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Solar wind influence of Ultra-Low Frequency wave activity in the magnetosphere

Theodoros E. Sarris

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Ioannina, Sept. 7, 2011

Outline:

1) ULF Waves and their significance in Radiation Belt dynamics

Test-particle simulations of drift-resonant interactions of radiation belt energetic (MeV) electrons with ULF waves

2) ULF Waves during high-speed solar wind streams

Observations and modeling of ULF waves generated during periods with high solar wind velocity. Calculations of mode-number & wave propagation characteristics

3) ULF Waves during Solar Wind pressure perturbations

Observations and modeling of ULF waves generated during SW pressure pulses. Estimates of the efficiency of a pressure/density perturbation in creating ULF waves.

4) A Statistical Study of the Solar Wind influence on ULF waves

E & B-field measurements from the THEMIS constellation of s/c are used to statistically study the correlation between ULF wave power and the various solar wind parameters.

Background:

- "Ultra" Low Frequencies: lower than the natural frequencies of plasmas in the magnetosphere

- Classification of ULF waves according to the period of pulsations:

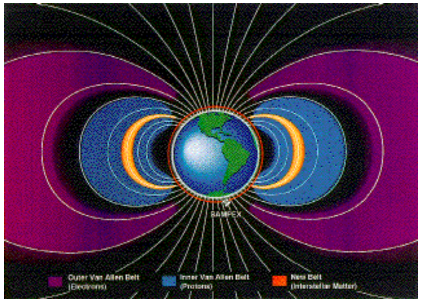
	Pc-1	Pc-2	Pc-3	Pc-4	Pc-5
Period (sec):	0.2-5 sec	5-10 sec	10-50 sec	50-150 sec	150-600 sec
Frequency:	5-0.2 Hz	0.2-0.1 Hz	100-22 mHz	22-7 mHz	7-2 mHz

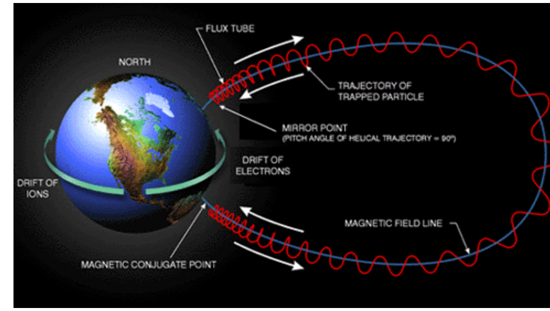
Jacobs et al.**, Classifications of geomagnetic micropulsations, JGR, **1964

- **Pc-4** and **Pc-5** ULF waves are of particular interest In Radiation Belt studies due to their drift-resonant interaction with energetic particles

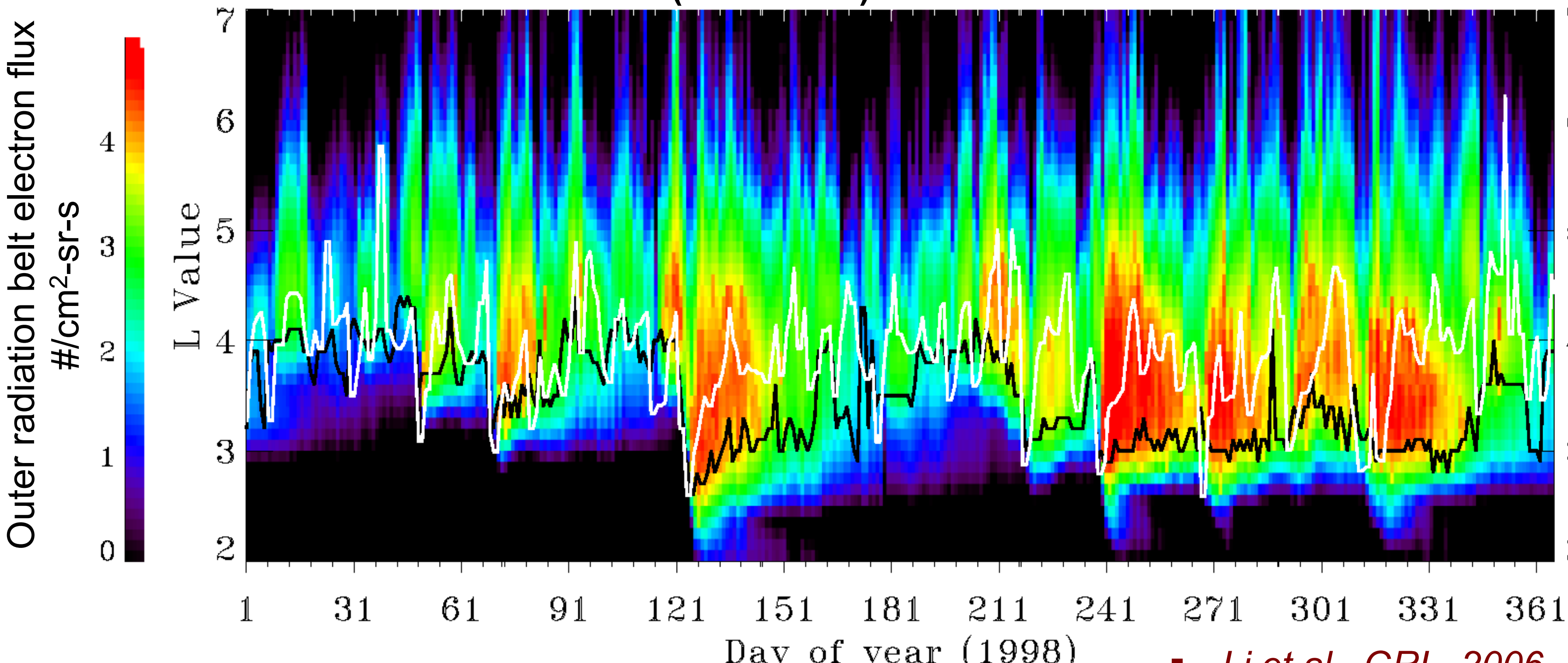
- **Pc-4** and **Pc-5** ULF waves contribute to particle transport and radial diffusion in the magnetosphere and may thus play an important role in magnetospheric dynamics

The Radiation Belts:





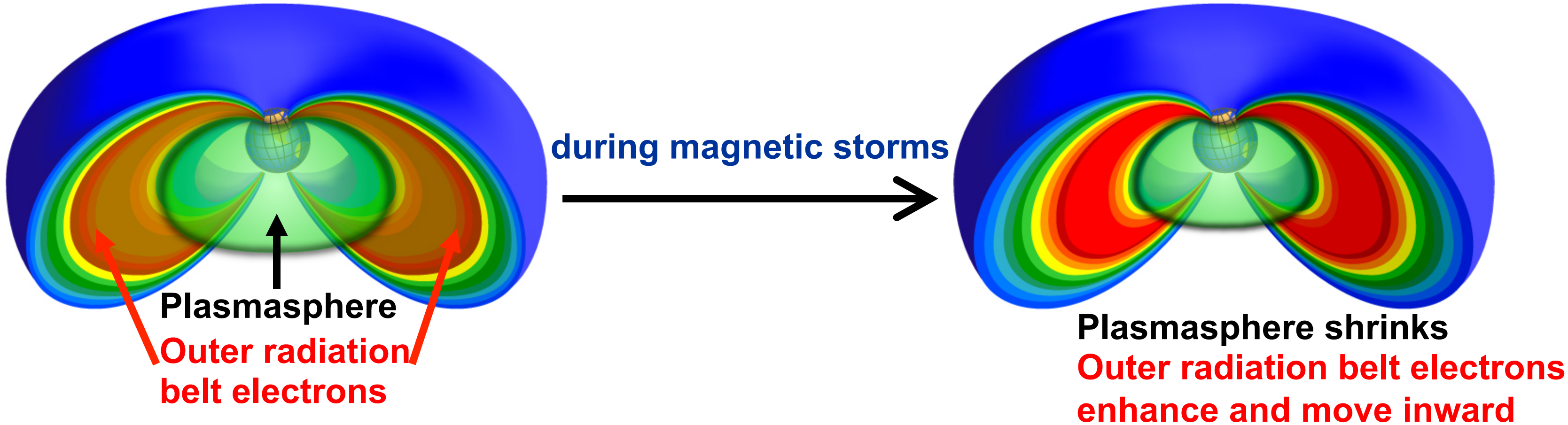
SAMPEX (LEO Orbit): 2-6 MeV Electron Flux

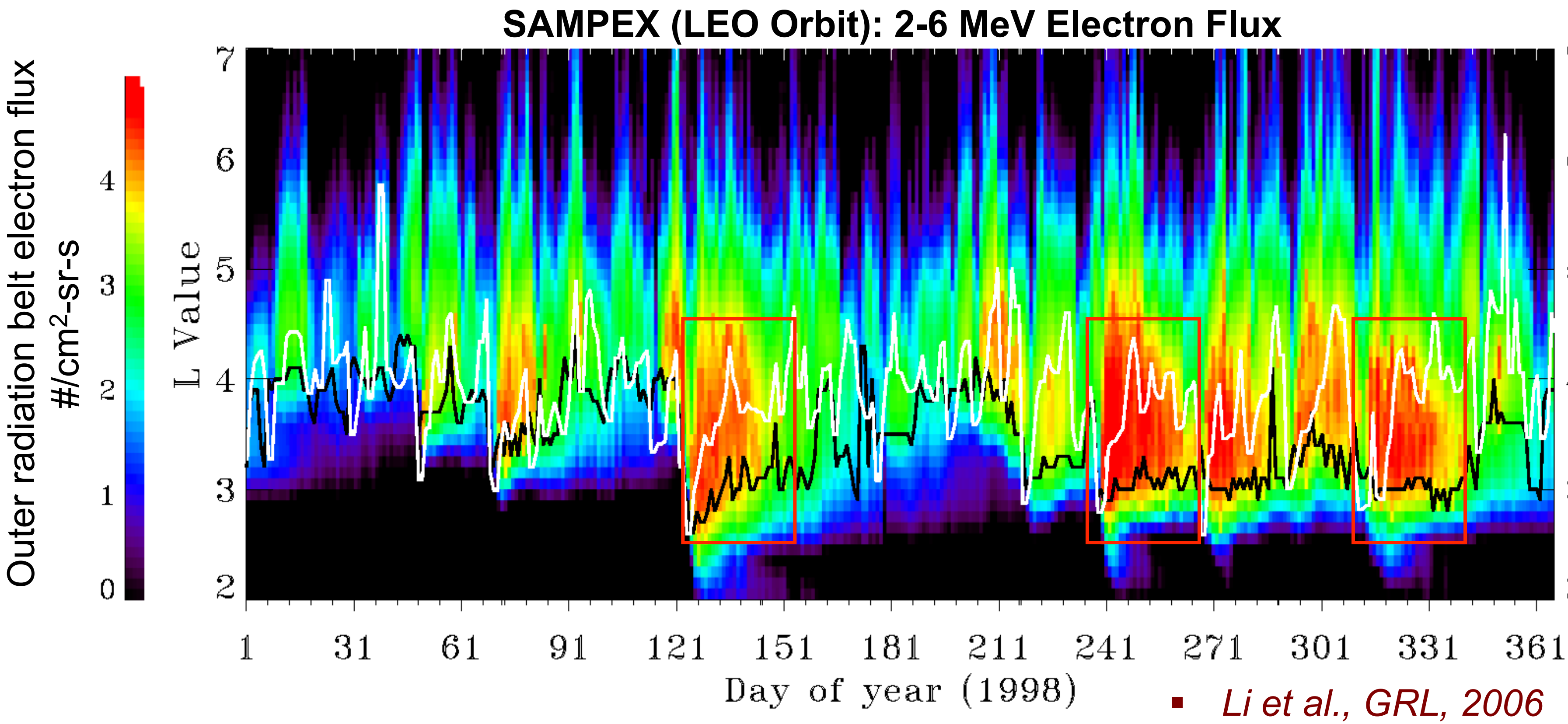


- *Li et al., GRL, 2006*

* White curve: Daily min plasmapause based on empirical model

** Black curve: Daily L where the flux is 40% of the peak flux on the same day.





* White curve: Daily min plasmapause based on empirical model

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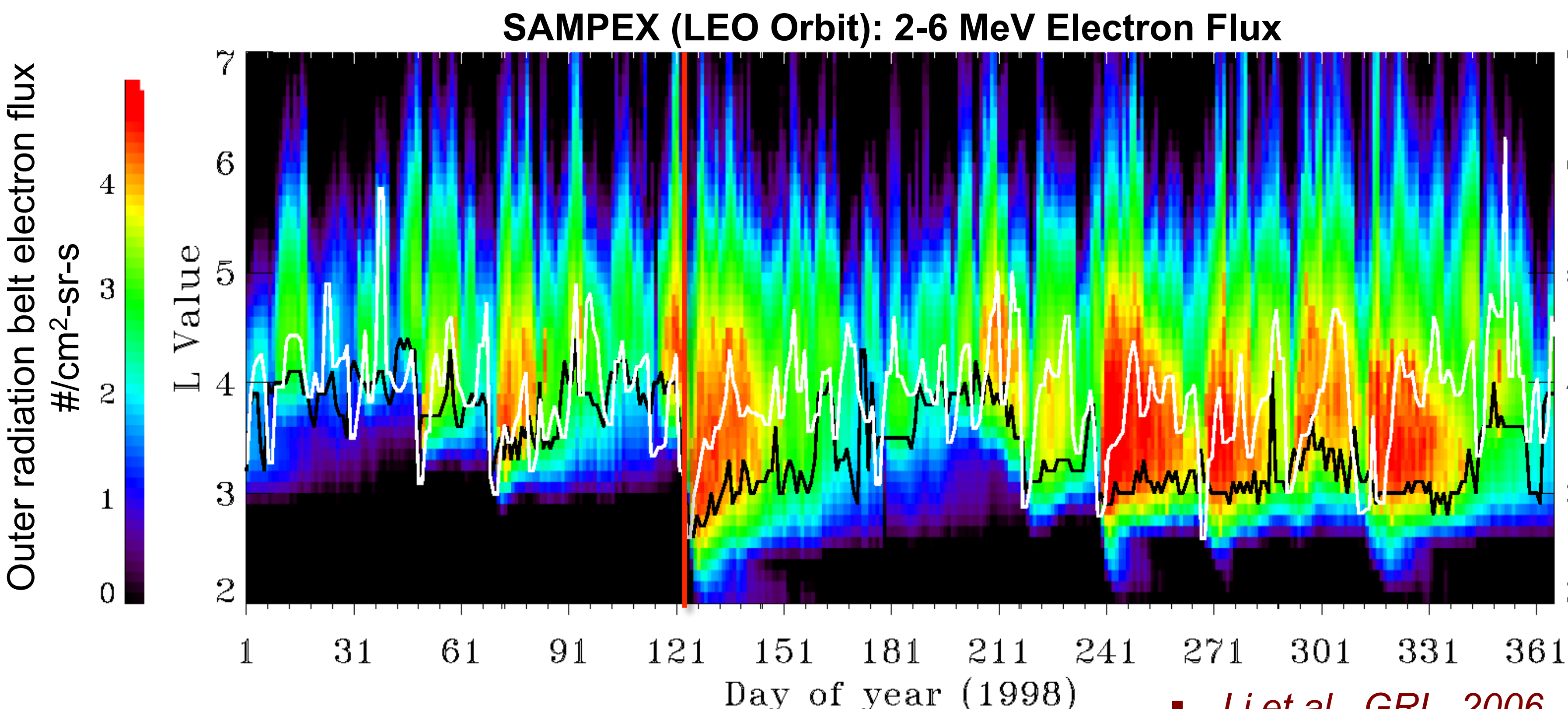
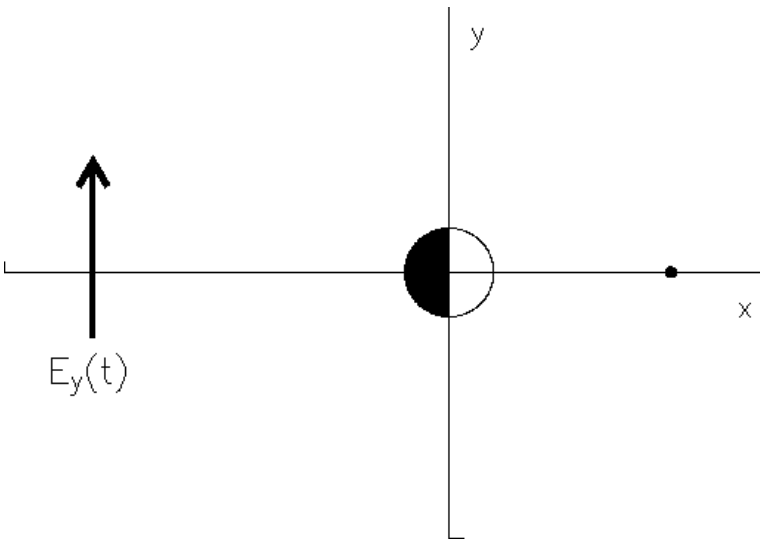
Radial Diffusion During Solar Storms:

- Solar storms are accompanied by intense ULF wave activity
- ULF waves cause diffusion of MeV particles and inward / outward radial transport

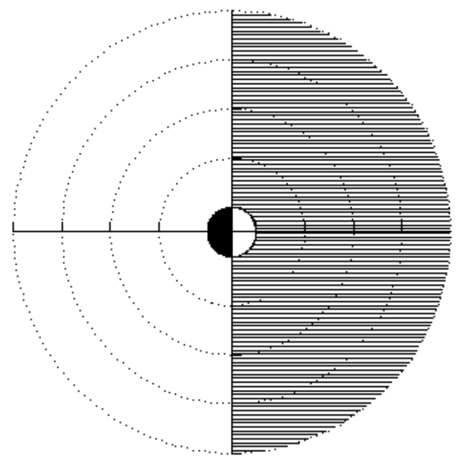


▪ *Li et al., GRL, 2006*

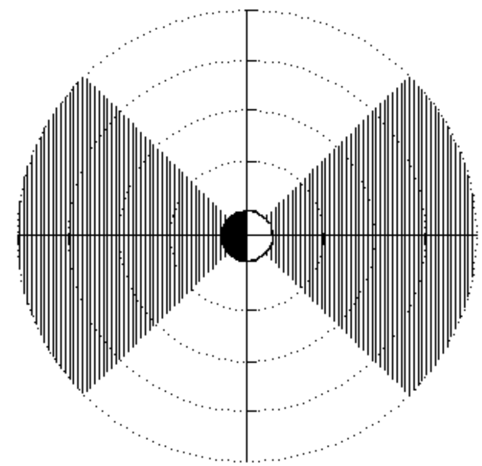
Particle Drift Resonance with ULF waves:



$m = 1$



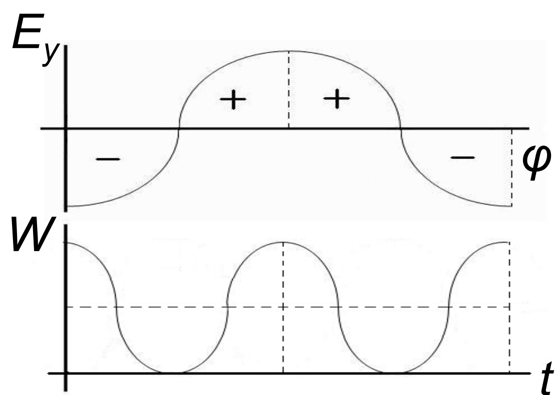
$m = 2$



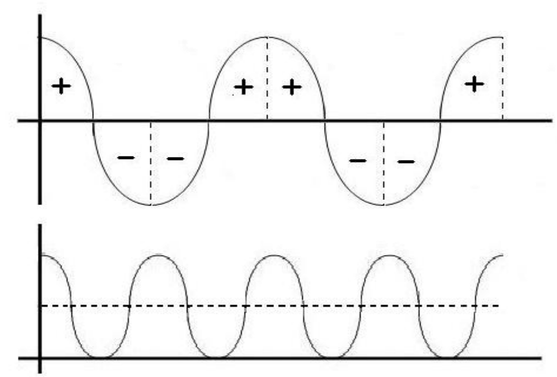
Theoretical derivation of the Diffusion Coefficient:

$$D_{LL}^{B,Sym} = \frac{\mu^2}{8q^2 B_E^2 R_E^4} \frac{L^4}{\gamma^2} \boxed{\sum_m m^2 P_m^B (m\omega_d)}$$

- *Falthammar [1968];*
- *Schultz and Lanzerotti [1974]*
- *Fei et al. [2005]*



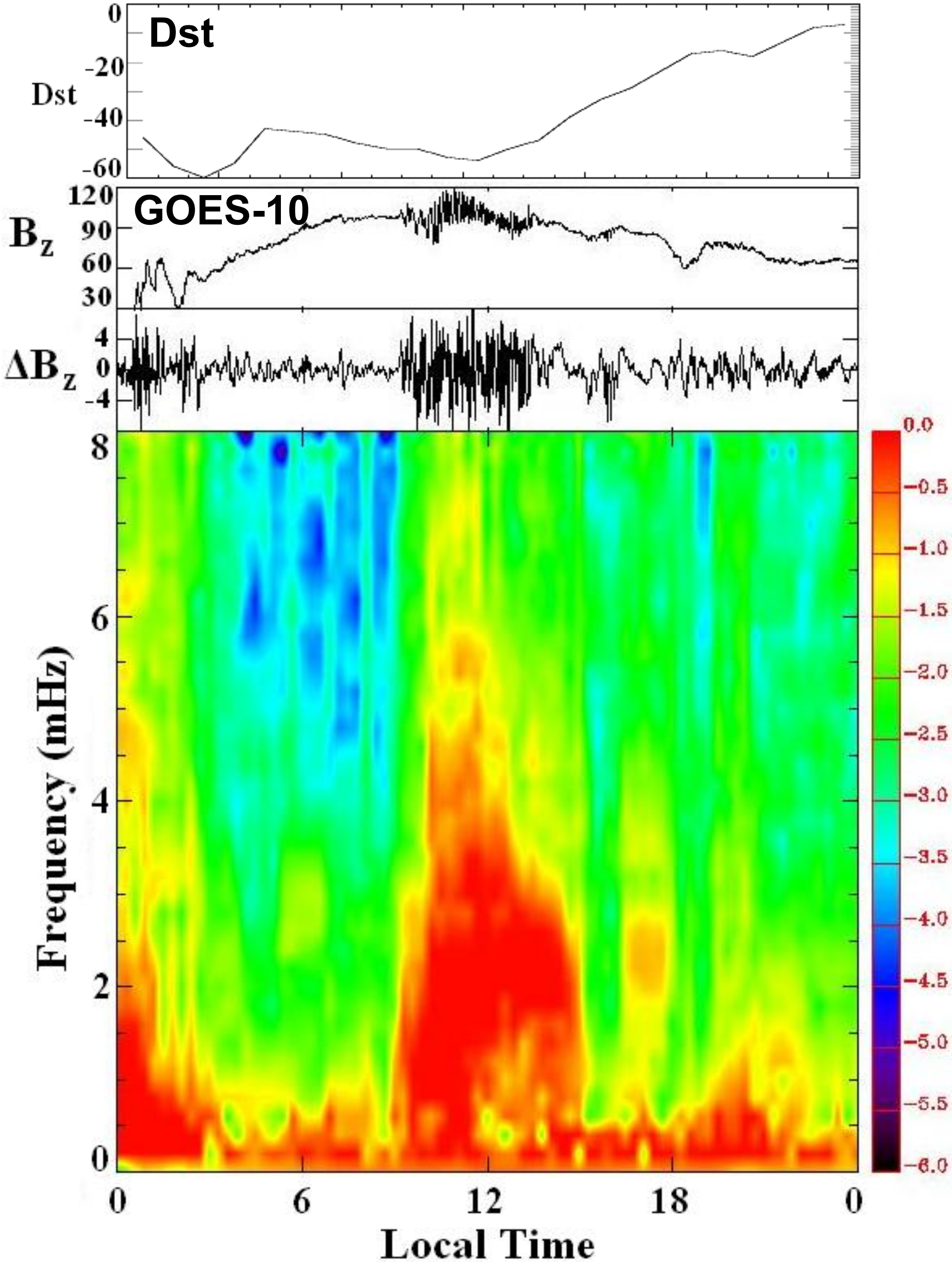
ω_d resonates with $\omega = \omega_d$



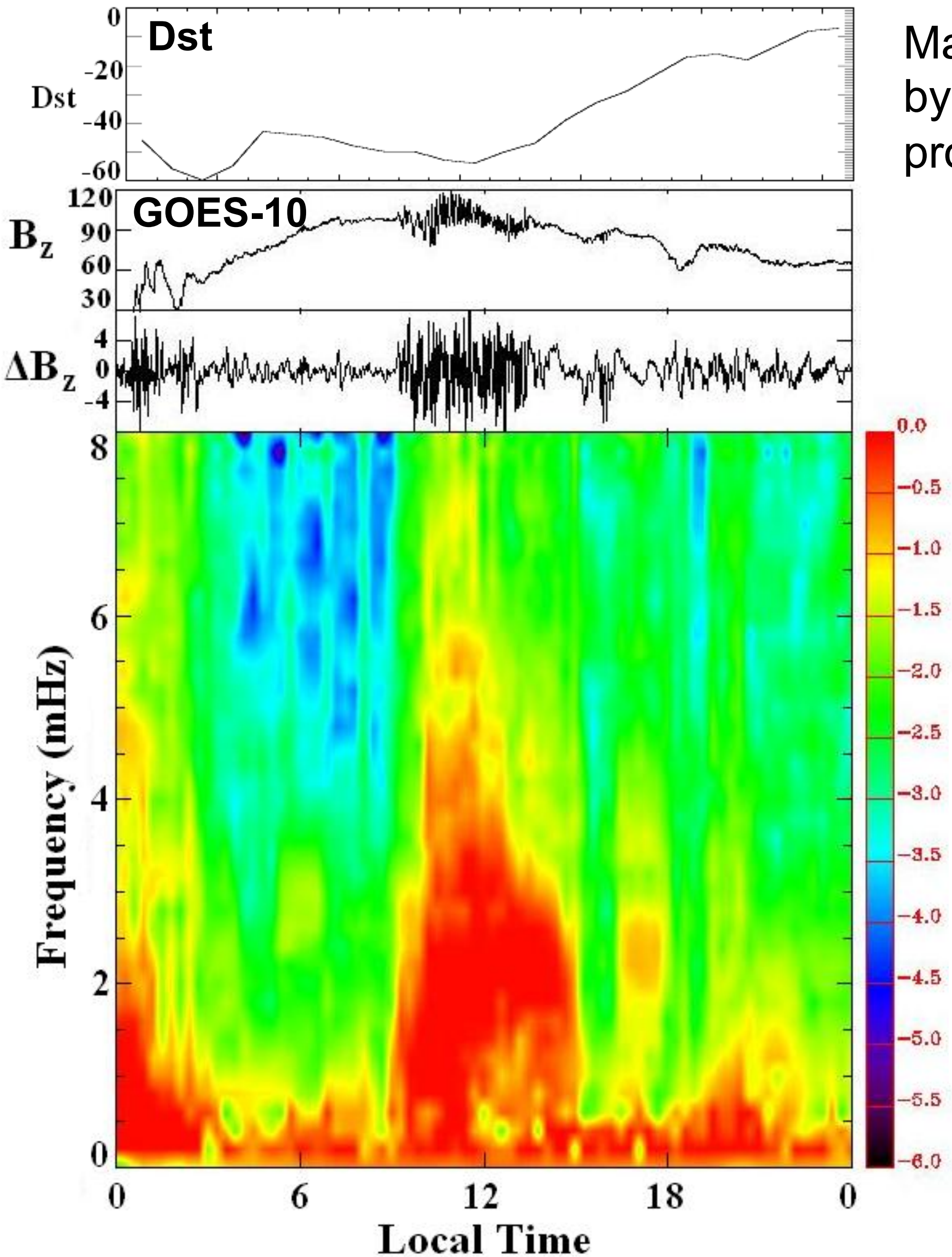
ω_d resonates with $\omega = 2\omega_d$

Measurements

Model

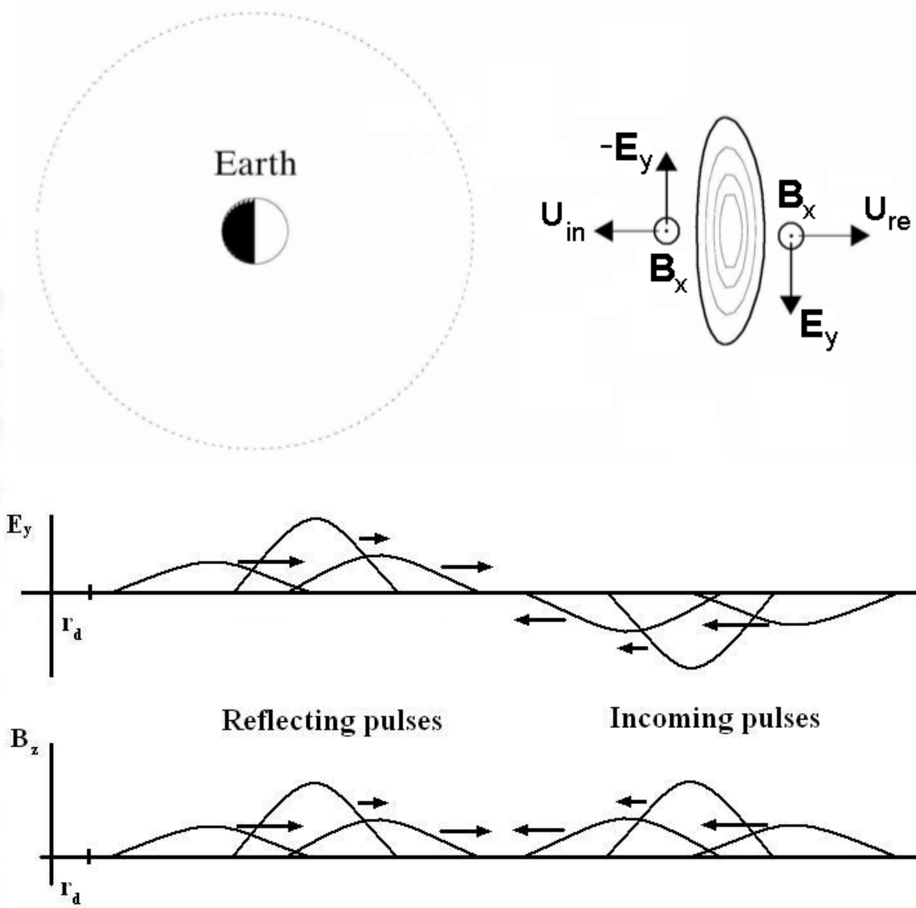


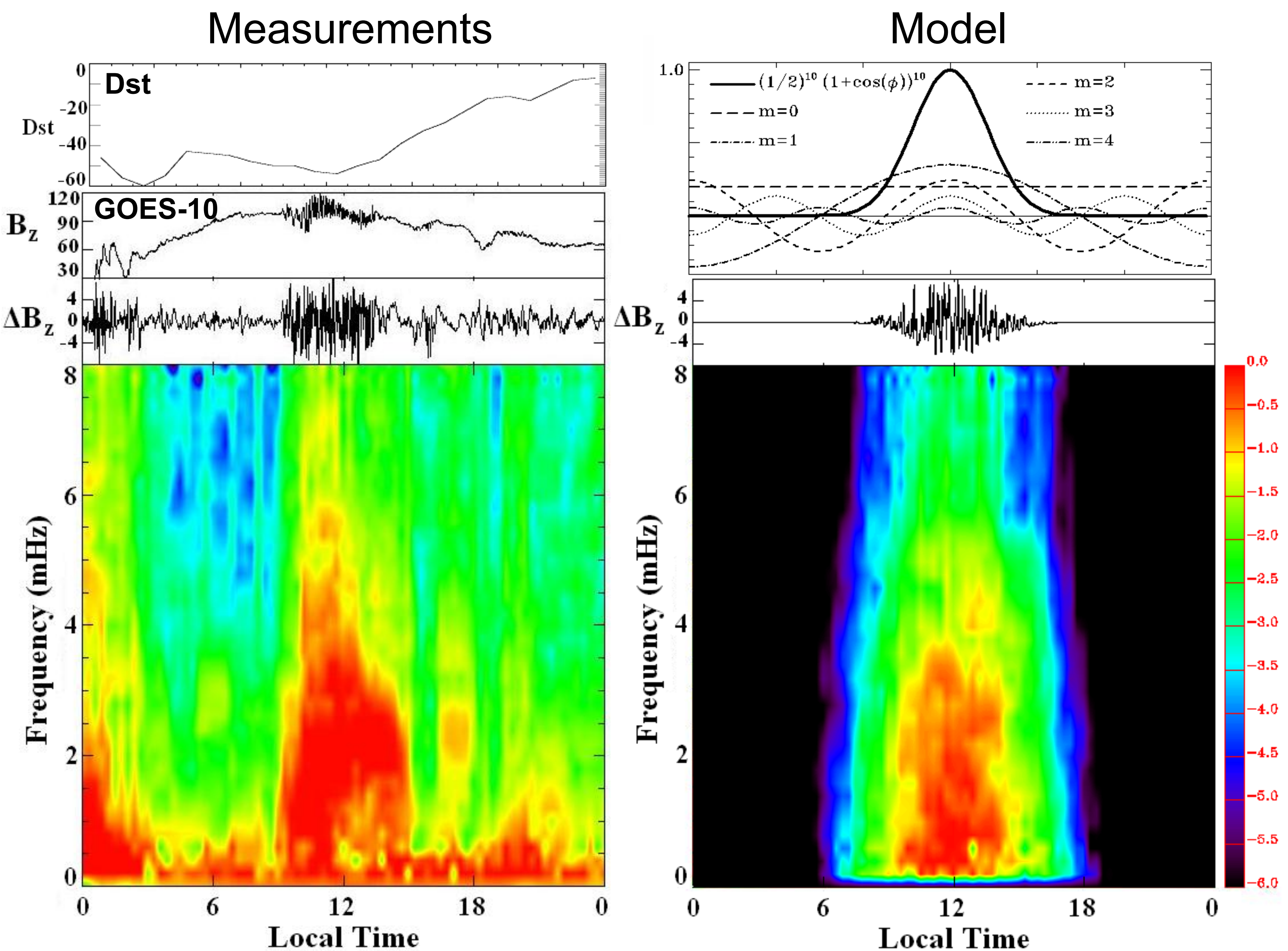
Measurements



Model

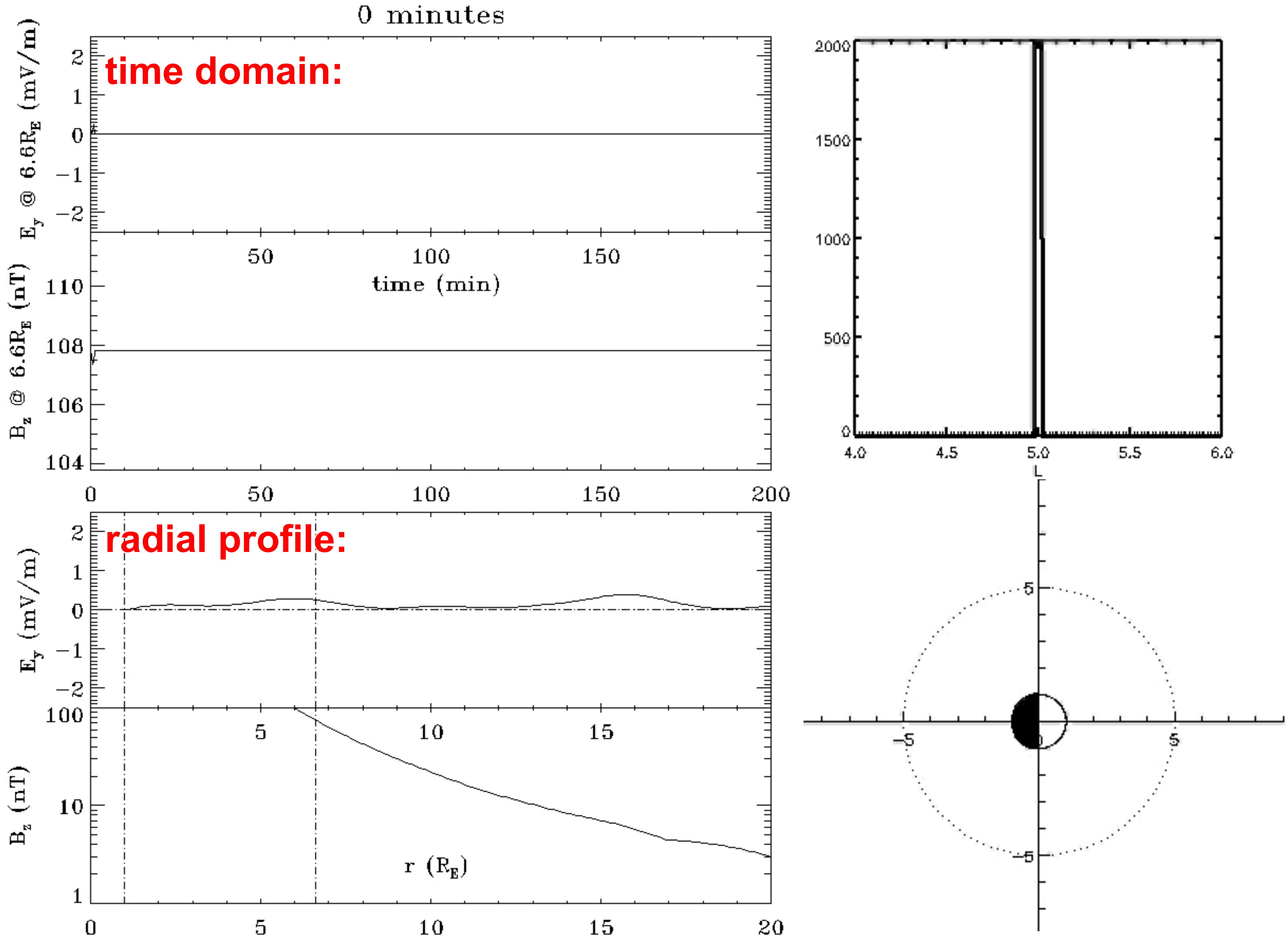
Magnetospheric ULF variability is simulated by superimposing a large number of propagating Gaussian E & M pulses.





Measurements
Model
Dst
GOES-10
B_z
ΔB_z
Frequency (mHz)
Local Time
$(1/2)^{10}\ (1+\cos(\phi))^{10}$
m=0
m=1
m=2
m=3
m=4

Simulated particle diffusion by ULF waves

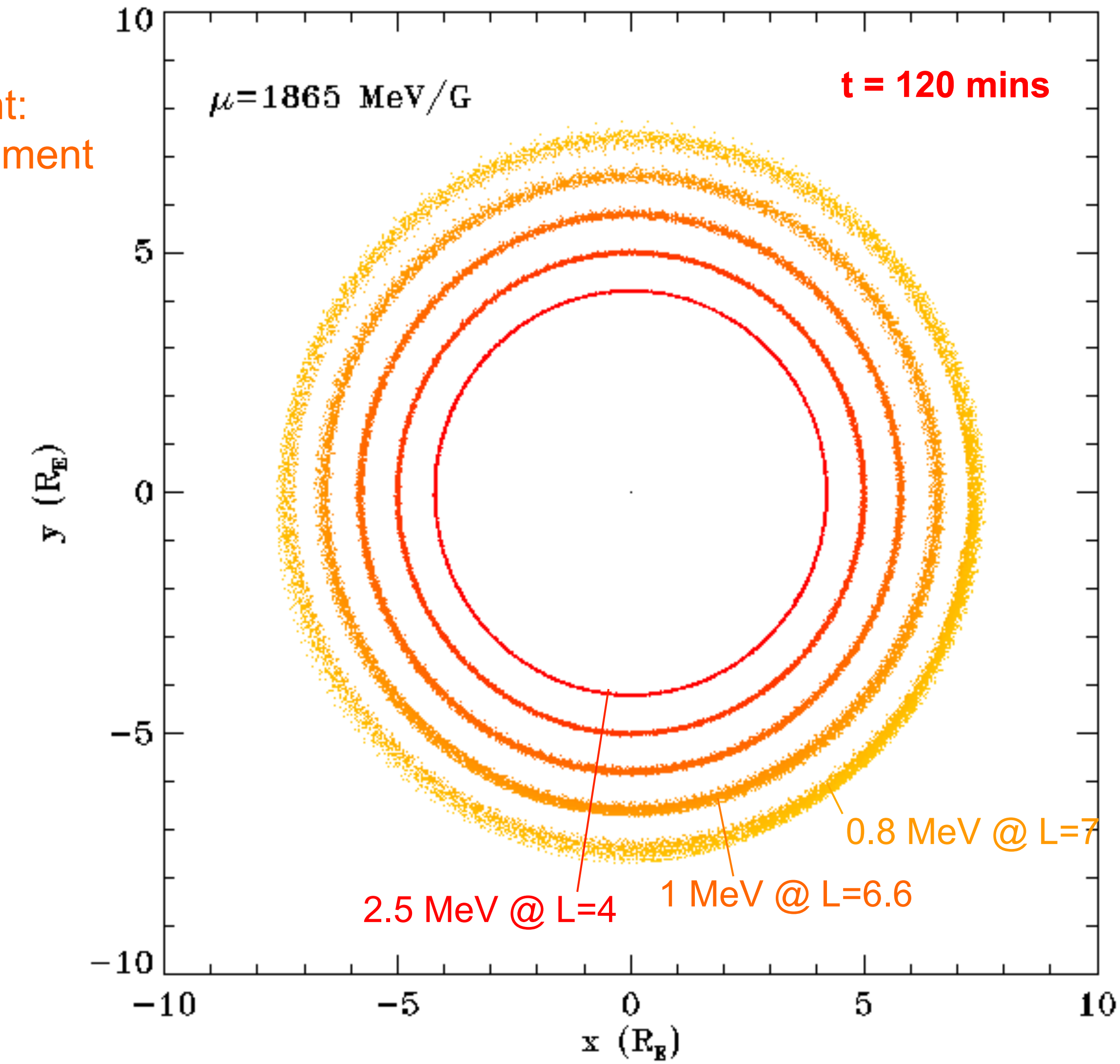


Numerical Calculation of the Diffusion Coefficient:

Definition of the diffusion coefficient:
Rate of Average Squared Displacement

$$D_{LL}^{B} = \frac{<(\Delta r)^2>}{2\tau}$$

Tracing Particle Rings:



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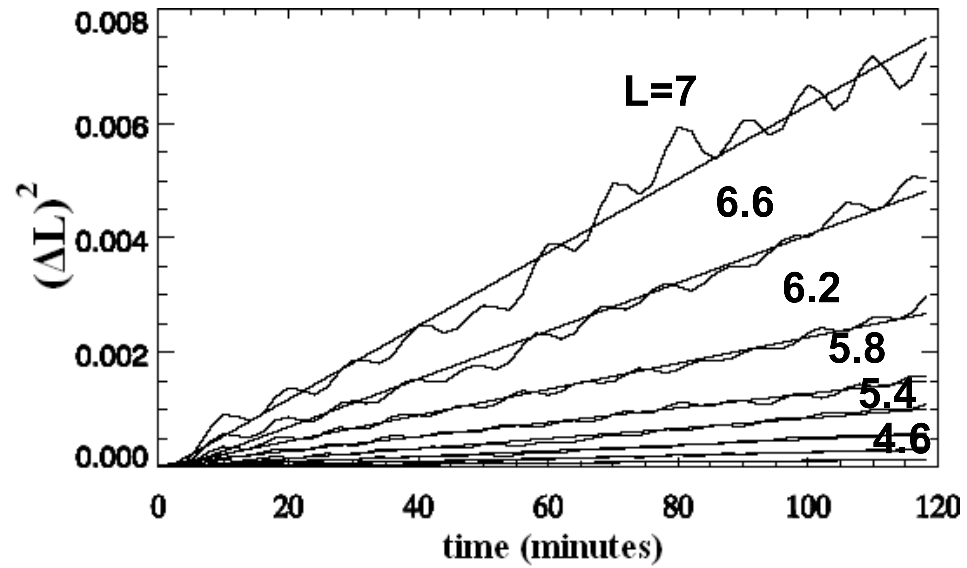

Theoretical derivation of the
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- *Falthammar [1968];*
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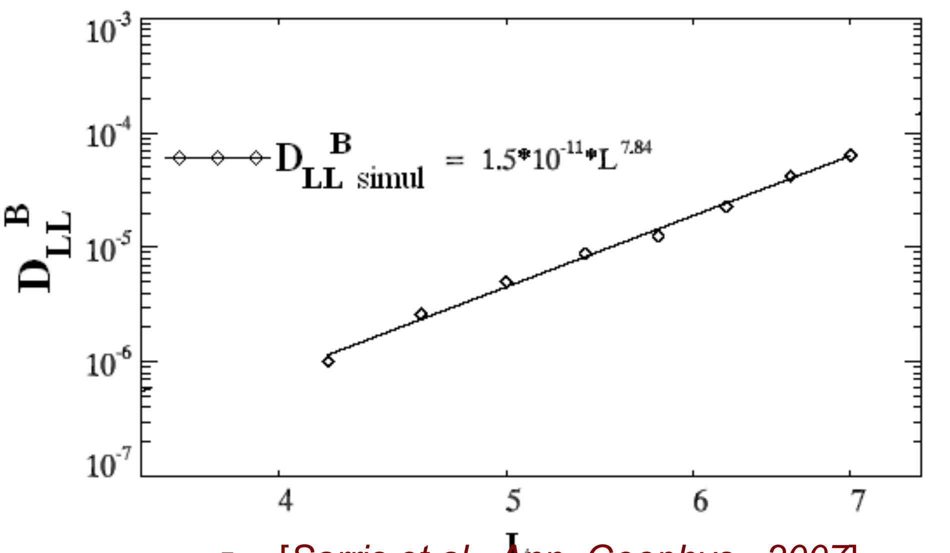


- [*Sarris et al., Ann. Geophys., 2007*]

Outline:

1) ULF Waves and radial diffusion in the magnetosphere

Drift-resonant interactions of energetic particles with ULF waves, as seen through test-particle simulations

2) ULF Waves during high-speed solar wind streams

Observations and modeling of ULF waves generated during periods with high solar wind velocity. Calculations of mode-number & wave propagation

3) ULF Waves during Solar Wind pressure perturbations

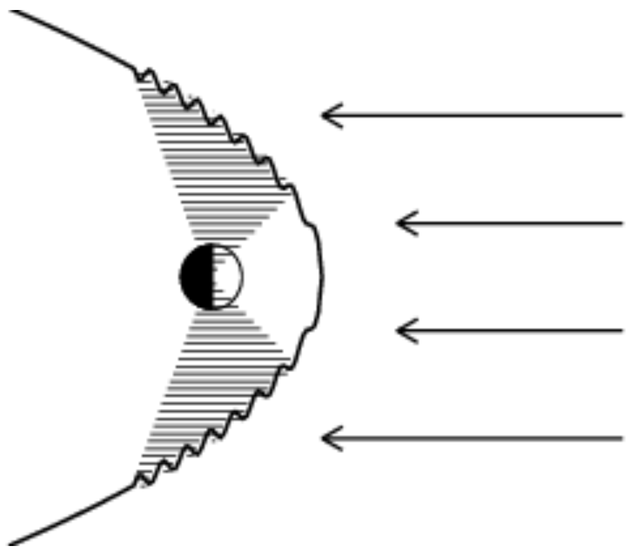
Models and observations of ULF waves generated during SW pressure pulses. Estimates of the efficiency of a density/pressure perturbation to create ULF waves.

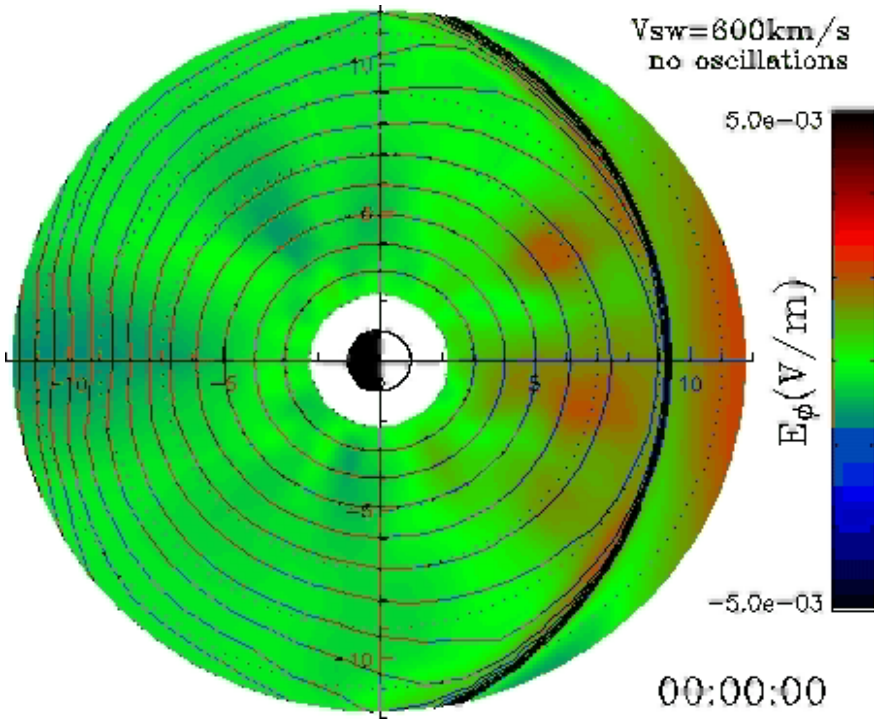
4) A Statistical Study of the Solar Wind influence on ULF waves:

We use simultaneous E & B-field measurements from THEMIS to statistically study the correlation between ULF wave power and various solar wind parameters, such as velocity, dynamic pressure and the variation in dynamic pressure.

ULF Waves during high-speed solar wind streams

- MHD model (LFM) is driven with high solar wind velocity 600 km/s.
- Constant dynamic pressure





Scot Elkington, LASP/CU

- Shear instabilities of Kelvin-Helmholtz type develop in the magnetosphere flanks
- ULF waves develop along flanks and propagate tailward and inward

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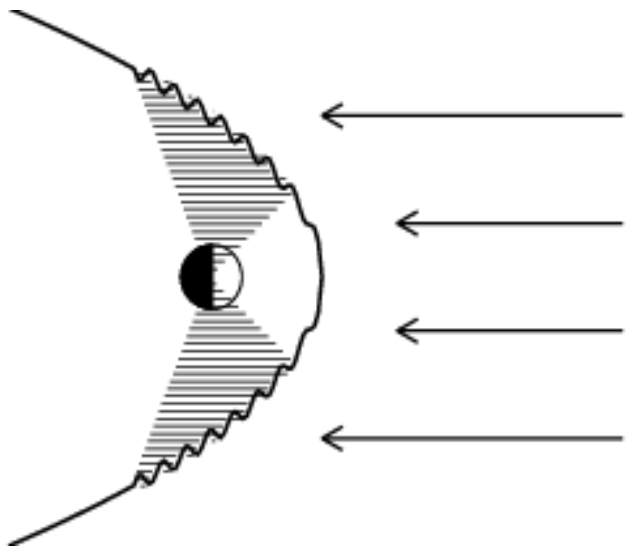

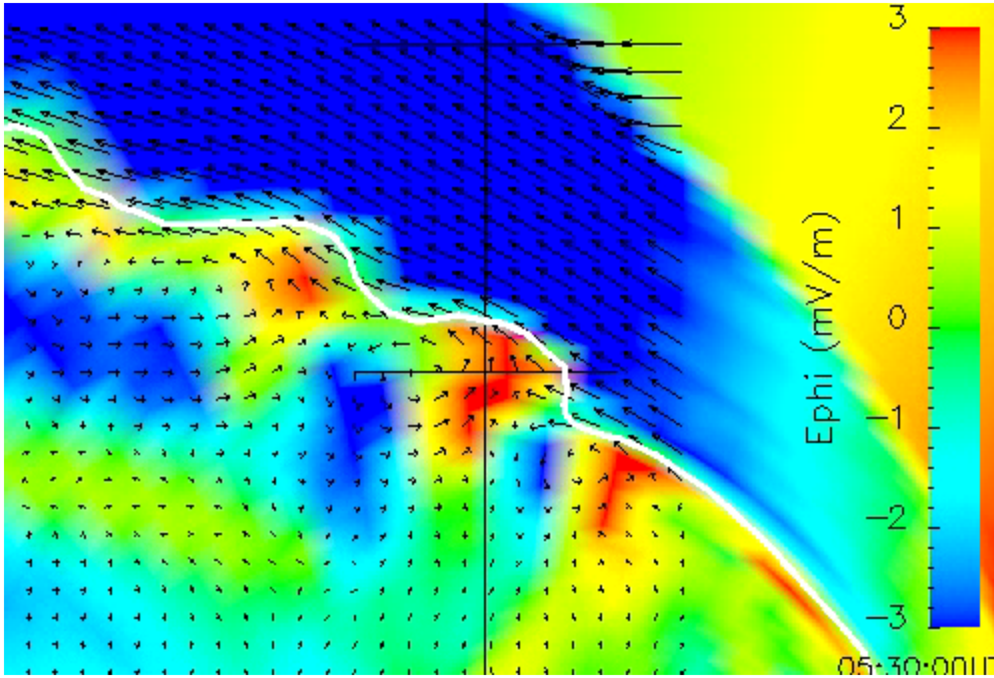

Seth Claudepierre, LASP/CU

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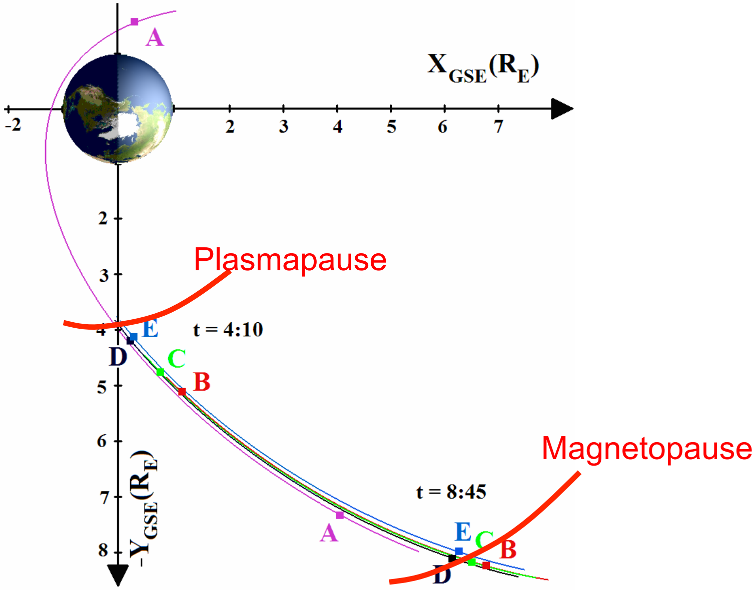
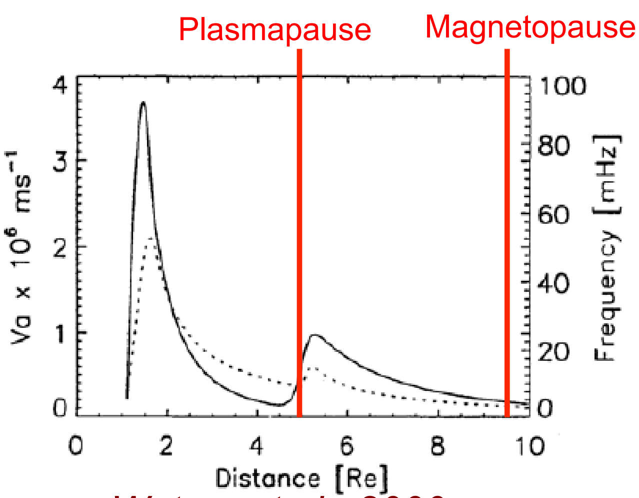
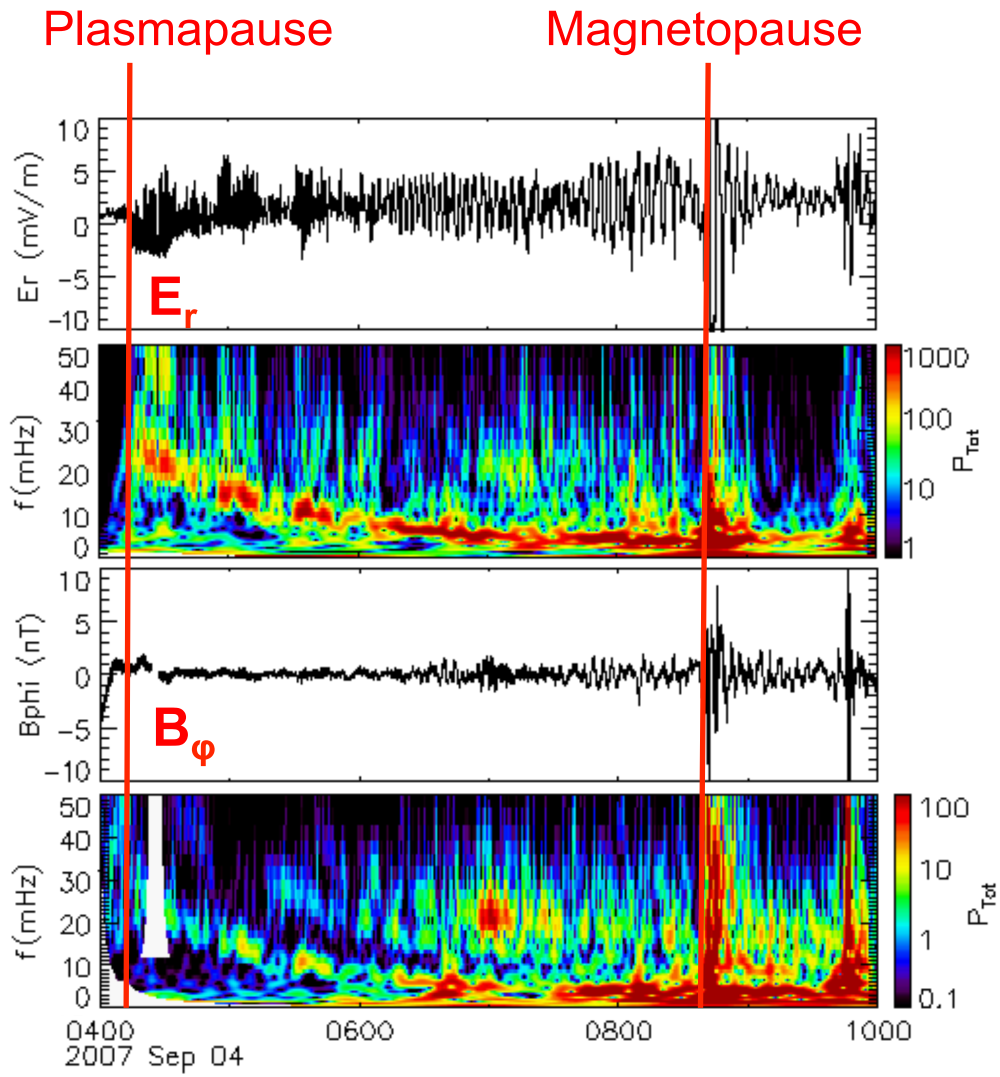
ULF Waves during high-speed solar wind streams

- THEMIS spacecraft multipoint observations:





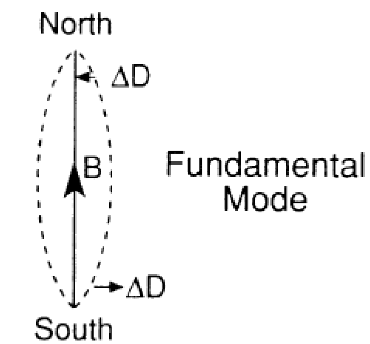
- *Waters et al., 2000*

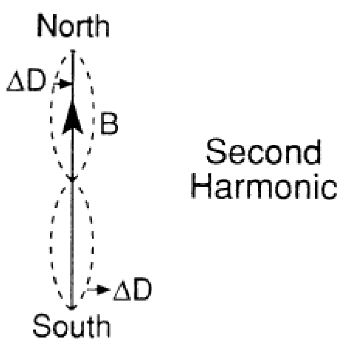


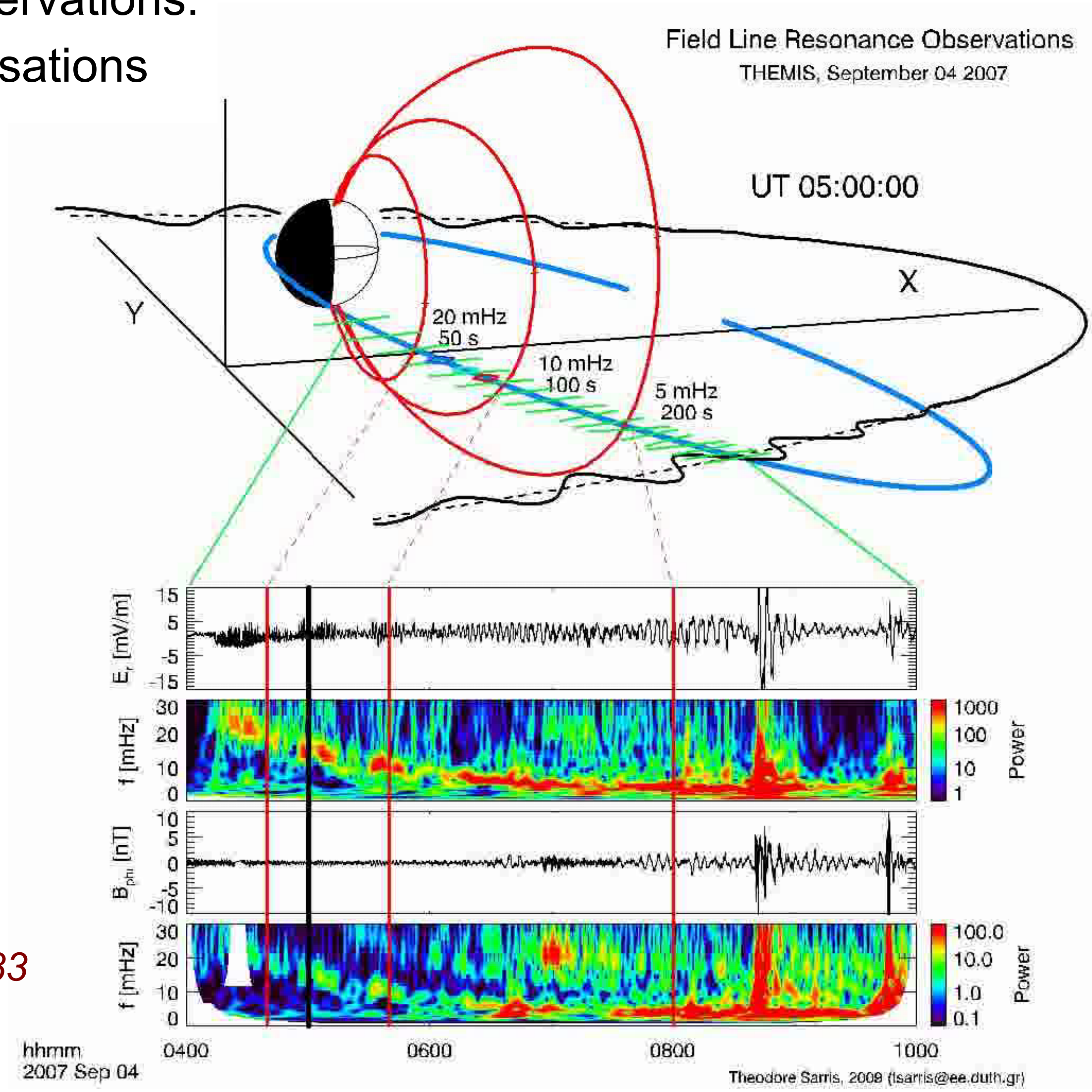
- *Sarris et al., GRL, 2009 (GRL Highlight)*

ULF Waves during high-speed solar wind streams

- THEMIS spacecraft multipoint observations:
- Fundamental mode of Toroidal Pulsations





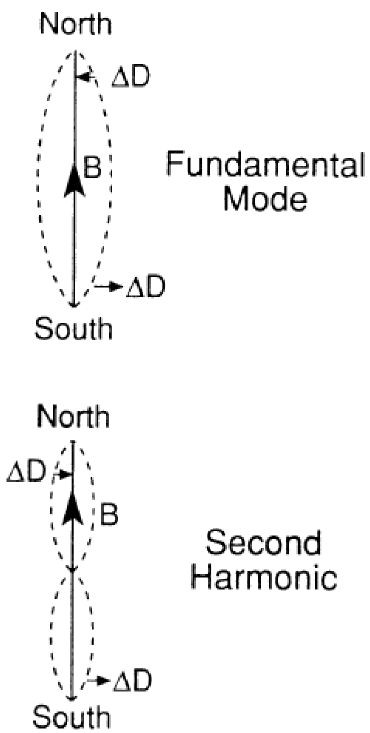


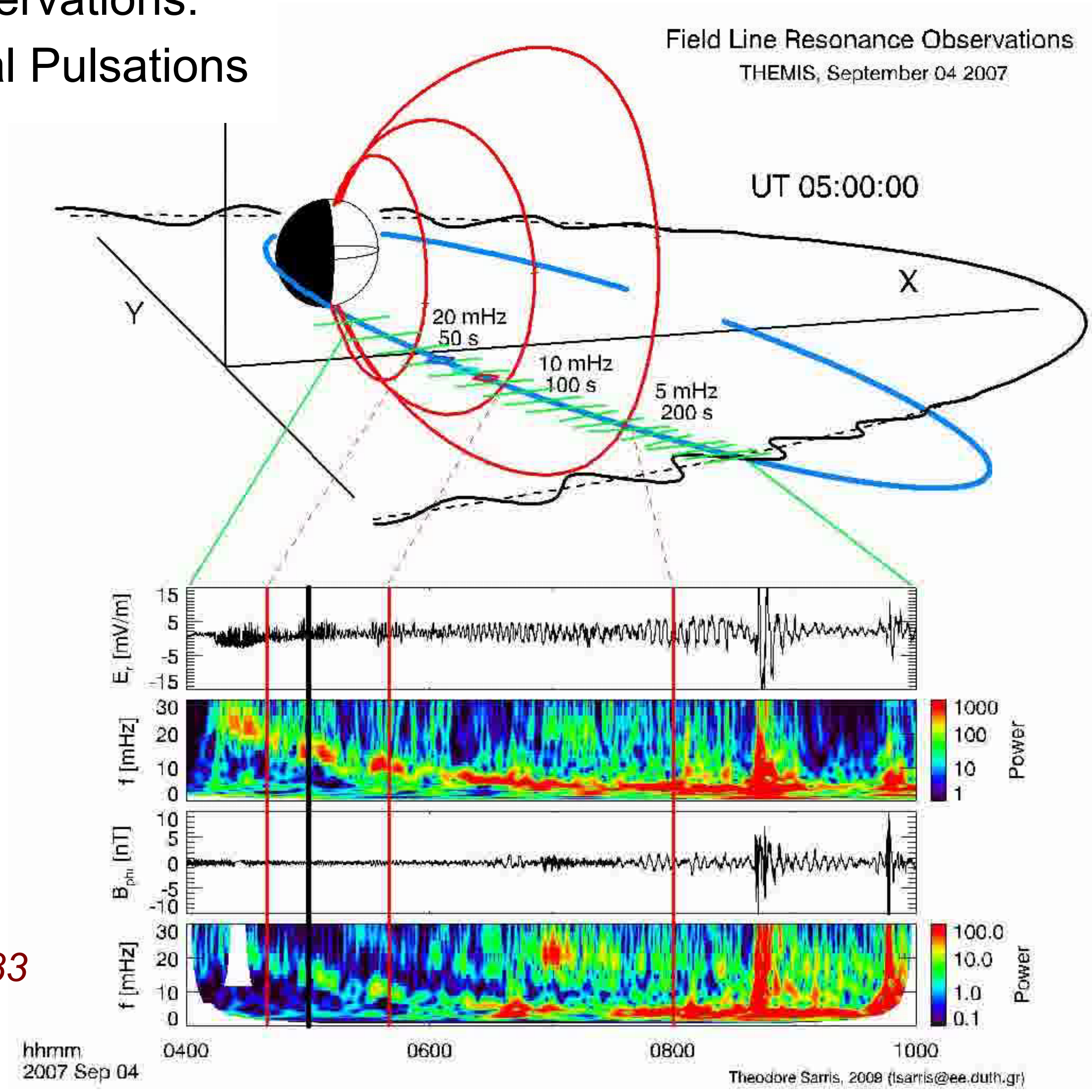
- *Southwood & Hughes, Space Sci Rev,1983*
- *Hudson et al., Ann. Geophys., 2004*

- *Sarris et al., GRL, 2009 (GRL Highlight)*

ULF Waves during high-speed solar wind streams

- THEMIS spacecraft multipoint observations:
- Second Harmonic mode of Toroidal Pulsations



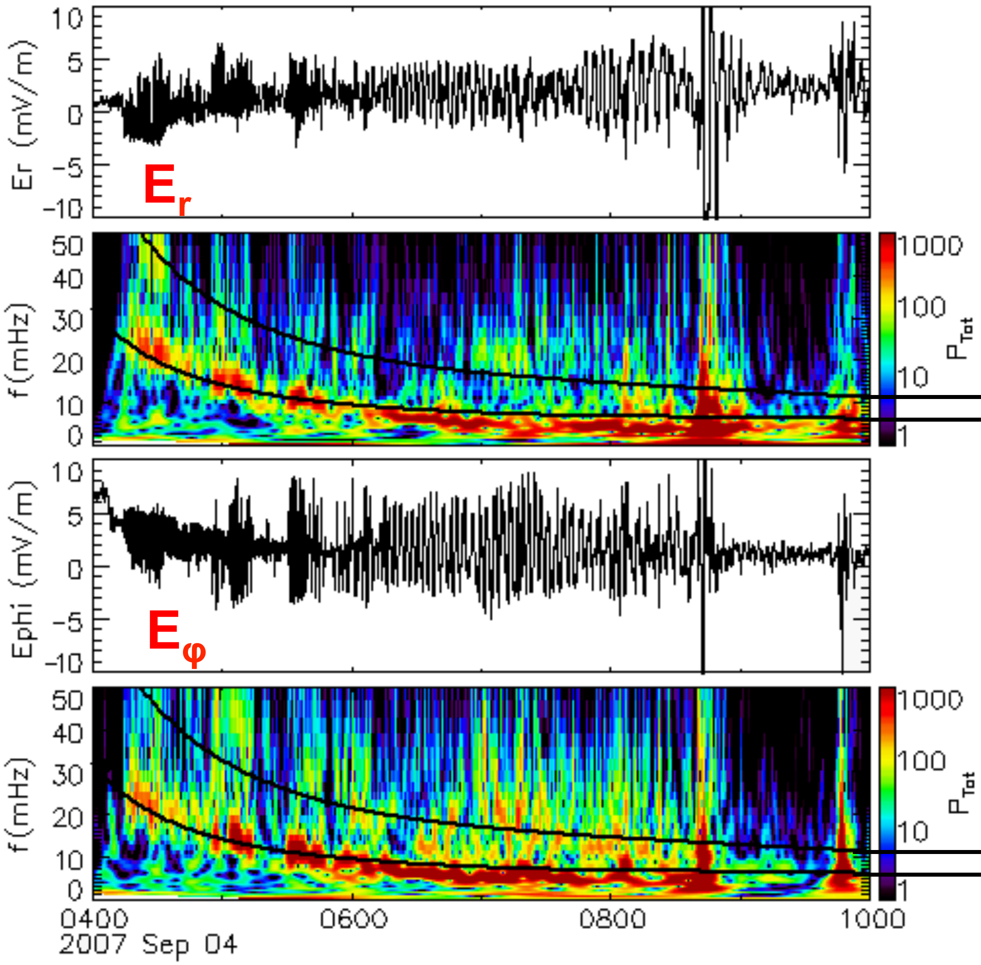


- *Southwood & Hughes, Space Sci Rev,1983*
- *Hudson et al., Ann. Geophys., 2004*

- *Sarris et al., GRL, 2009 (GRL Highlight)*

ULF Waves during high-speed solar wind streams

- Comparison to model of Rankin et al. (2007):



Black lines: toroidal mode
(prediction, model of Rankin et al, 2007)

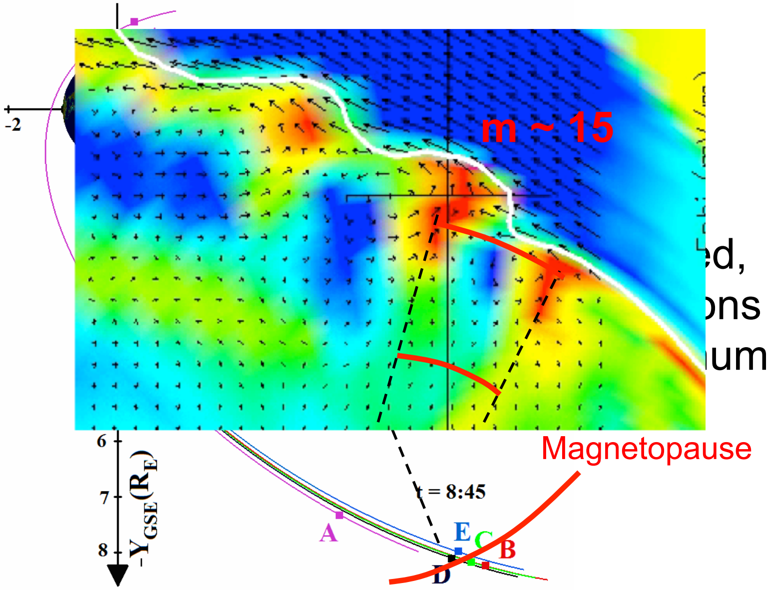
Model 2nd harmonic mode
Model fundamental mode

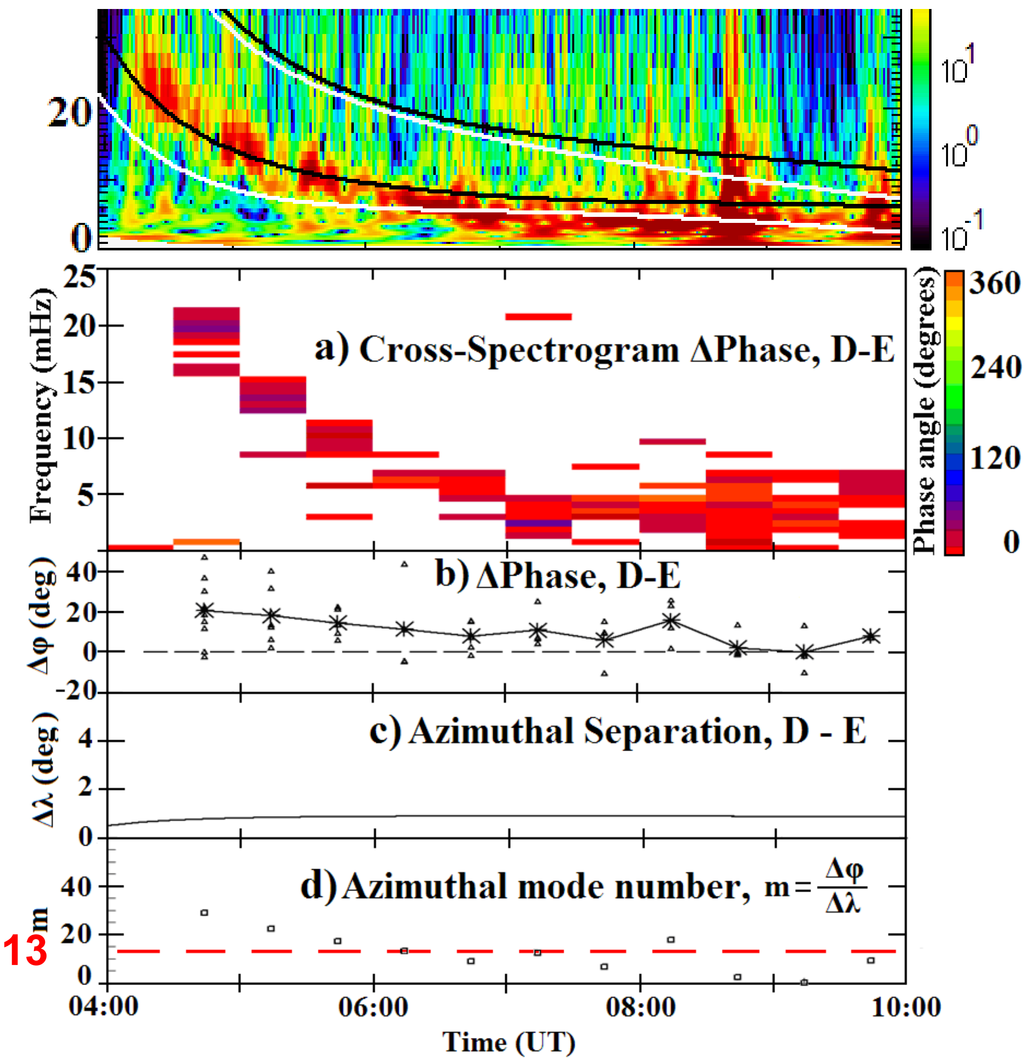
Model 2nd harmonic mode
Model fundamental mode

➢ Comparison to *Rankin et al. (2007)* model confirms model predictions of resonant frequencies

ULF Waves during high-speed solar wind streams

- Phase difference and Mode number calculation:



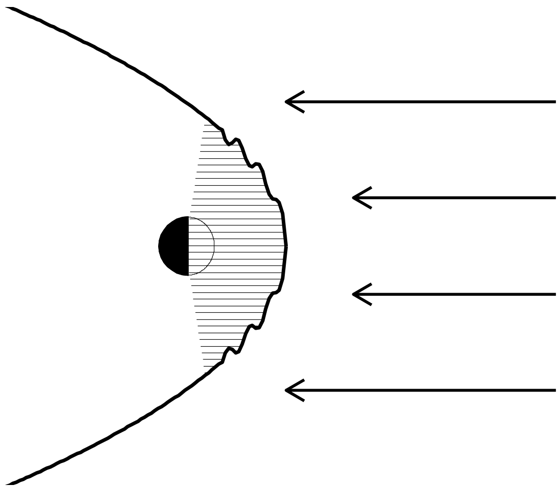


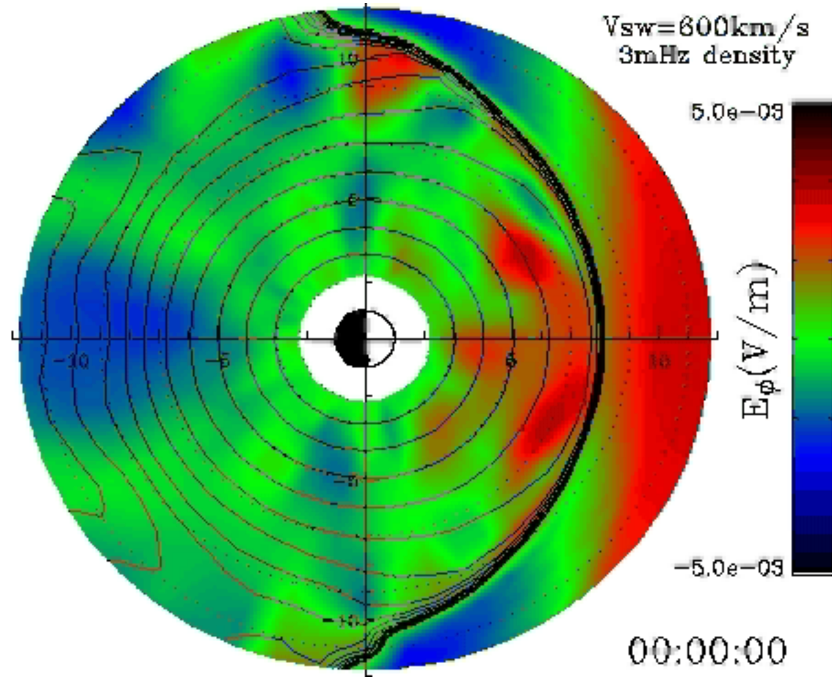
- ULF waves with mode numbers of order of 10-20 have been related to Kelvin-Helmholtz instability at the magnetopause flanks *(Claudepiere et al, 2009)*

- *Sarris et al., GRL 2008GL036732*

ULF Waves during Solar Wind pressure perturbations

- MHD model (LFM) is driven with solar wind density / dynamic pressure variations:
- Constant solar wind speed



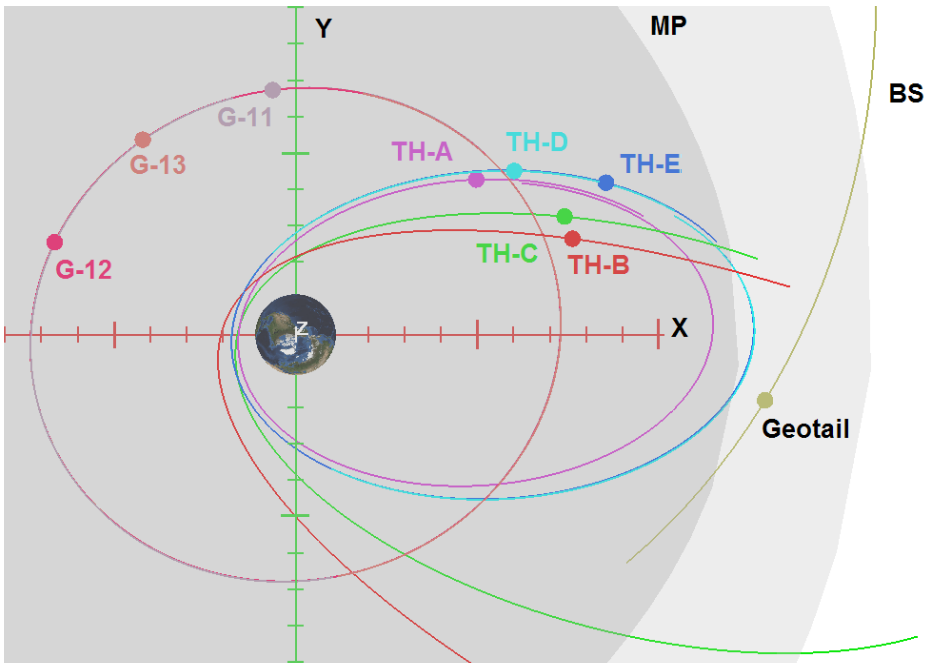


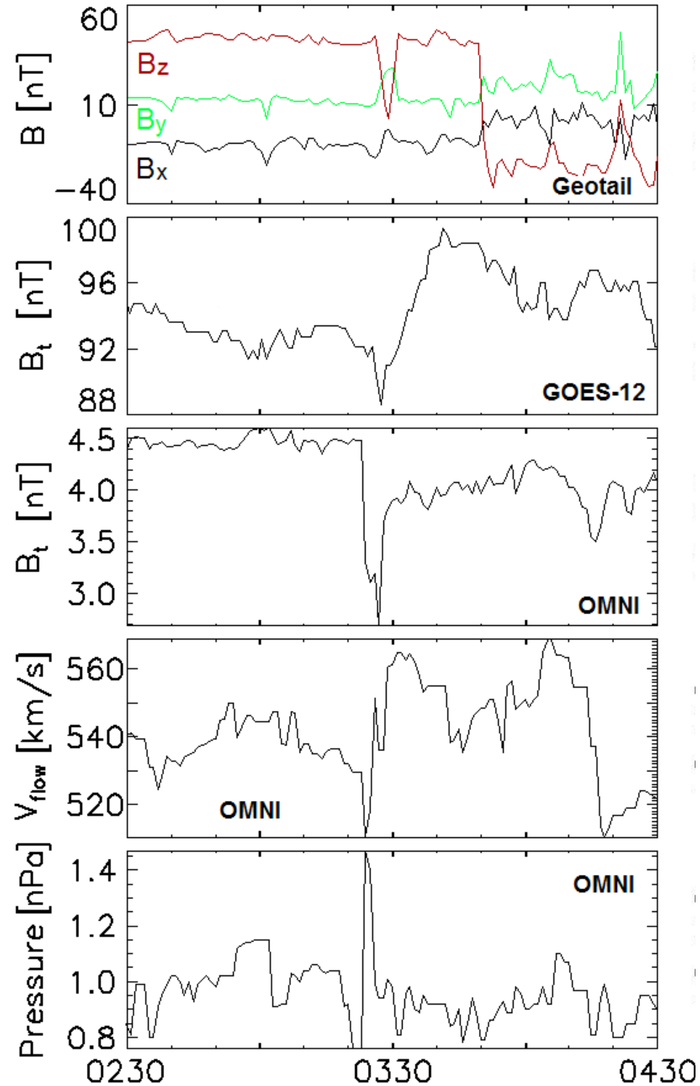
Scot Elkington, LASP/CU

- Compressional perturbations develop in the dayside magnetopause
- ULF waves propagate inside the magnetosphere

ULF Waves during Solar Wind pressure perturbations

- Observation of a Solar Wind Pressure Pulse propagating to the magnetosphere:





- *Sarris et al., GRL, 2010GL044125*

ULF Waves during Solar Wind pressure perturbations

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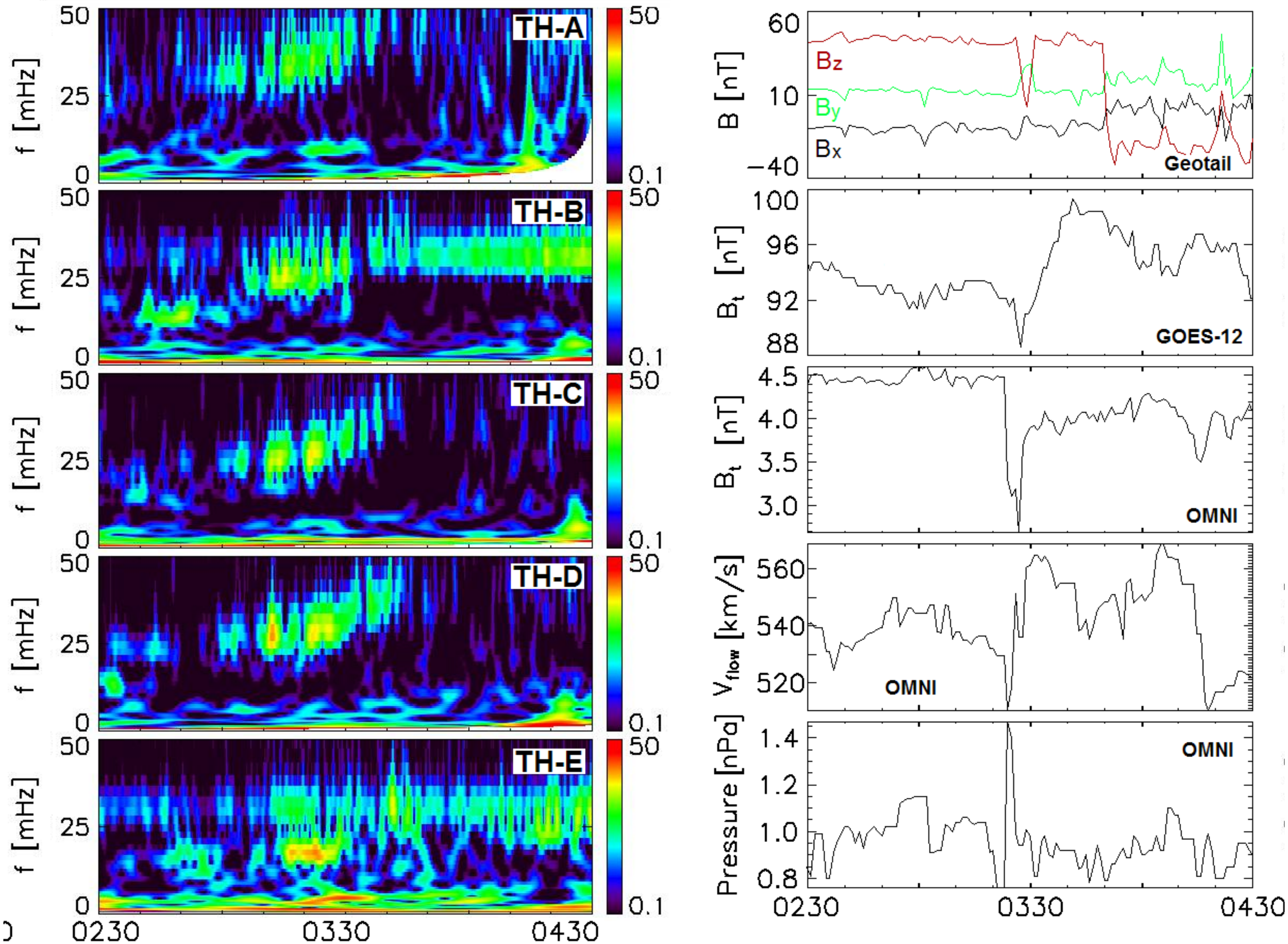

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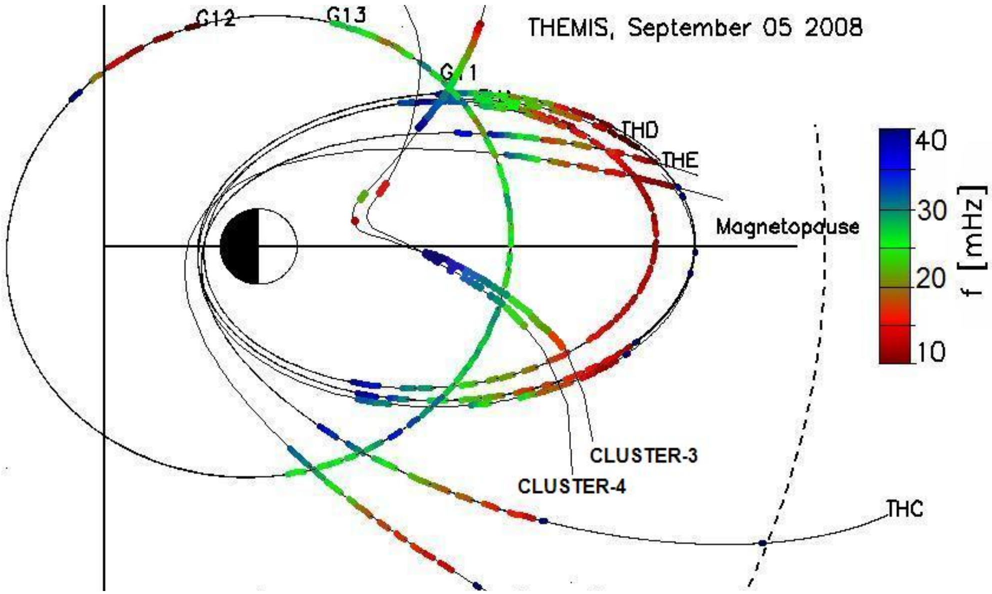
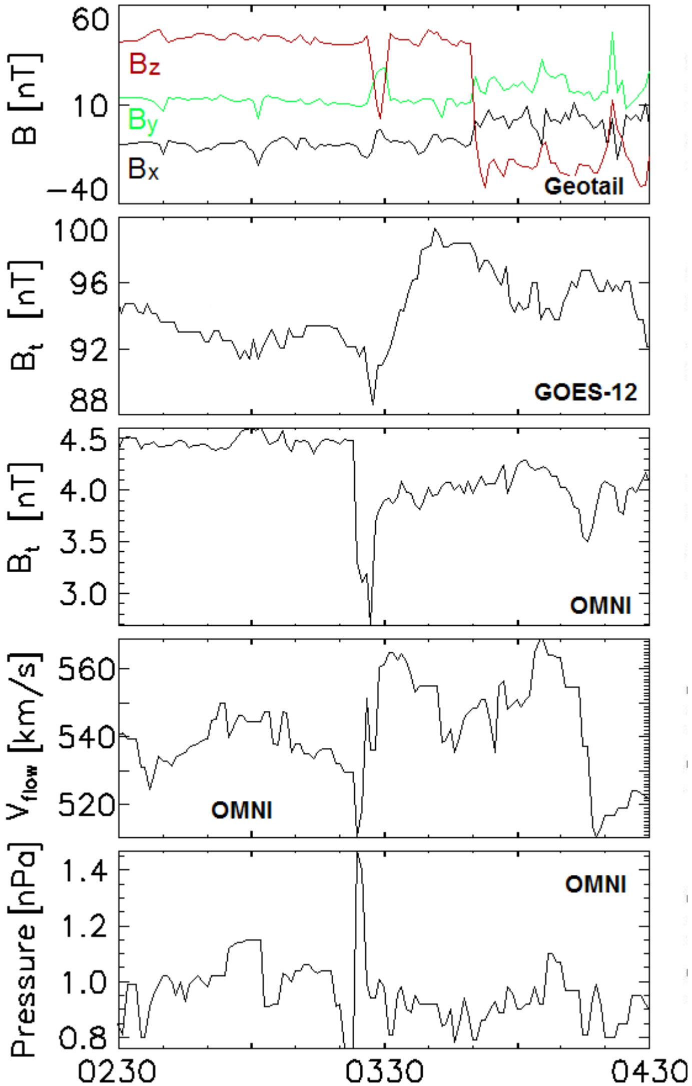
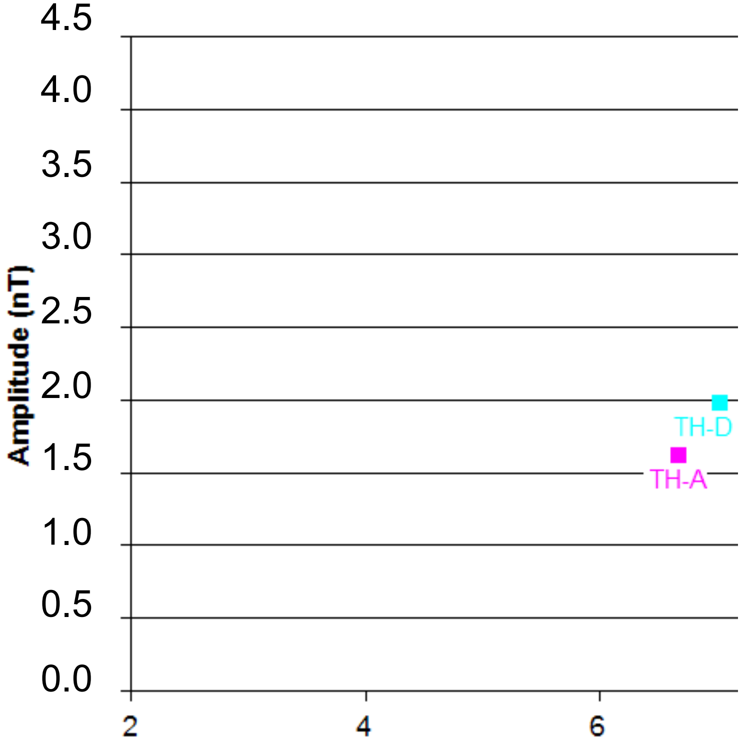
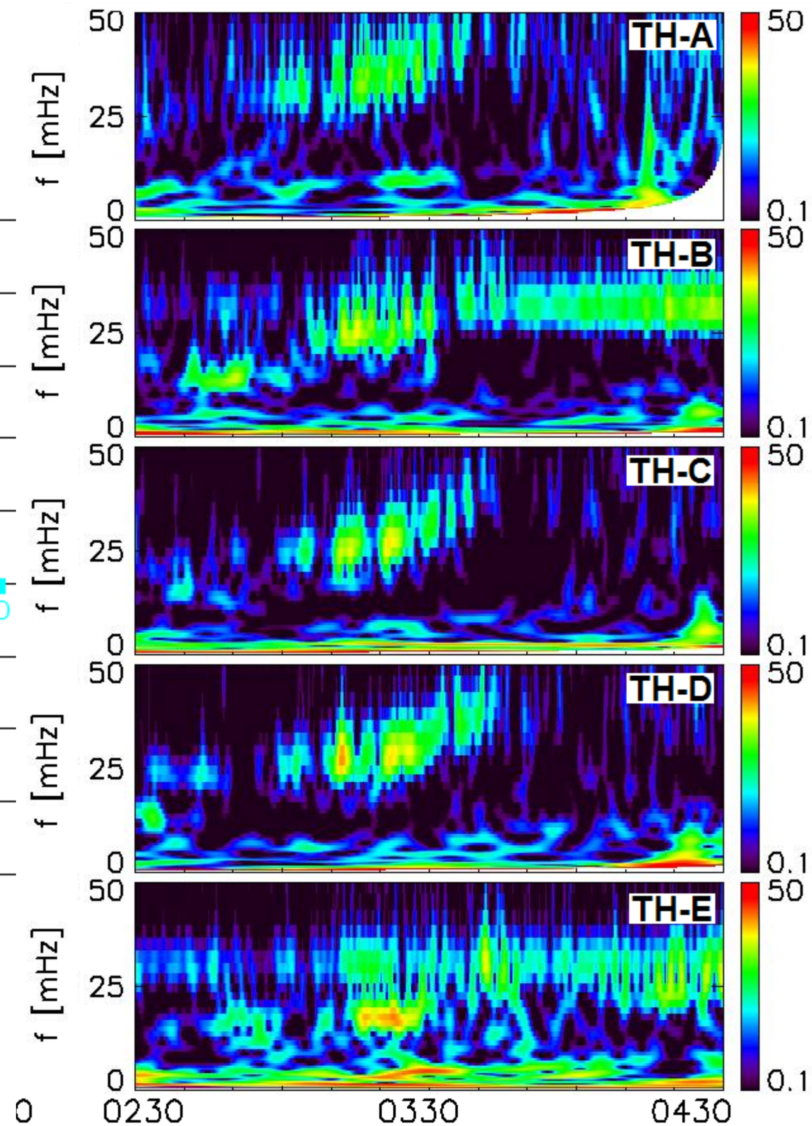




- *Sarris et al., GRL, 2010GL044125*

ULF Waves during Solar Wind pressure perturbations

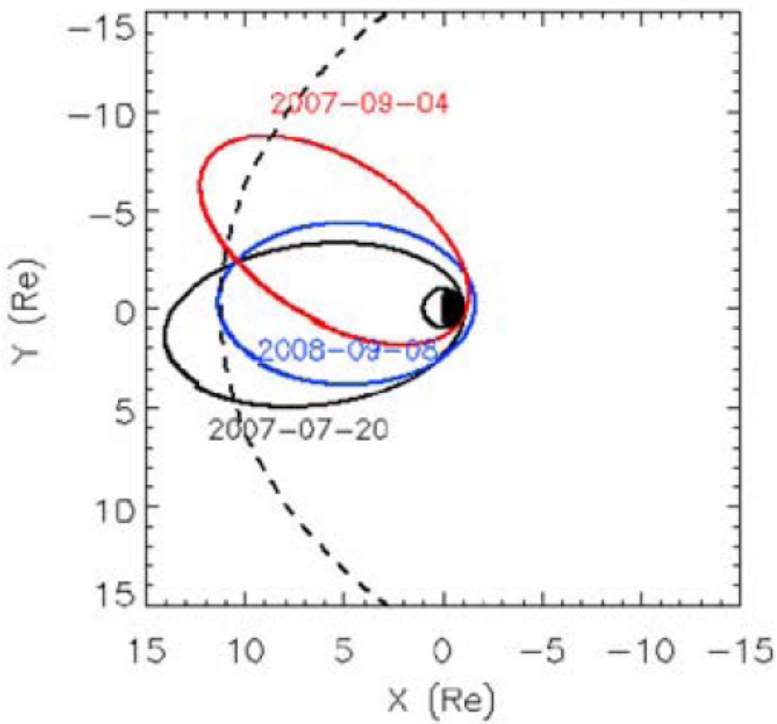




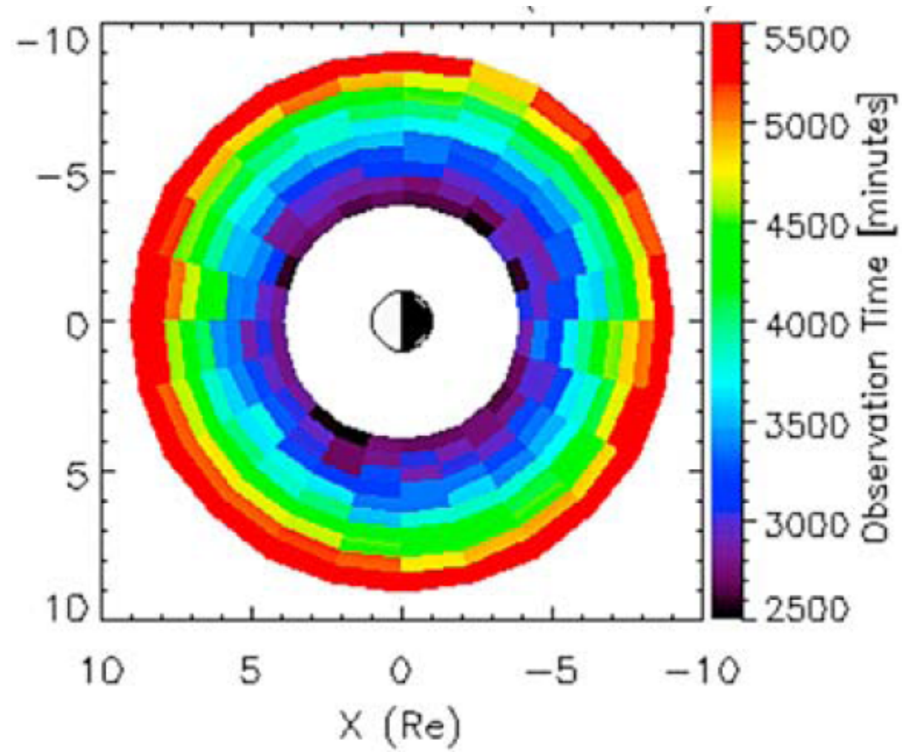
A Statistical Study of the Solar Wind influence on ULF waves

- Observations of ULF Waves using THEMIS: Observation Time

Sample THEMIS Orbits



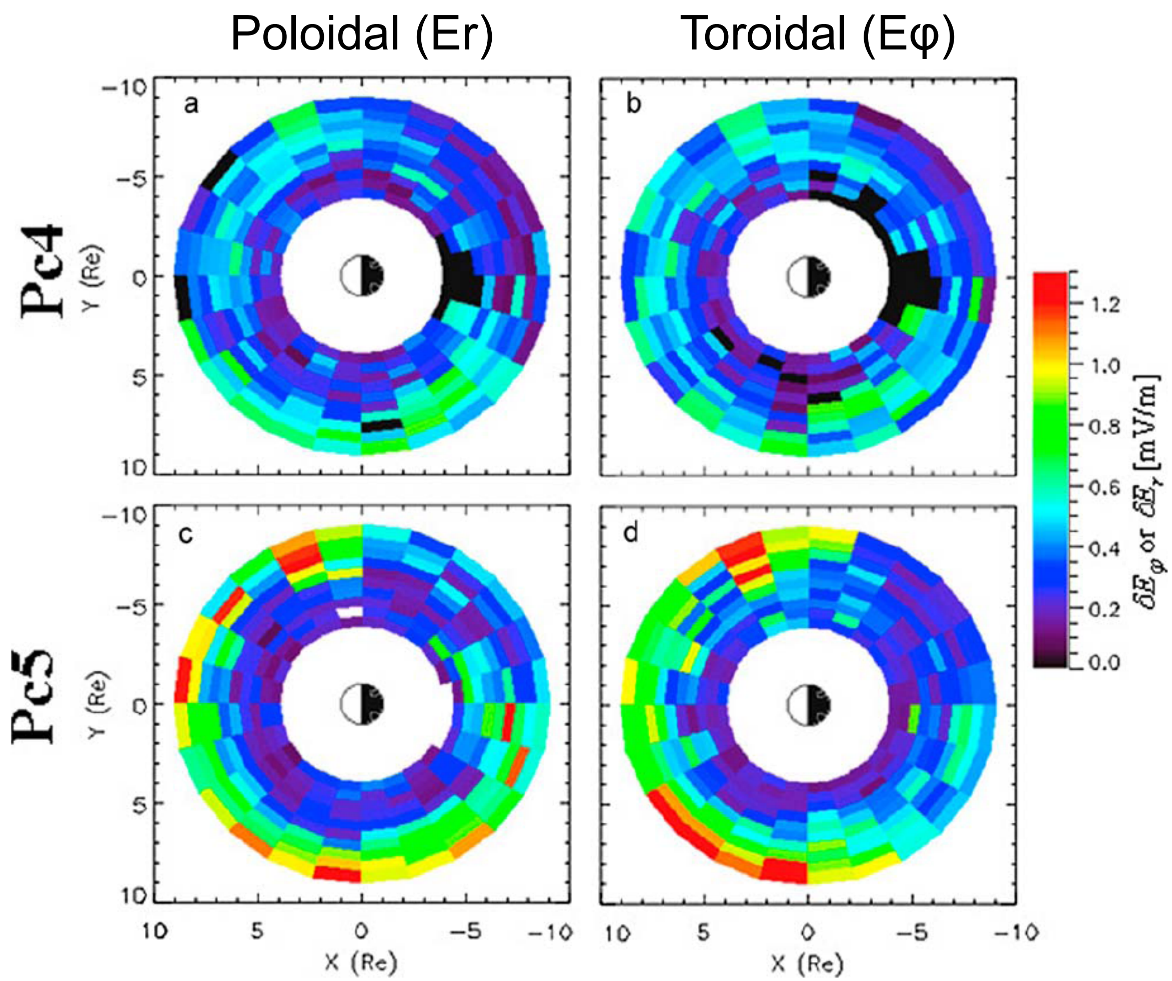
Total THEMIS Observation Time



- *Liu, Sarris, et al., Statistical Study on ULF Waves, JGR, 2009JA014243*

A Statistical Study of the Solar Wind influence on ULF waves

- Observations of ULF Waves using THEMIS: Distribution of Wave Power



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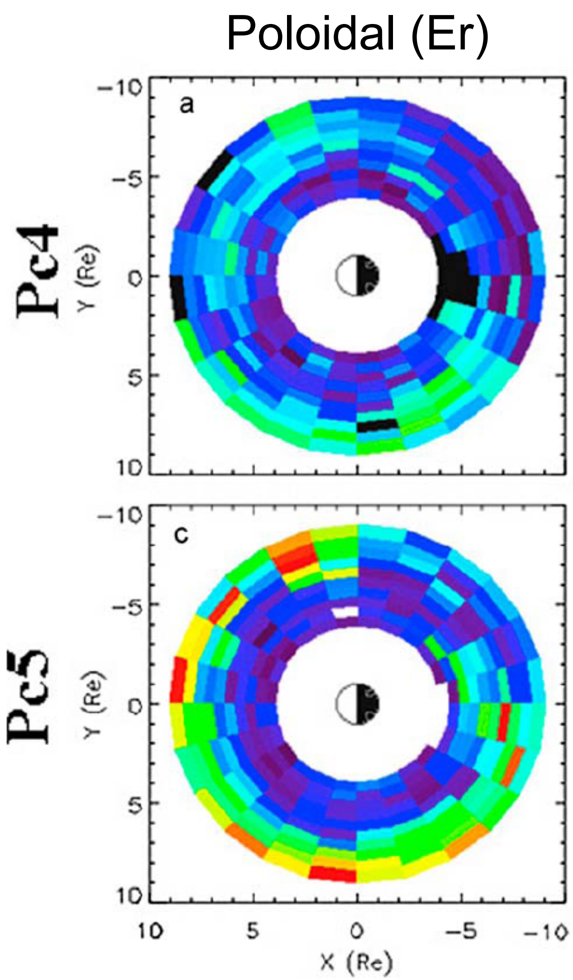

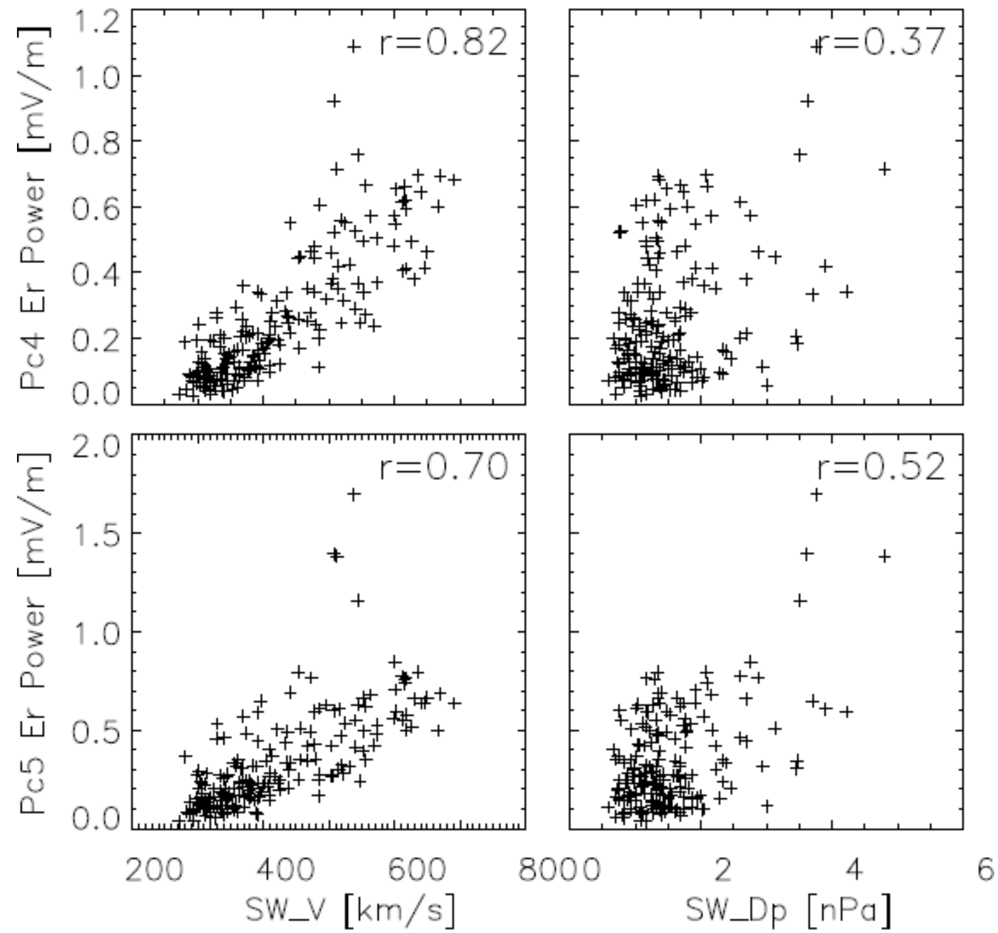

- *Liu, Sarris, et al., Statistical Study on ULF Waves, JGR, 2009JA014243*
- *Liu, Sarris, et al., SW influence on Pc4 & Pc5 ULF wave activity, JGR, 2010JA015299*

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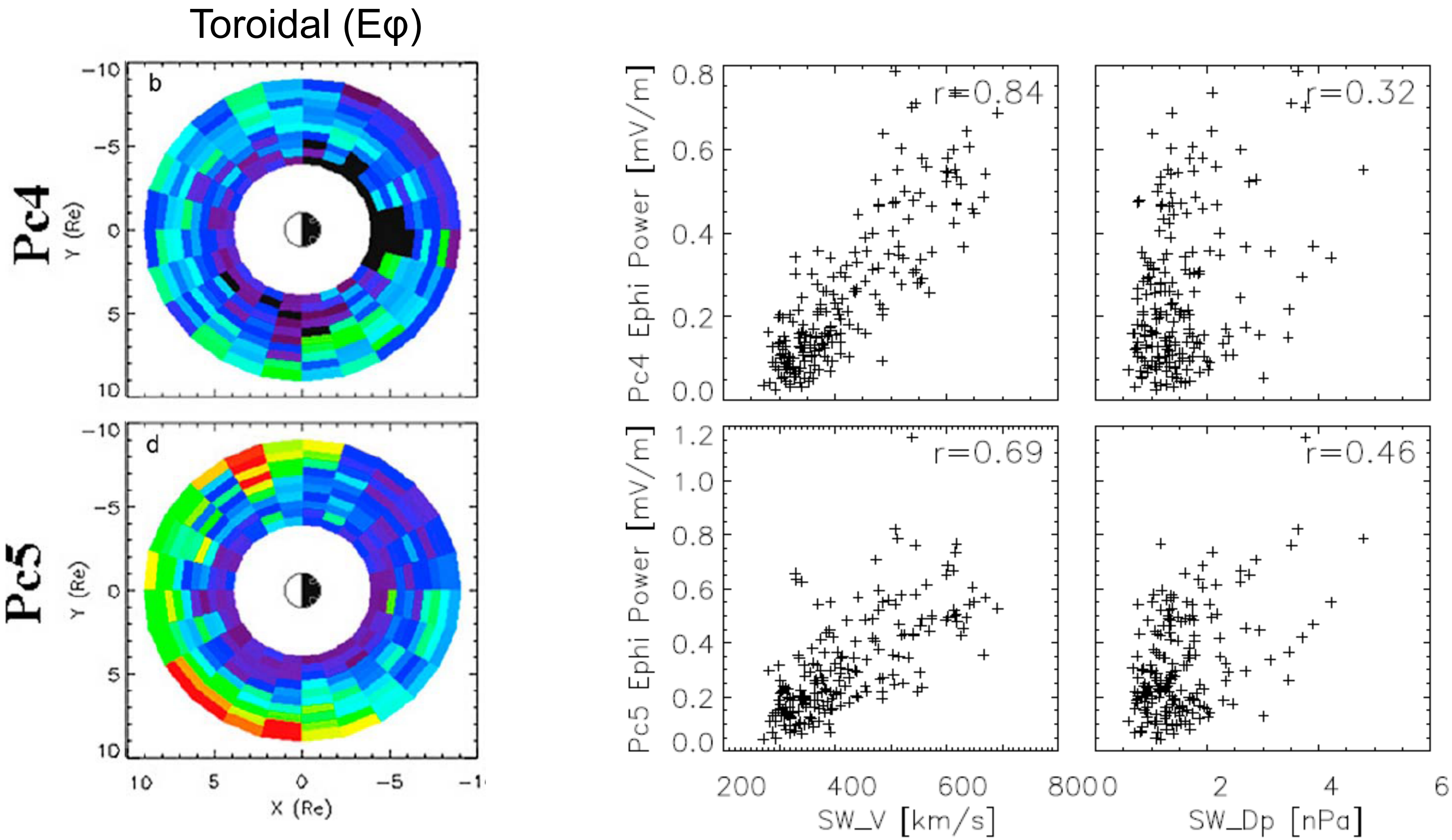

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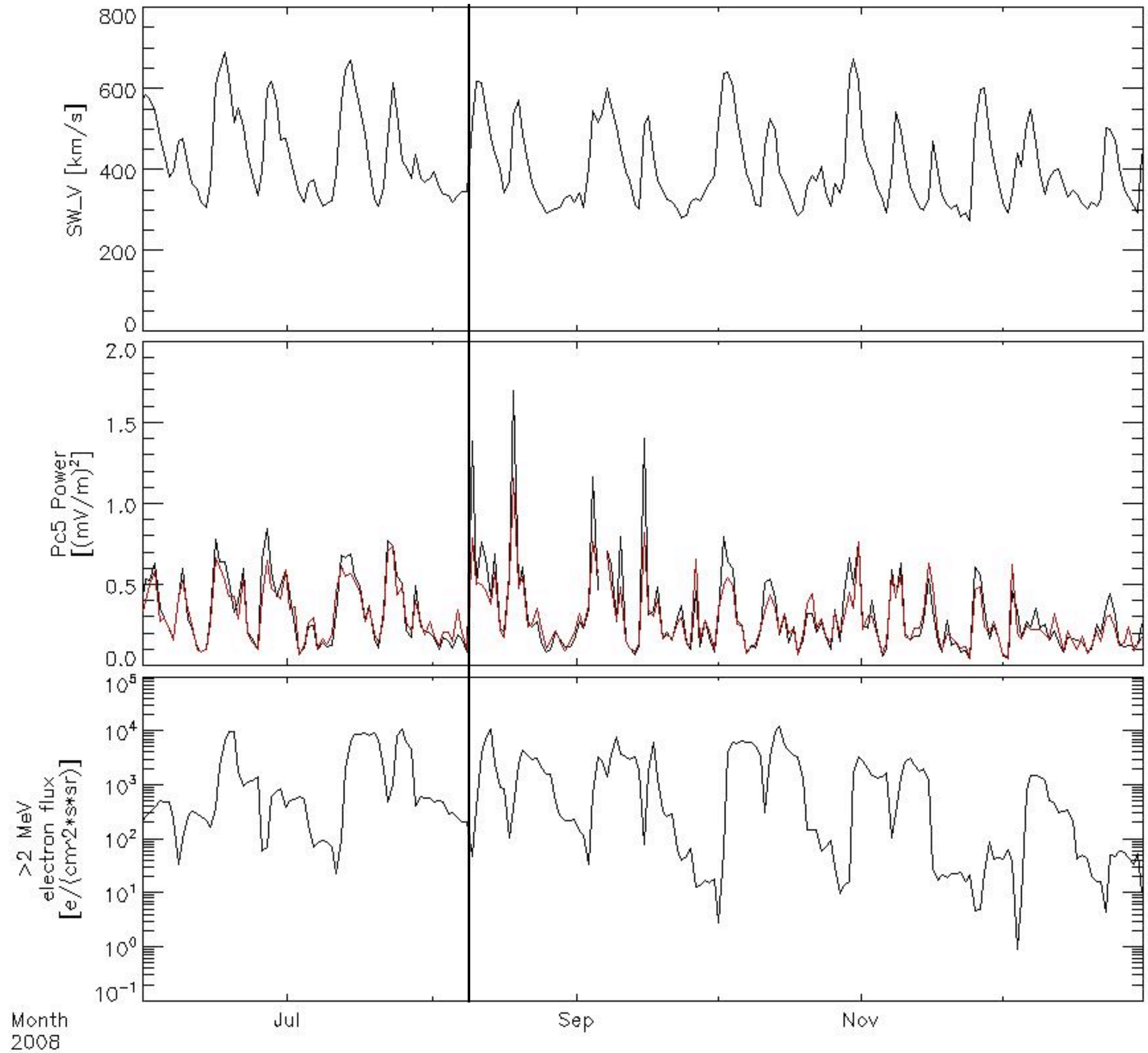
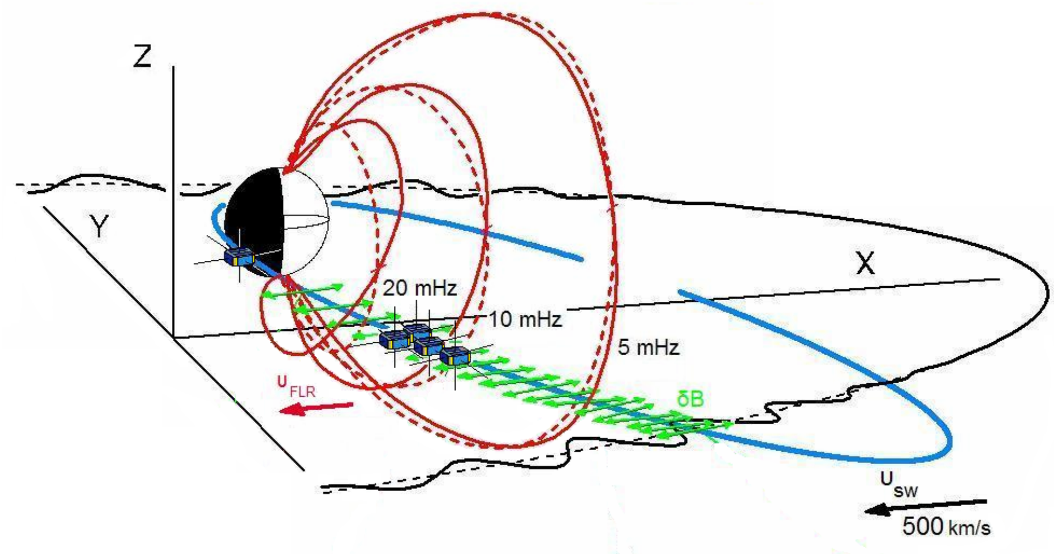
A Statistical Study of the Solar Wind influence on ULF waves

- Correlation between colar wind velocity, Pc5 wave power and electron flux:



Conclusions:

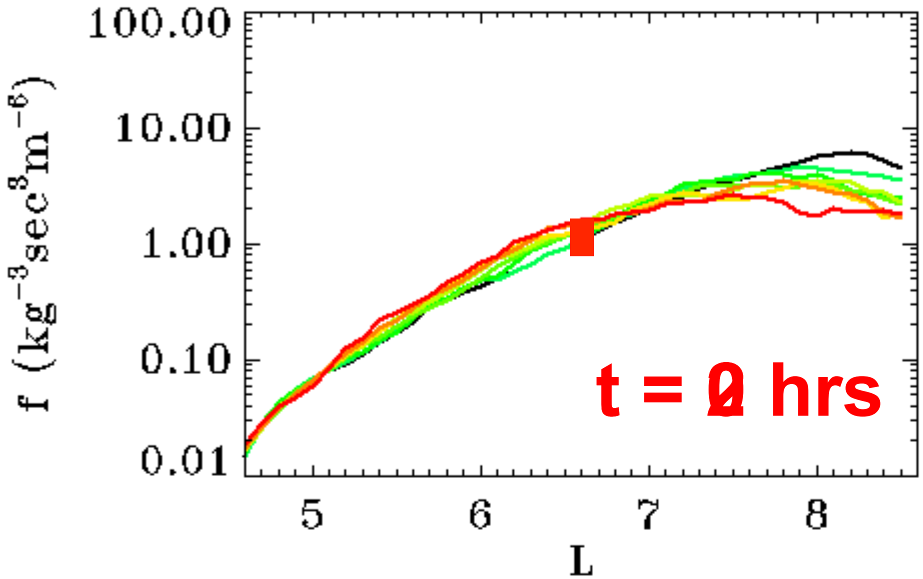


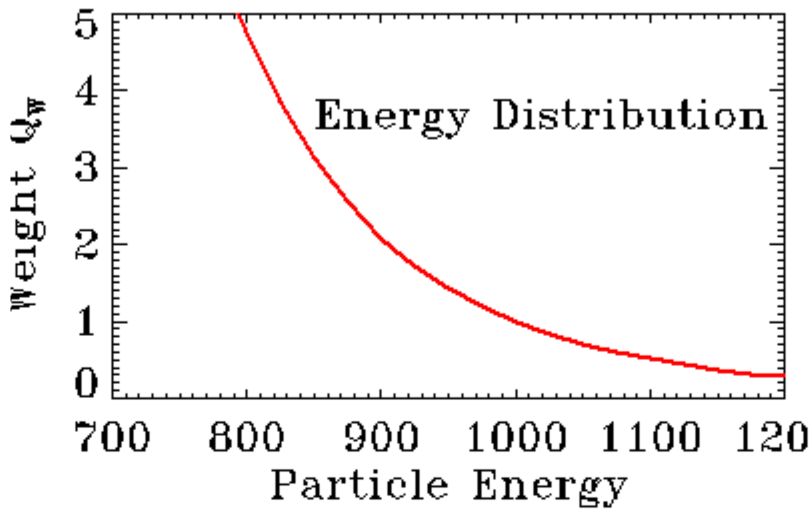
- **A:** ULF waves play a critical role in the **diffusion of radiation belt energetic particle fluxes**, particularly during and after solar storms

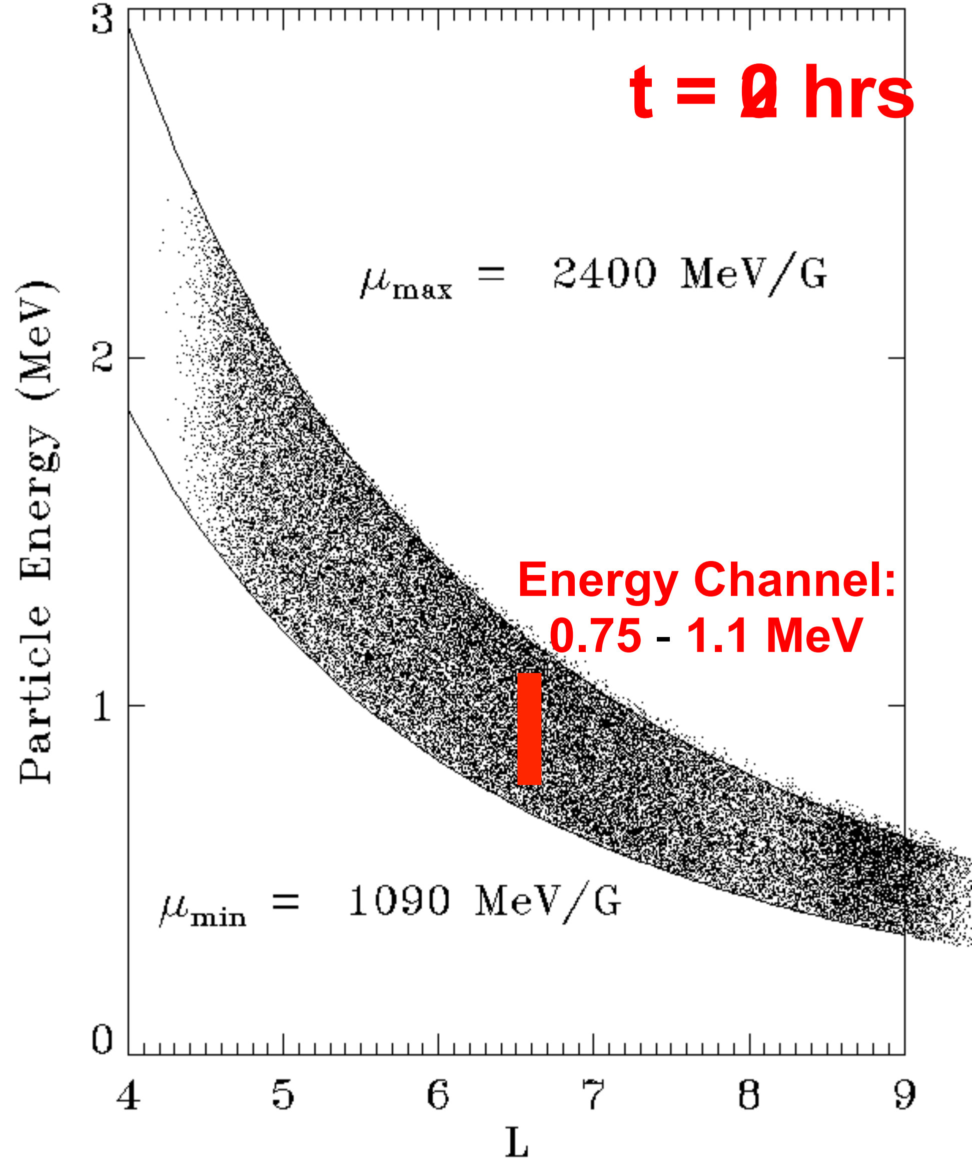
- **B:** Multi-point measurements allow the investigation of key ULF wave parameters, such as **mode number** and **wave power**, that are critical in modeling the effects of ULF waves on radiation belt energetic particles

- **C:** The solar wind velocity shows a higher correlation with both Poloidal and Toroidal ULF waves than density and dynamic pressure, indicating that it is the primary influencing factor for ULF wave generation

Numerical Calculation of the Diffusion Coefficient:

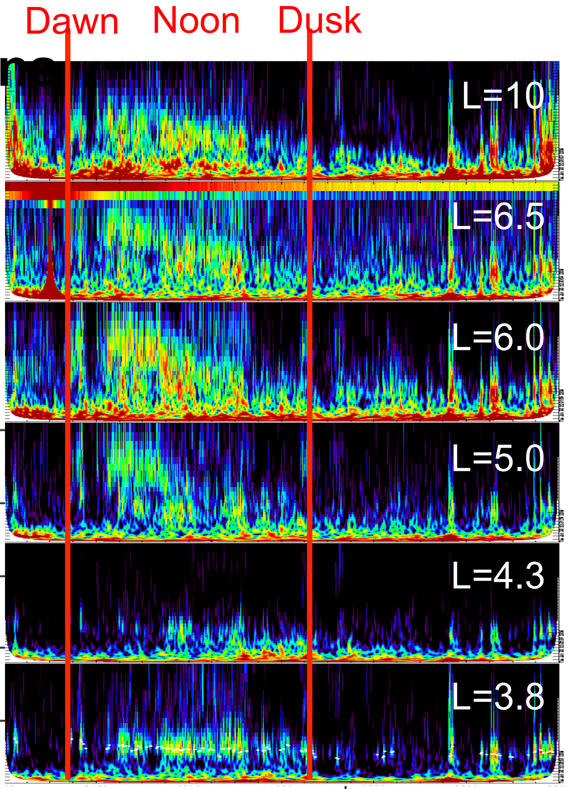


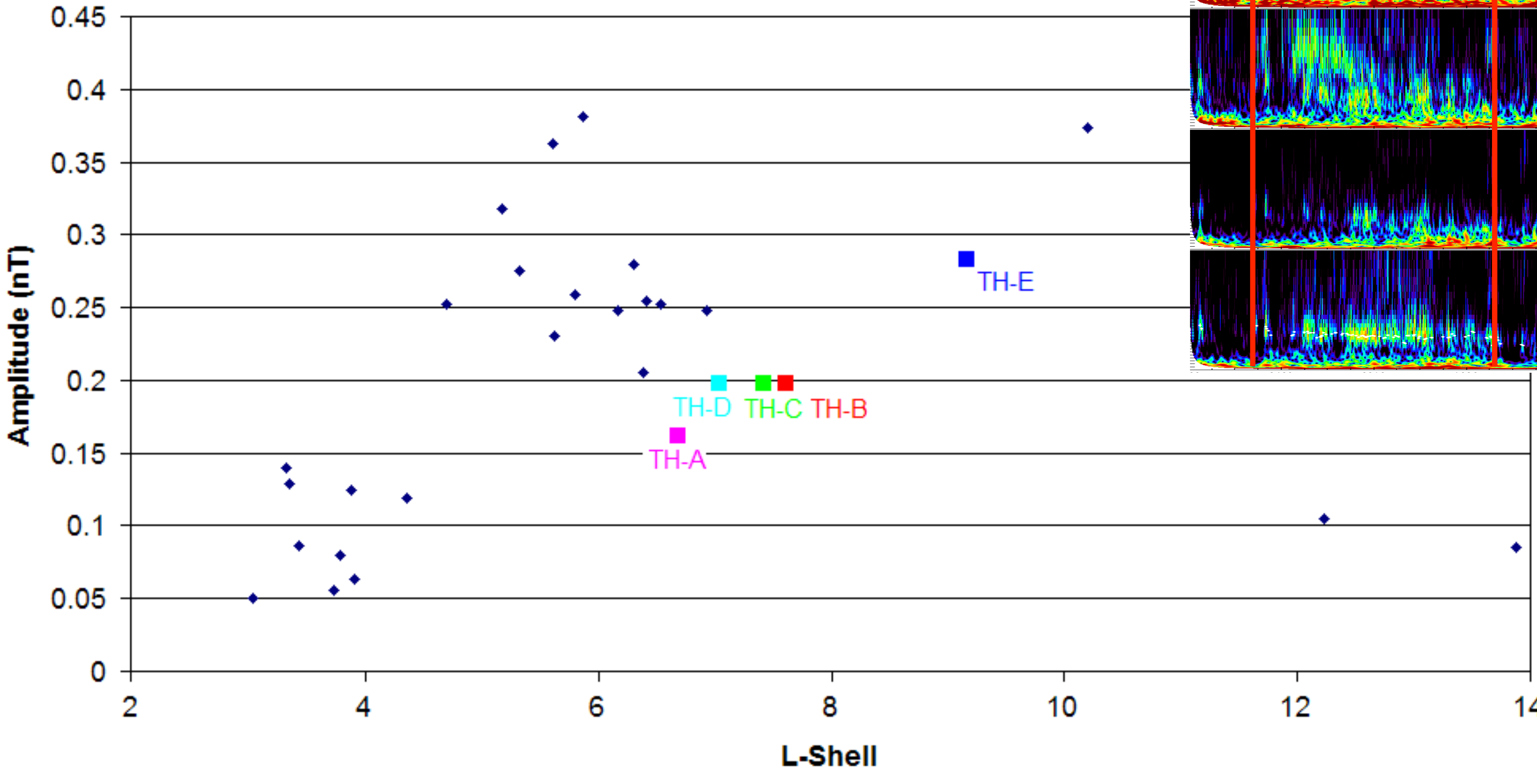




ULF Waves during Solar Wind pressure perturbations

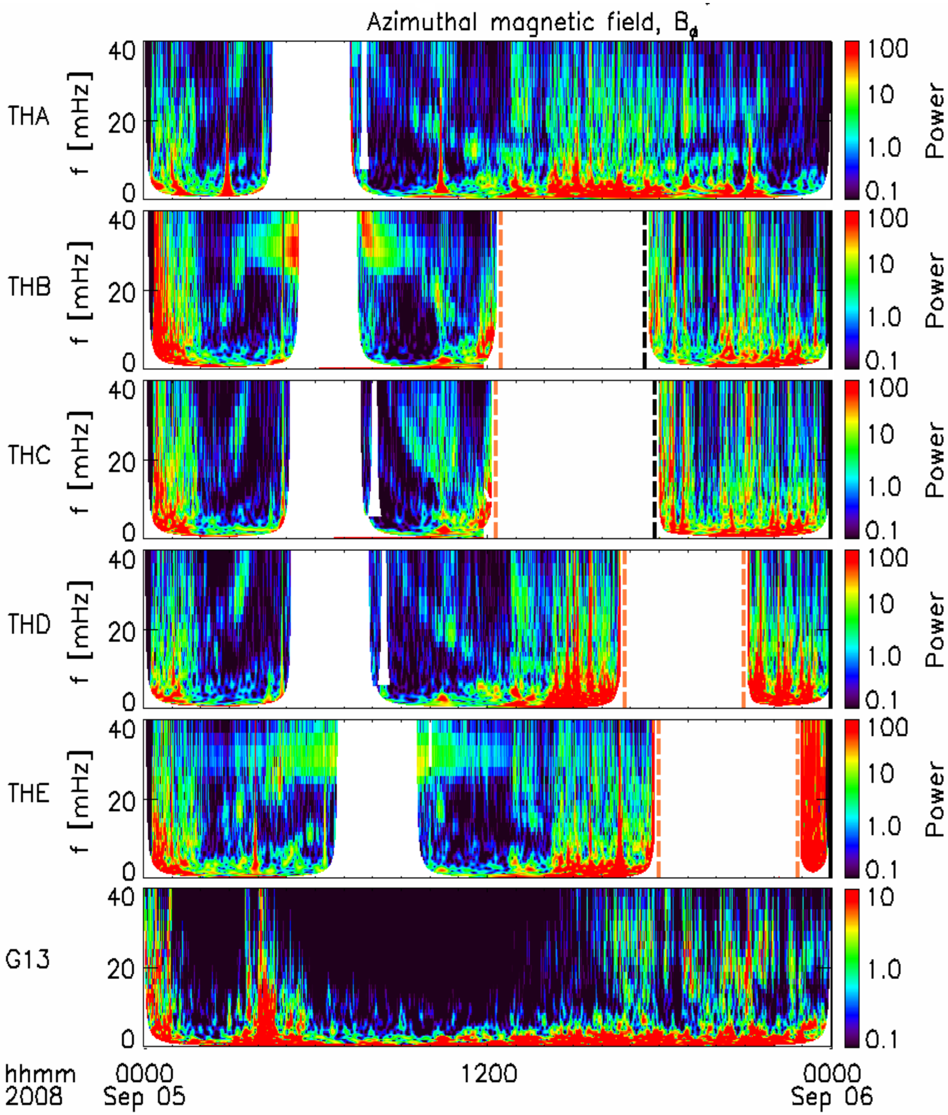
IMAGE Ground Magnetometers:

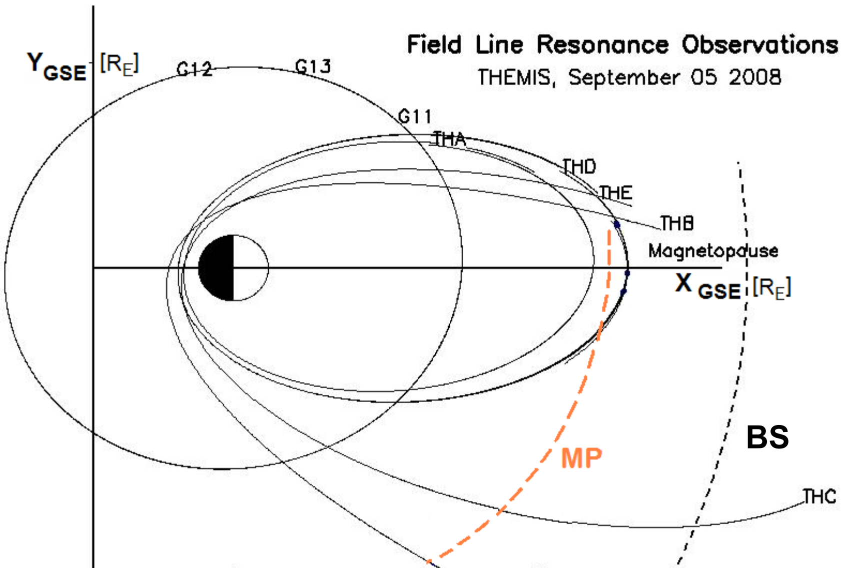




• Amplitude of FLR frequency is normalized by total power at the time of excitation

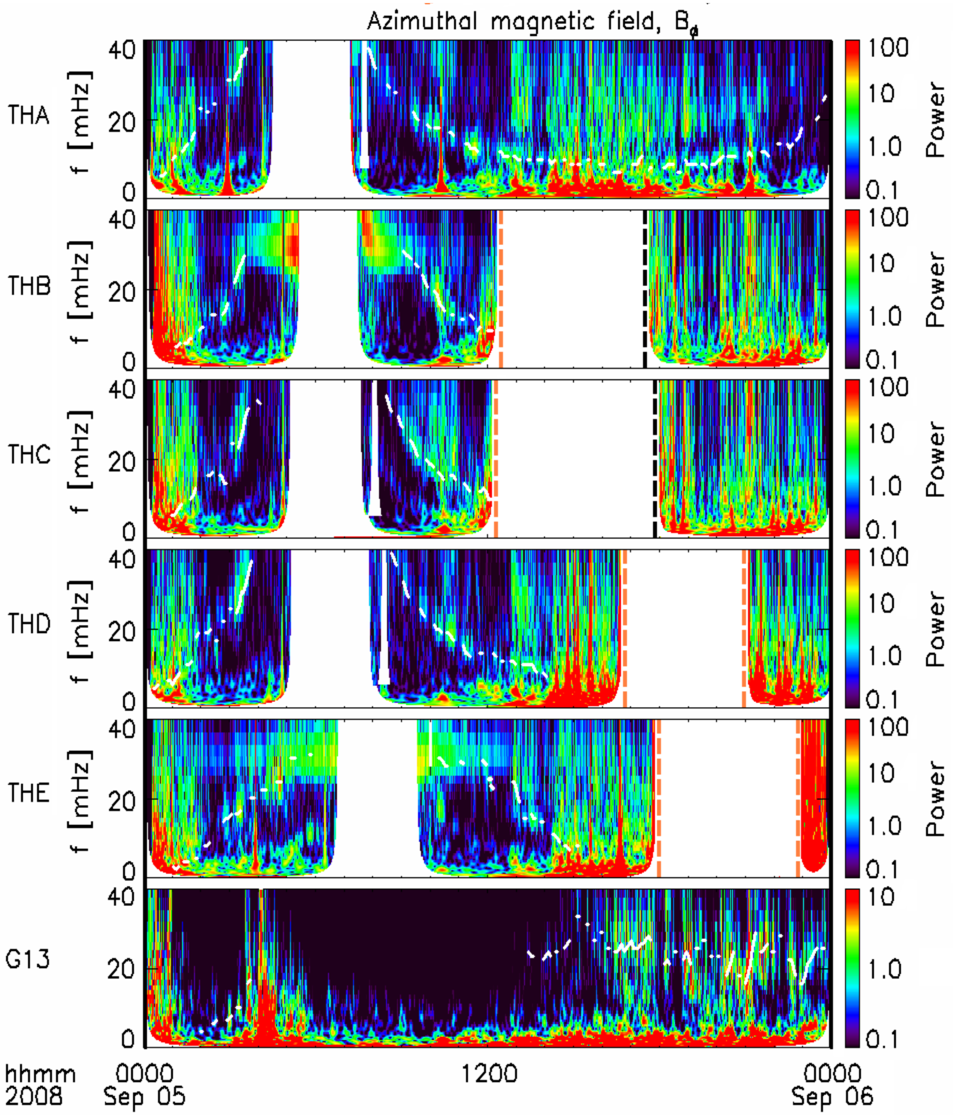
ULF Waves during Solar Wind pressure perturbations

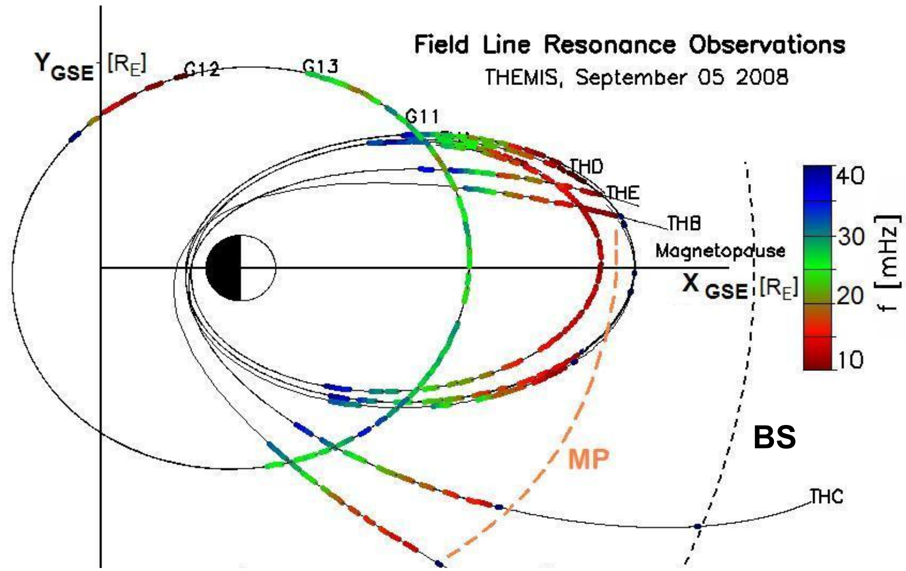




- *Sarris et al., GRL, 2010GL044125*

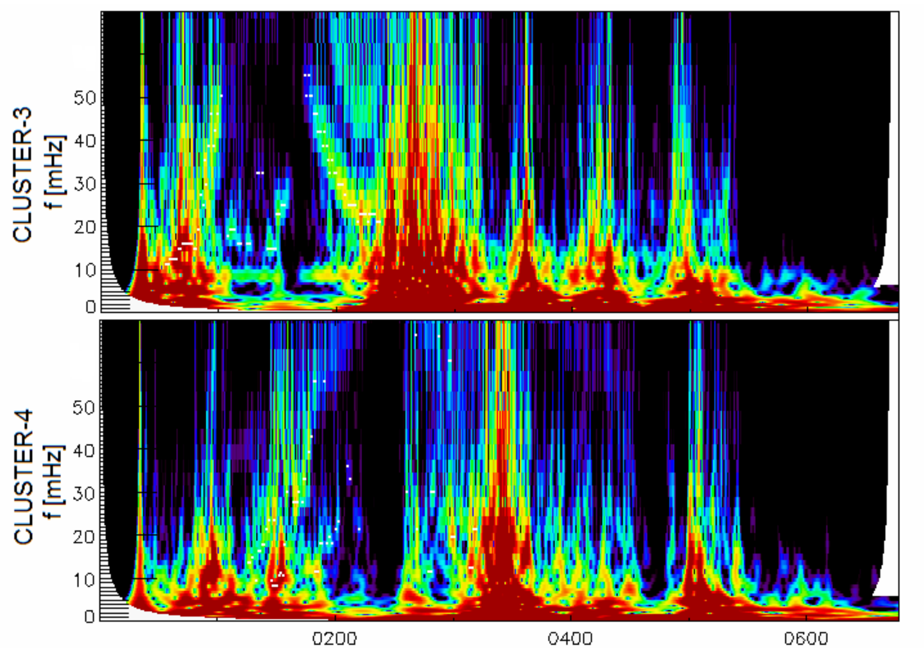
ULF Waves during Solar Wind pressure perturbations

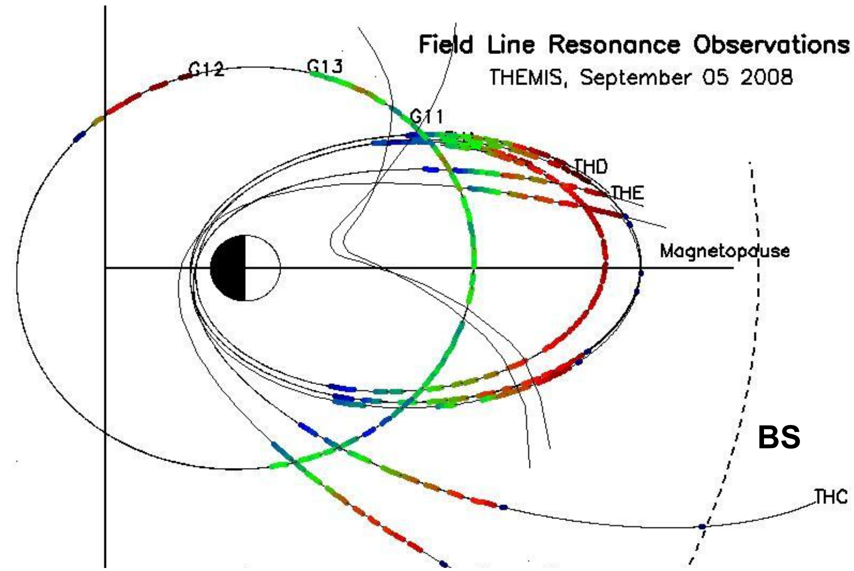




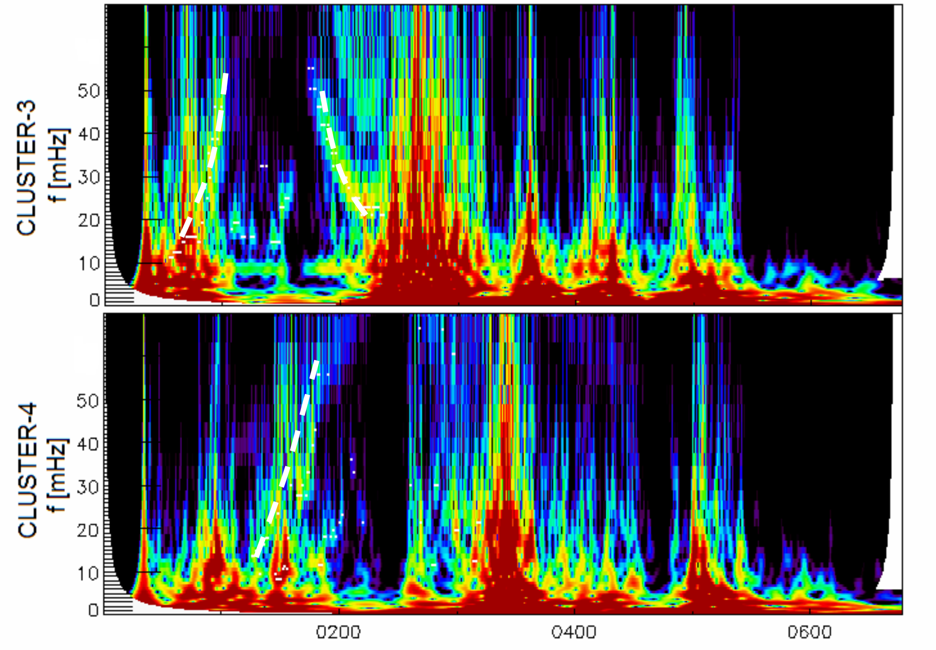
- *Sarris et al., GRL, 2010GL044125*

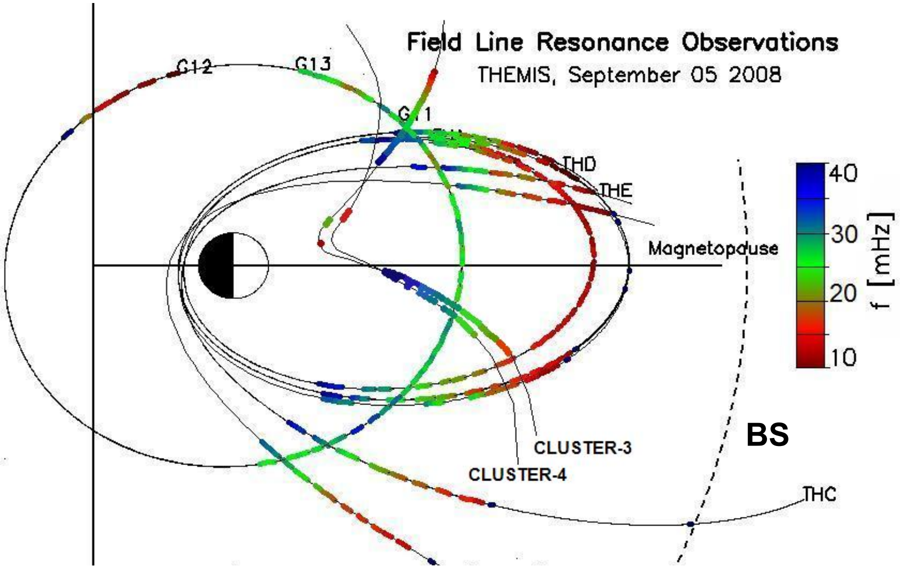
ULF Waves during Solar Wind pressure perturbations



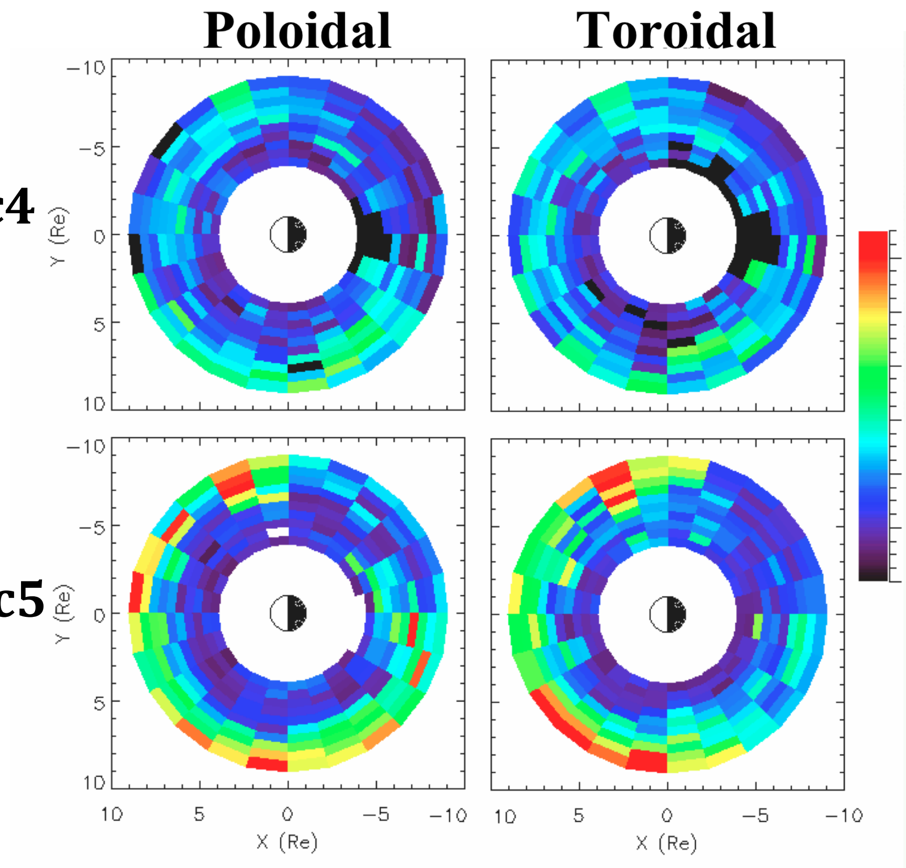


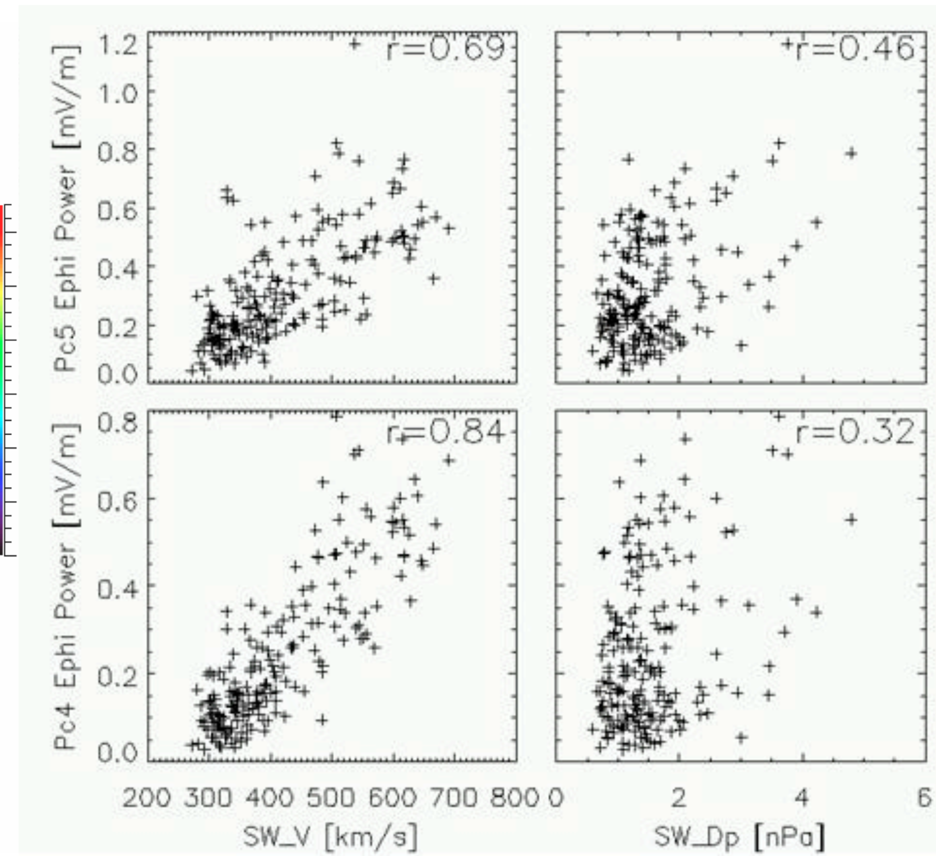
ULF Waves during Solar Wind pressure perturbations





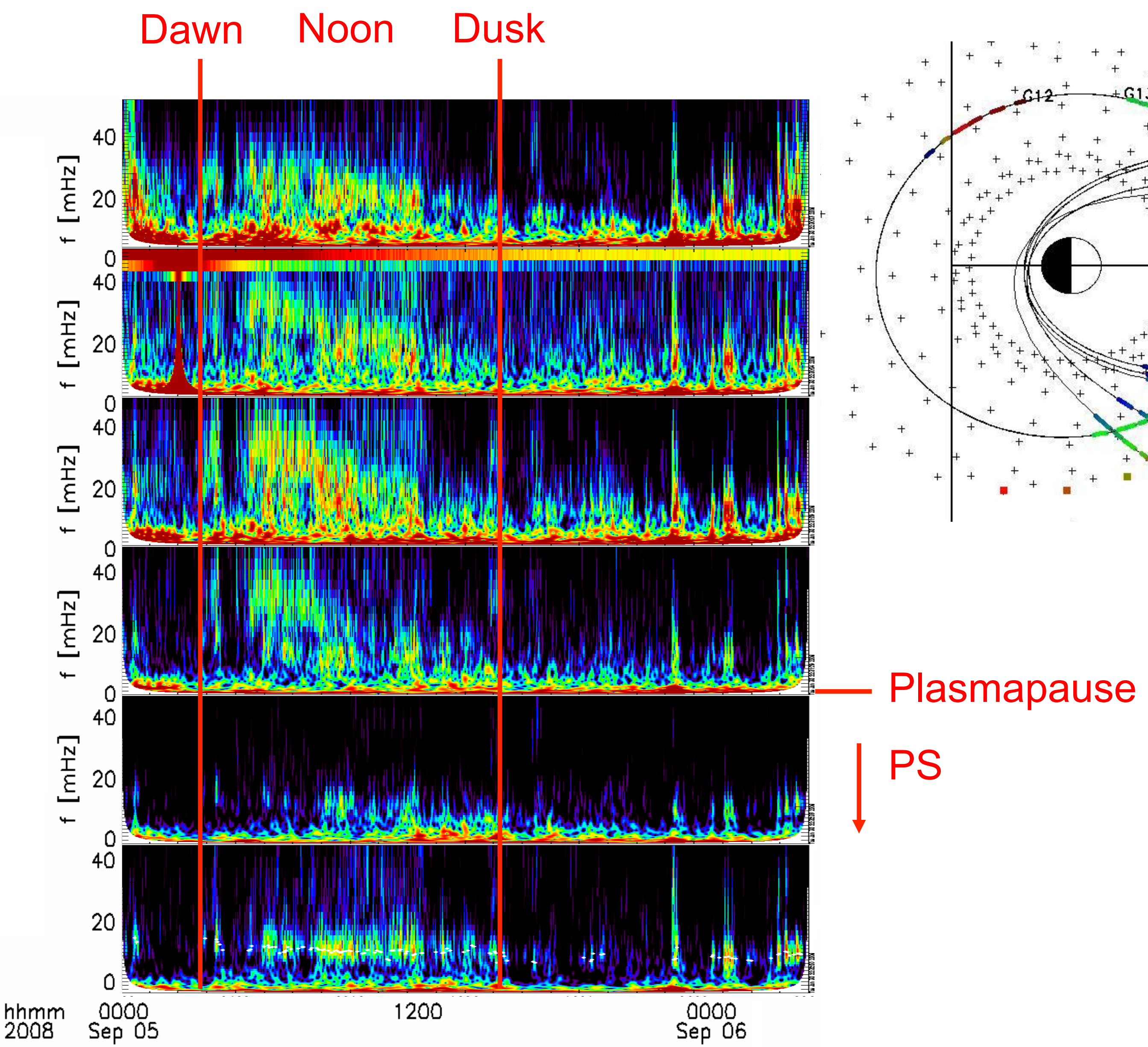
A Statistical Study of the Solar Wind influence on ULF waves

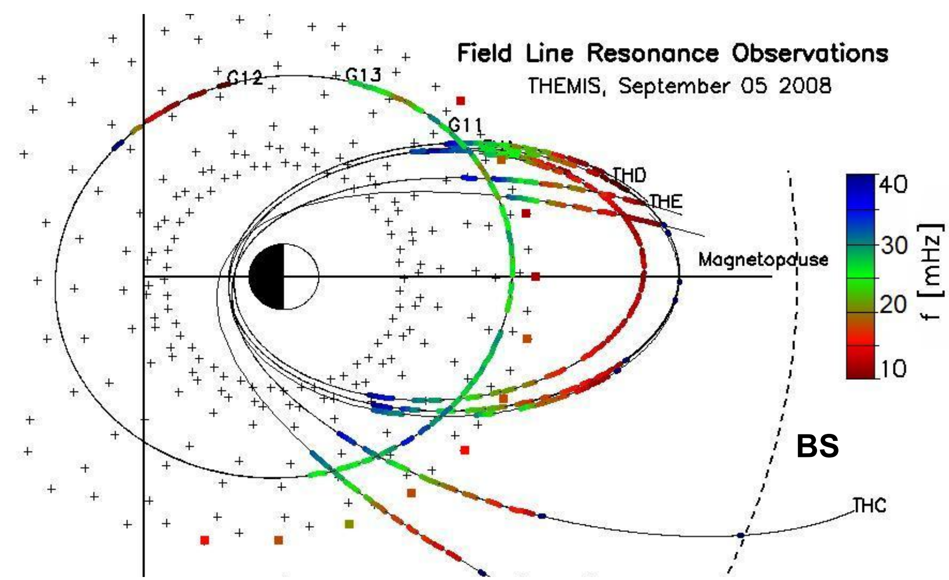




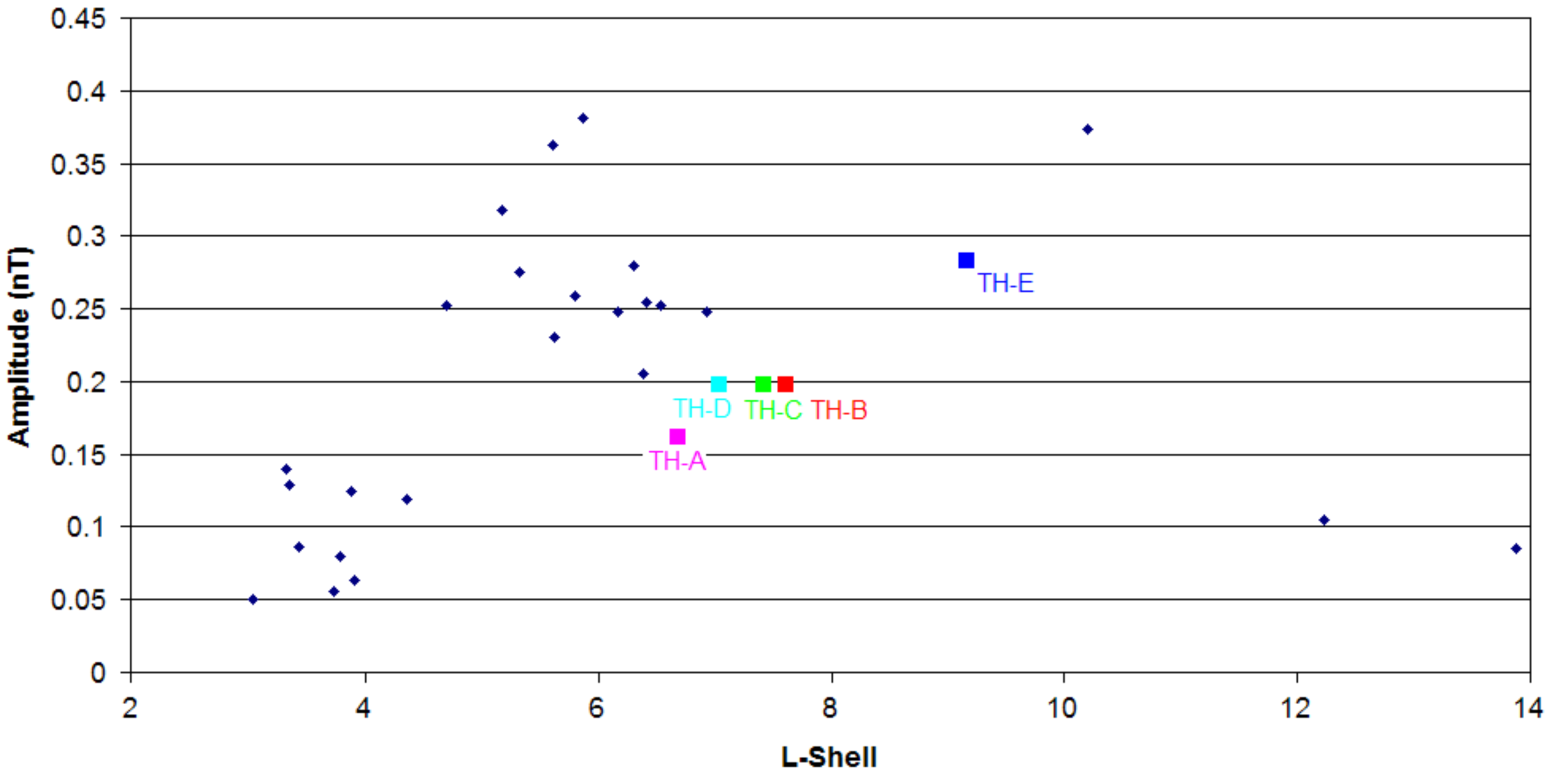
- *Liu, Sarris, et al., Statistical Study on ULF Waves, JGR, 2009JA014243*
- *Liu, Sarris, et al., SW influence on Pc4 & Pc5 ULF wave activity, JGR, 2010JA015299*

Case B: Distribution and Excitation of FLRs – IMAGE Ground Mag





Case B: Pressure Pulse Excitation



- Amplitude of FLR frequency is normalized by total power at the time of excitation

Background:

- ULF pulsations are observed in the solar wind, the magnetosphere & on the ground

  Kepko et al.**, ULF waves in the solar wind as direct drivers of pulsations, GRL, 39, **2002

- There is strong Pc5 wave power during the main phase of geomagnetic storms

  Baker et al.**, CMEs, magnetic clouds & relativistic e^- events, JGR, 17279, **1998

- Pulsations might arise from oscillatory sources inherent in the solar wind

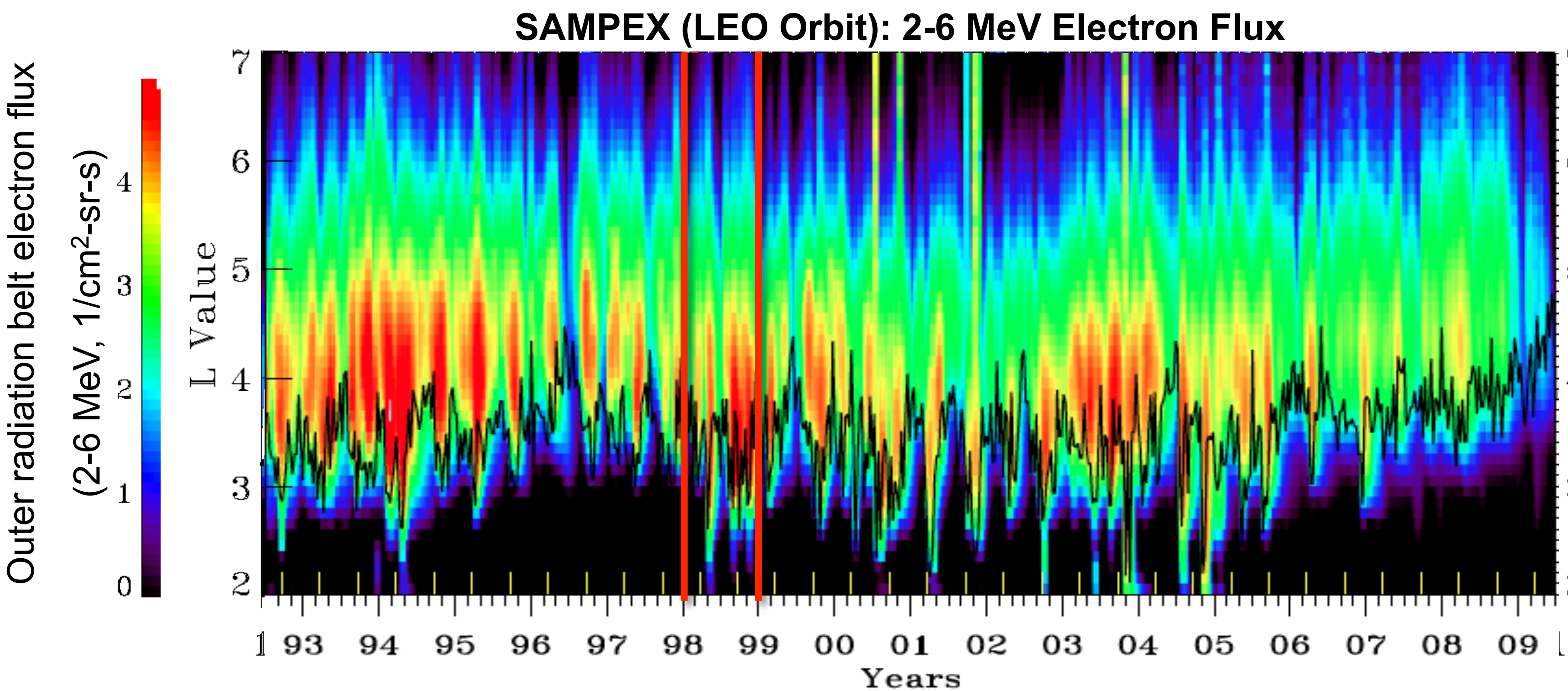
  Sarafopoulos**, Long duration Pc5 compressional pulsations inside the Earth's magnetic lobes, Ann Geoph, 13, 926, **1995

- Pc5 perturbations may provide the free energy needed to accelerate e^-

  Elkington et al.**, Acceleration of relativistic e^- via drift-resonant interaction with toroidal-mode Pc5 ULF oscillations, JGR, 3273, **1999

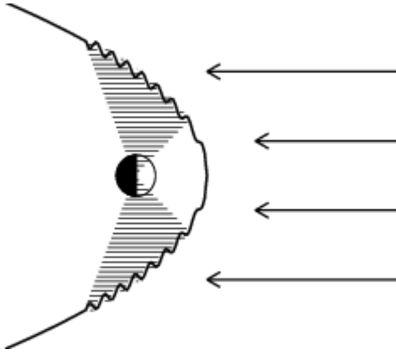
Radial Diffusion During Solar Storms:

- Solar storms are most commonly associated with energetic (MeV) particle flux enhancements and are accompanied by ULF wave activity
- ULF waves are believed to be causing inward as well as outward radial transport and diffusion of MeV particles, through drift-resonant interaction



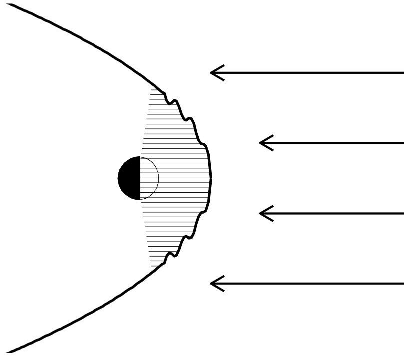
Determining the influence of solar wind on ULF Waves:

Case 1: ULF Waves driven by SW High-Speed Stream:



The calculation of phase differences between waves as measured at closely spaced probes allows the identification of the ULF wave mode number.

Case 2: ULF Waves driven by a SW Pressure-Pulse:



The distribution of probes throughout the magnetosphere allows the identification of the excitation mechanism of ULF waves; we show an example of the magnetospheric response to a Solar Wind pressure pulse

A Statistical Study of the Solar Wind control of ULF waves:

We use, for the first time, simultaneous E & B-field measurements from THEMIS to statistically study the correlation between ULF wave power and various solar wind parameters: velocity, dynamic pressure, and the variation in dynamic pressure.