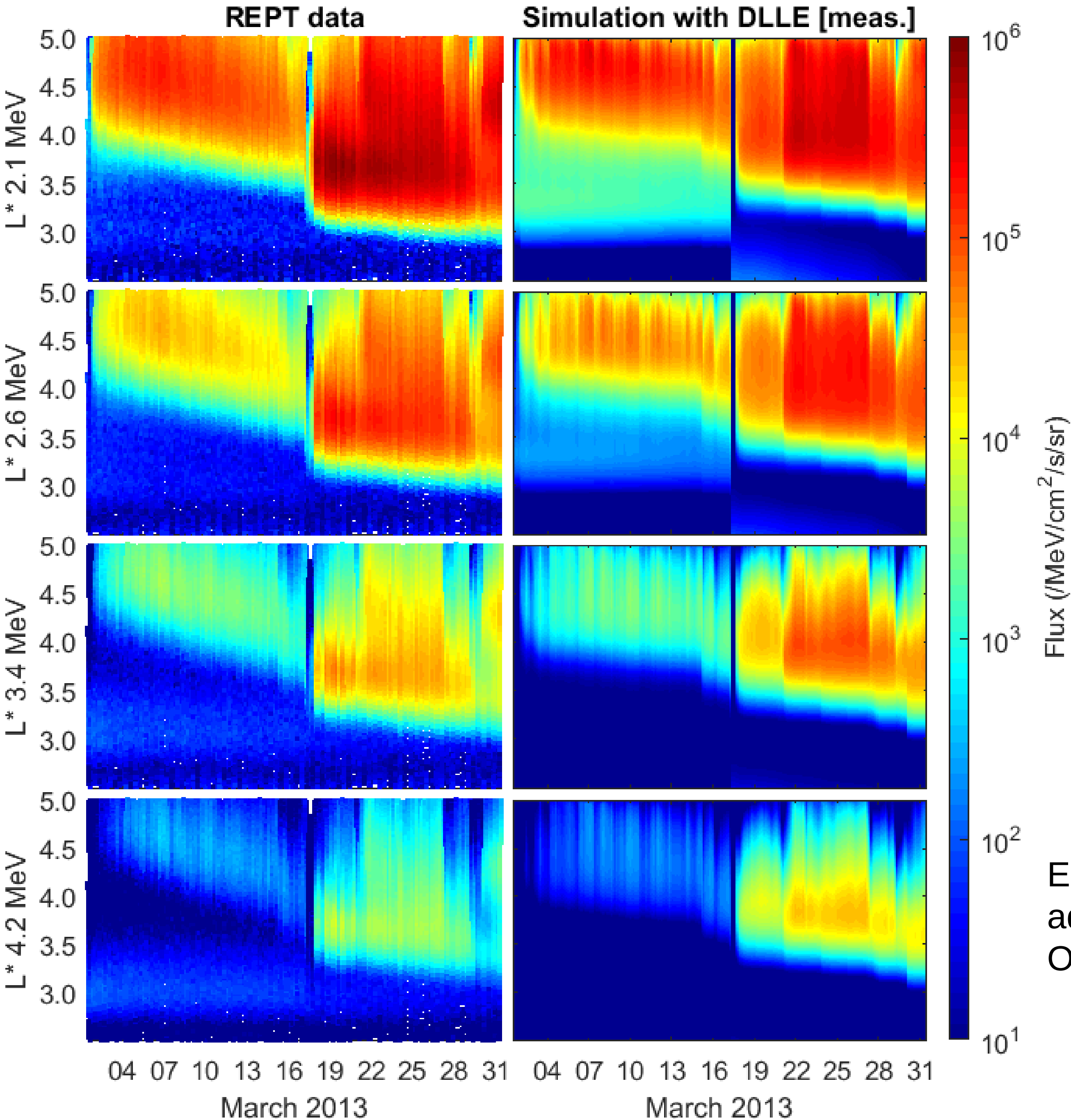


3.4 MeV

5.2 MeV

"This presentation is being recorded"

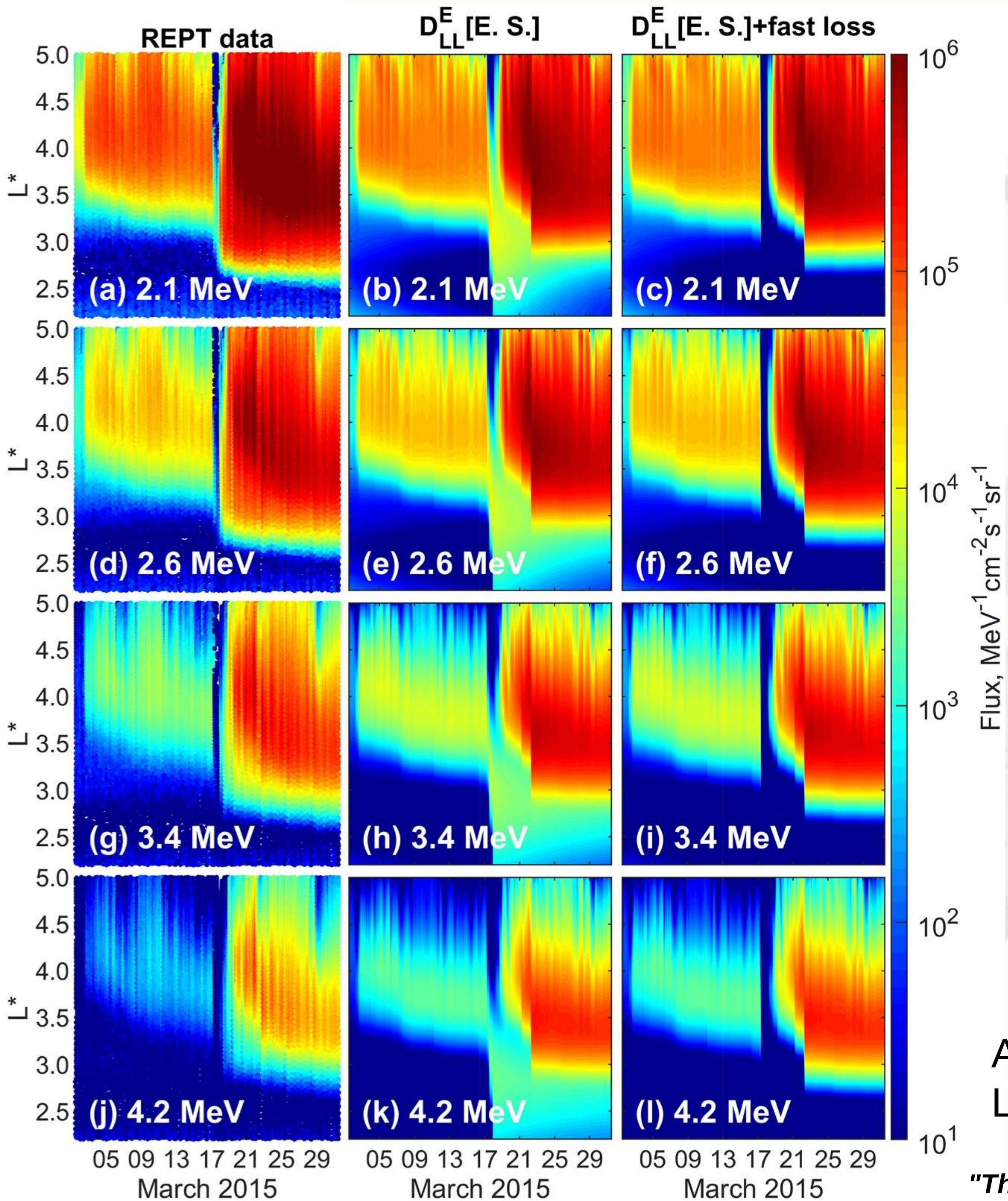
ULF Wave Radial Diffusion: Data Driven Transport



March 2013 Storm
(Ozeke et al. 2020)

Enhanced very short additional DLL based on Olifer et al. (2019)

"This presentation is being recorded"



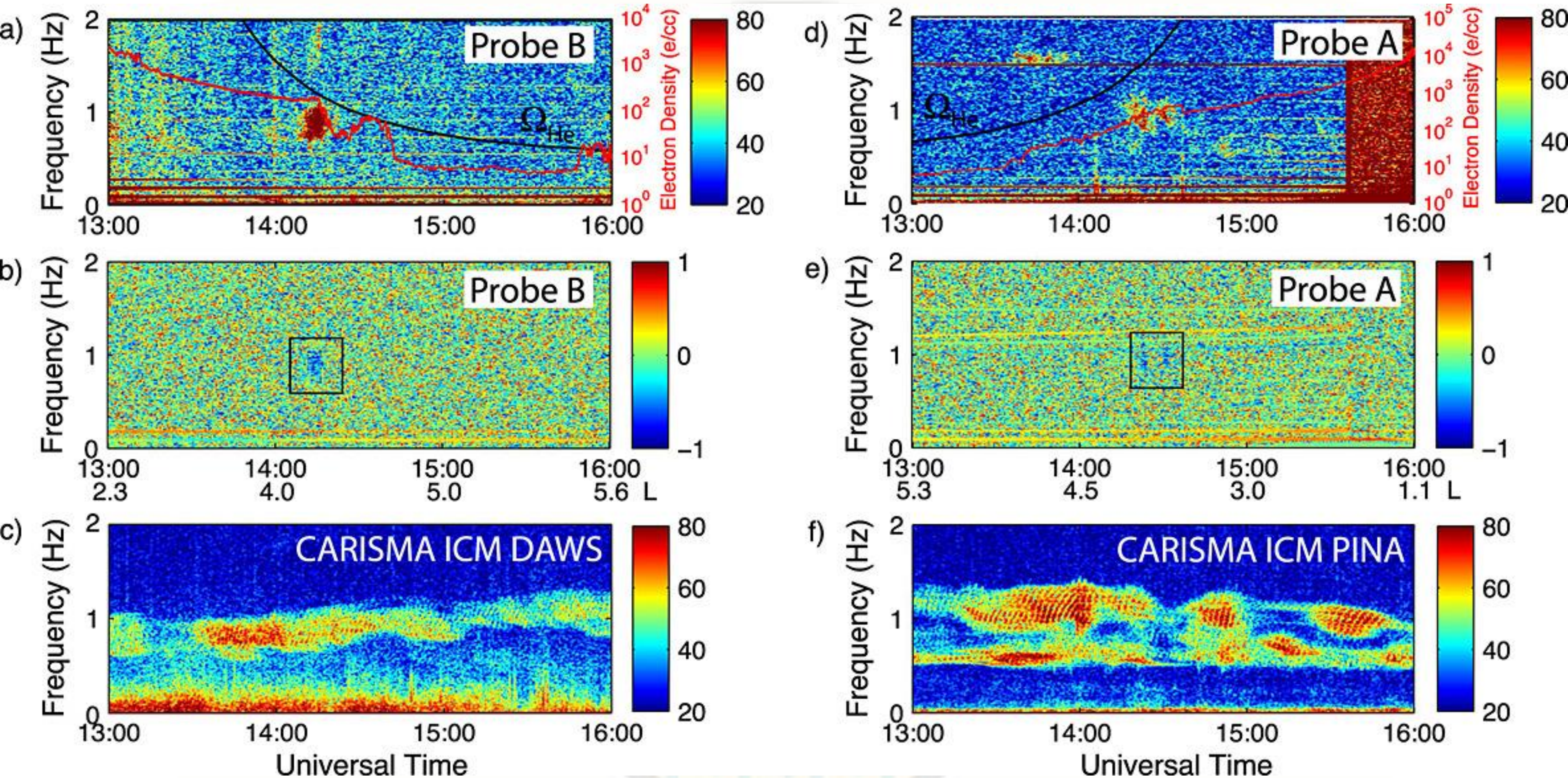
ULF Wave Radial Diffusion: Data Driven Transport

March 2015 Storm (Ozeke et al. 2020)

Additional Loss at L<=3.5

"This presentation is being recorded"

Electromagnetic Ion Cyclotron (EMIC) Waves



Institute for Space Science, Exploration and Technology
University of Alberta

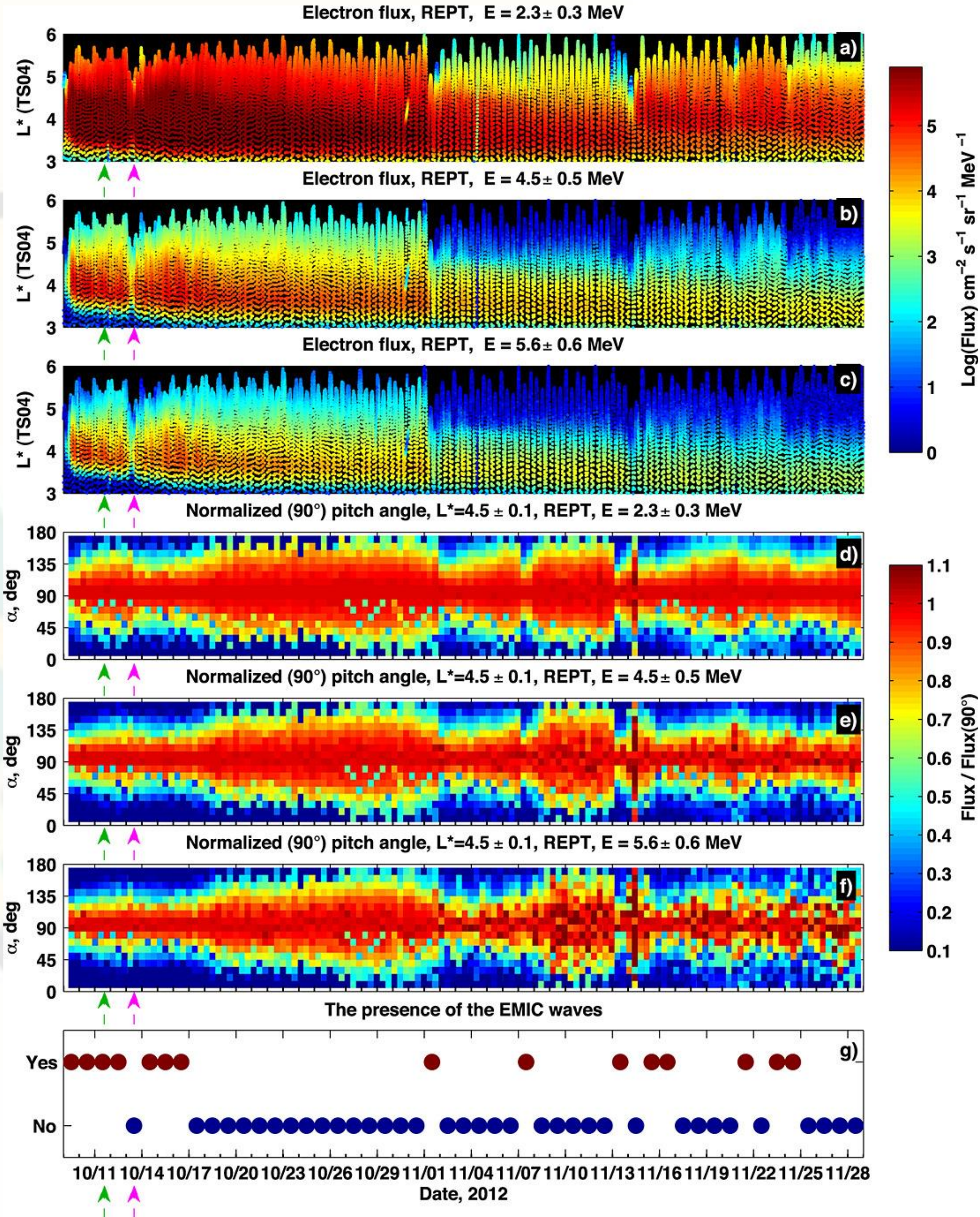
Van Allen Probes and Ground -
Mann et al. GRL (2014)

"This presentation is being recorded"

Impact of EMIC Waves on Radiation Belt Electrons?

From Usanova et al. (2014). See also recent modelling from Drozdov et al., (2020).

"This presentation is being recorded"



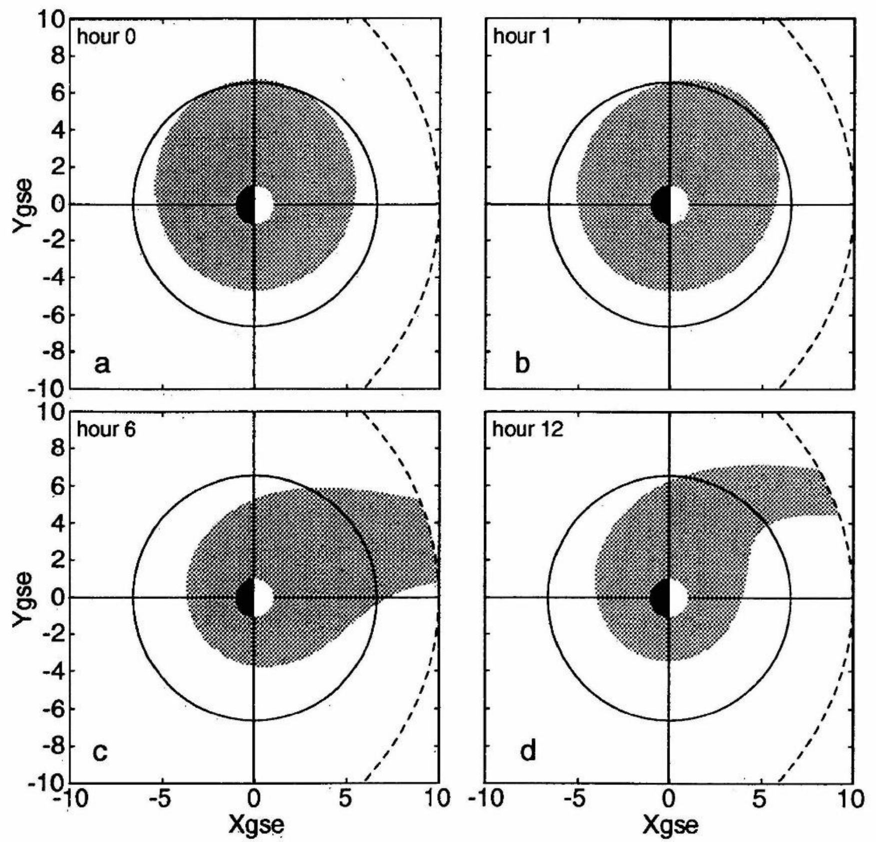
Institute for Space Science, Exploration and Technology
University of Alberta

Magnetoseismology: The cross phase technique

- Cross phase allows the determination of the field line resonant frequency between two latitudinally spaced ground magnetometers.
- The technique relies on the phase difference across the resonant field line.
- Works even when the signal at the resonance is not the dominant one.
- Can also be used with a magnetic field and field-aligned density model to invert into equatorial plasma mass density
- E.g., Baransky et al., 1985; Waters et al., 1991, 1994, 1995; Mathie et al., 1999a, 1999b; Chi et al., 2000,2005, 2013; Dent et al., 2006...

Storm-time Mass Density Dynamics

- Dynamic evolution of plasmasphere proposed as a result of distortion of plasmasphere in time dependent convection plus corotation field (e.g., Grebowsky, 1970).

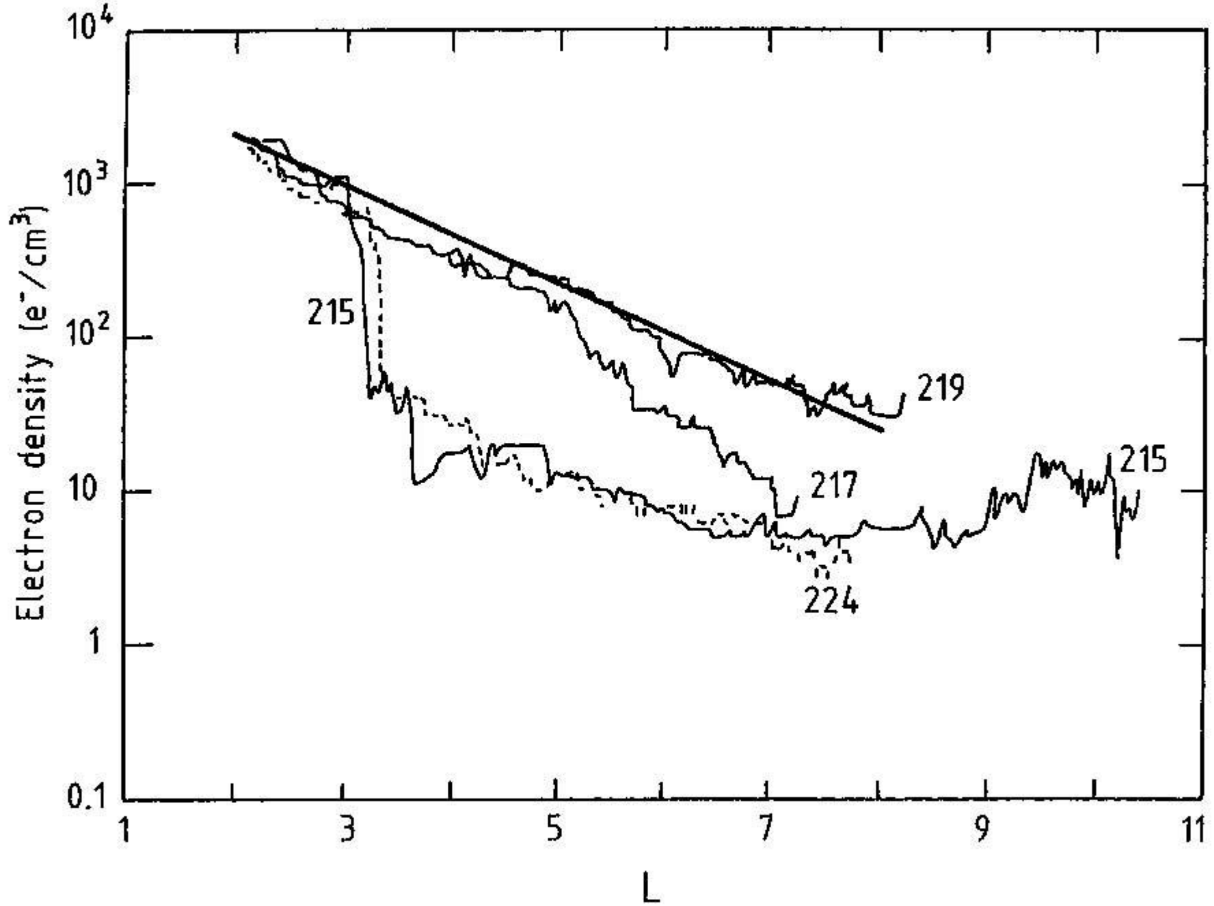


"This presentation is being recorded"

ISEE Electron Density Evolution

- Electron density dynamically eroded in plasmasphere and plasmapause dynamics.

(From Carpenter and Anderson, 1992)



Institute for Space Science, Exploration and Technology
University of Alberta

"This presentation is being recorded"

(From Adrian et al, 2004)

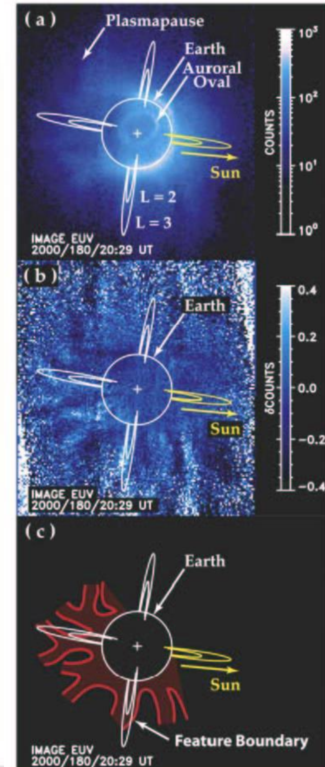
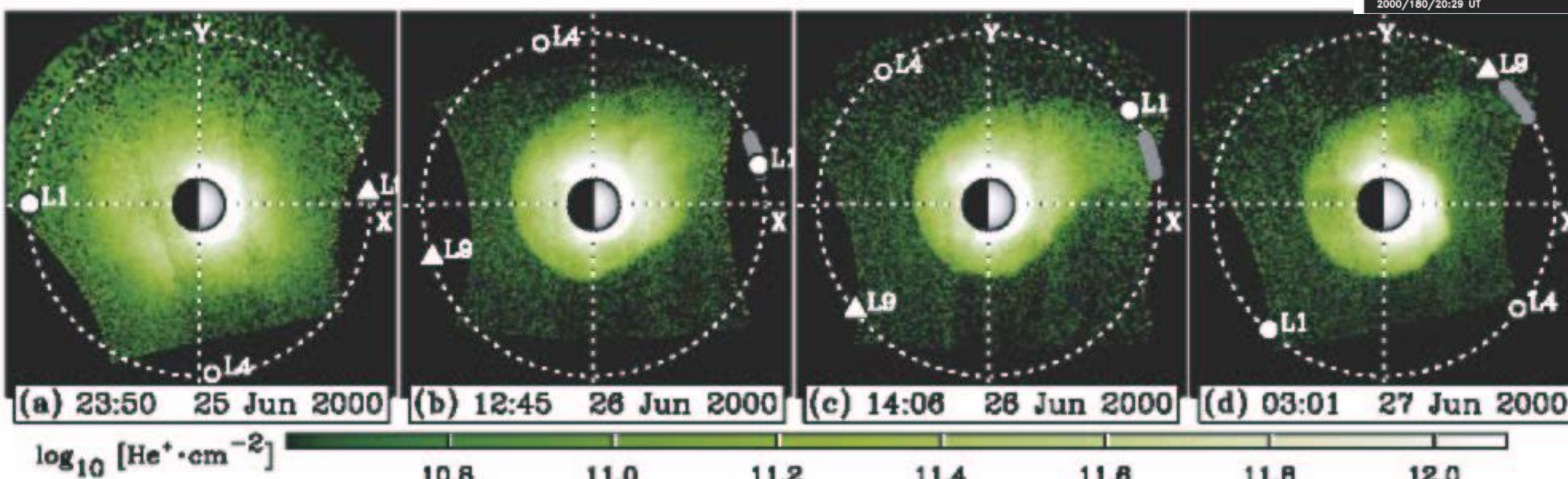


IMAGE Mission Observations

- Plasmaspheric evolution from IMAGE EUV (Goldstein et al., 2004)
- "Difference images show plasmaspheric structure inside plasmasphere (Adrian et al., 20004)

(From Goldstein et al, 2004)

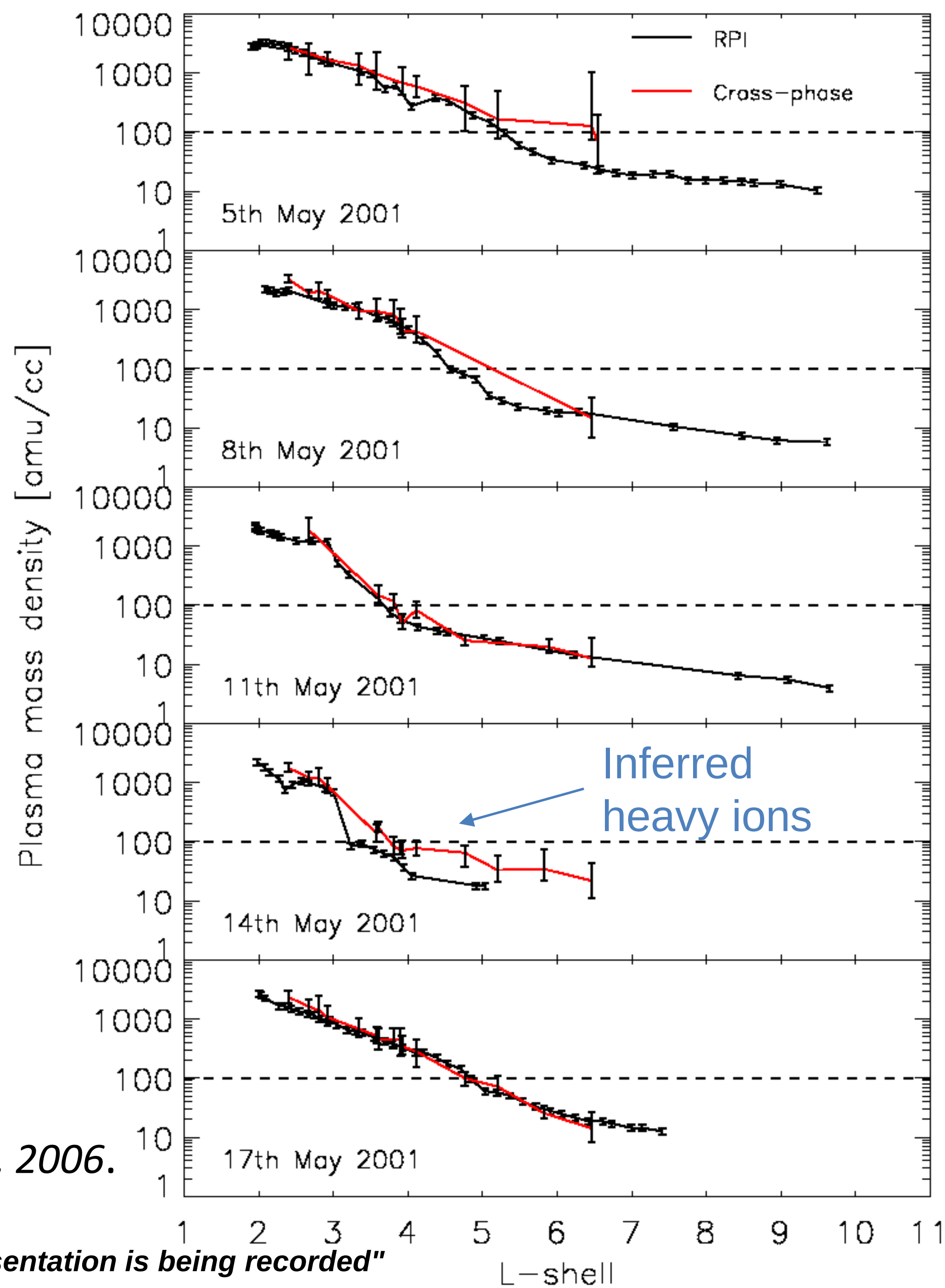


Cross-phase and IMAGE RPI plasma mass density profiles.

- Equatorial plane cross-phase densities have been calculated assuming a dipolar field geometry and a r^{-3} radial density distribution.

- In-situ RPI electron number densities are shown.

- The heavy ion population may be inferred from the difference between the two profiles. For example the O+ ion torus (cf. Fraser et al., 2005).



Dent et al., JGR, 2006.

Institute for Space Science, Exploration and Technology
University of Alberta

"This presentation is being recorded"

Summary and Conclusions

- Ground magnetometer networks can provide powerful global and dense meso-scale monitoring of geospace environment.
- Requires physics interpretation to map into geospace, but provides power augment to in-situ measurements from satellites.
- The field-guided nature of Alfvenic disturbances means ground-based magnetometry is a very powerful tool for discovery on a network basis.
- Comments or questions welcome: imann@ualberta.ca

Institute for Space Science, Exploration and Technology
University of Alberta

"This presentation is being recorded"

Acknowledgements

- IRM thanks many collaborators over many years, and for research materials used in this talk.

- The work is supported by Canadian NSERC, the Canadian Space Agency, Canada Foundation for Innovation, Compute Canada, and DND.

ISSET
Institute for Space Science, Exploration and Technology
University of Alberta

"This presentation is being recorded"

UNIVERSITY OF ALBERTA
QUAECUMQUE VERA