Role of ULF Waves in Ultra-relativistic Radiation Belt Dynamics: Explaining the 3rd Belt

I.R. Mann[1], L.G. Ozeke, K.R. Murphy, S. Claudepierre, D. Turner, I.J. Rae, D.K. Milling, A. Kale, J. Fennel and D.N. Baker

[1]Department of Physics, University of Alberta, Canada.

ian.mann@ualberta.ca

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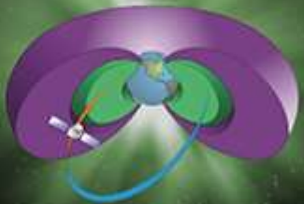
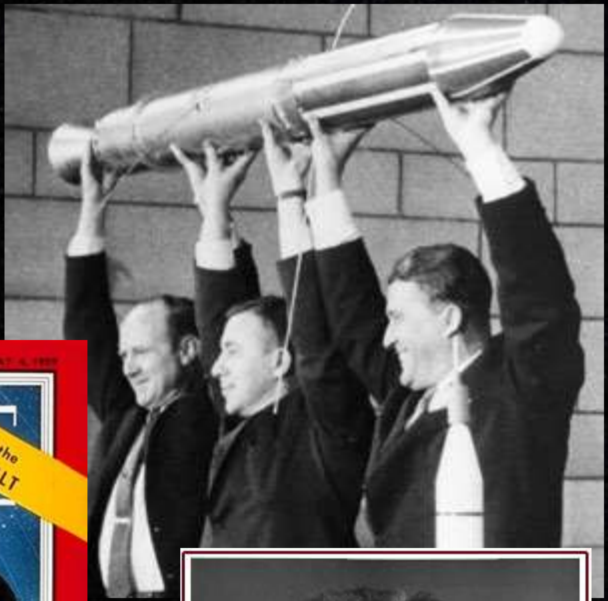


Van Allen Radiation Belts

- Radiation Belts discovered unexpectedly by James Van Allen.
- Explorer 1 spacecraft, launched on Redstone rocket on 31st Jan. 1958.
- Cover of Time magazine in 1959 ("Man of the Year").
- More than 50 years later, Van Allen radiation belts still a mystery.

From left: William H. Pickering, James Van Allen and Wernher von Braun



Images courtesy of NASA.

Space Environment Hazards

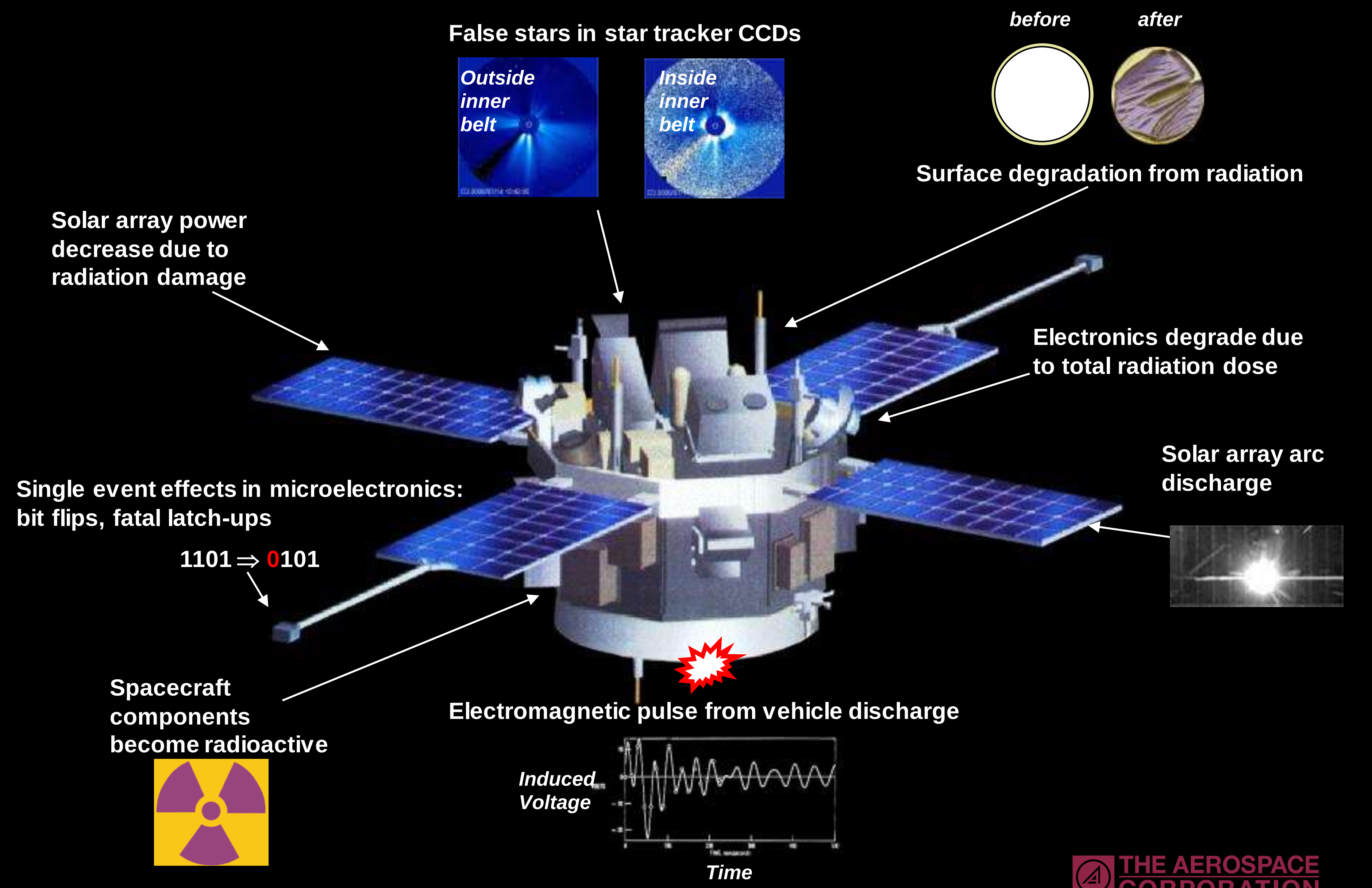
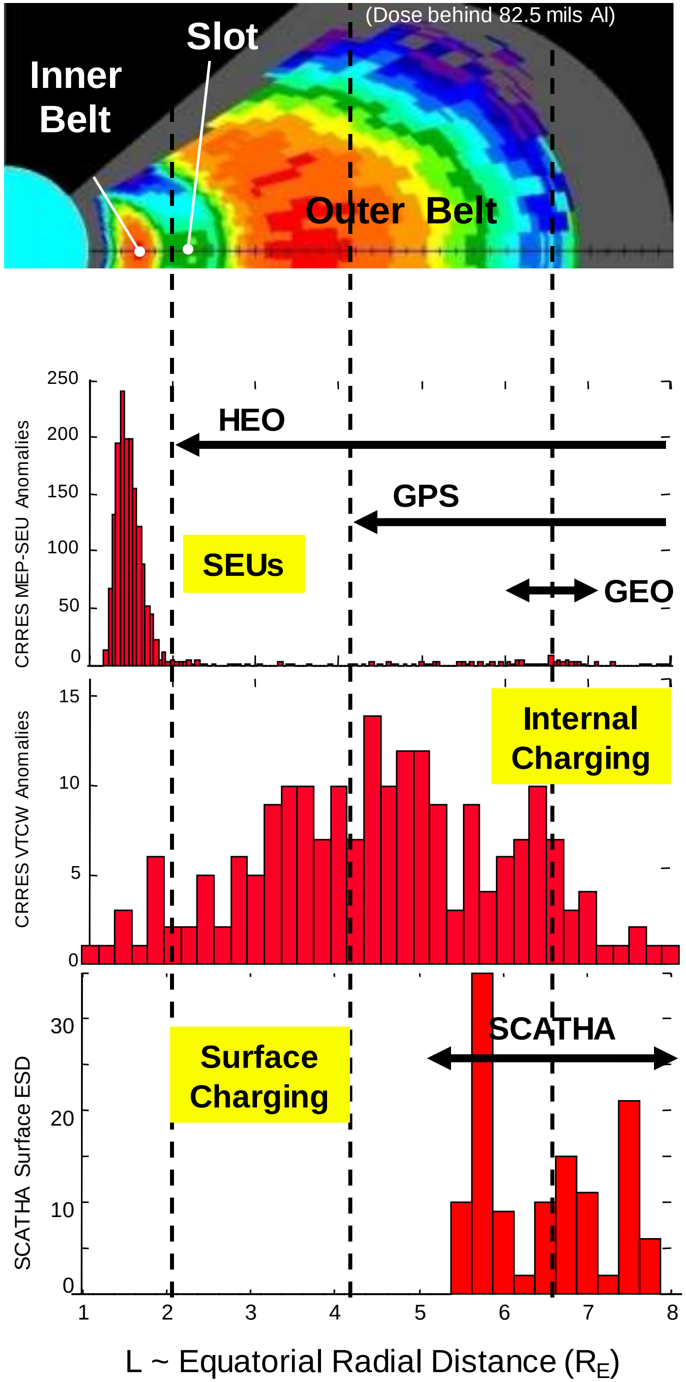


Figure courtesy of Joe Mazur, The Aerospace Corporation



Radiation Effects

- **Radiation Effects**
  - **Radiation Hazards to Spacecraft**
  - **User Needs**
  - **Next generation specifications**
- **Empirical/Statistical Models**
  - **Static: AE-8, AP-8, and CRRES-PRO, Roeder**
  - **Dynamic: CRRES-ELE, TPM-1, IGE/Pole**
  - **Monte Carlo: TEM-1**
  - **Large domain problems**
- **Identified international need to advance current radiation belt specification models for satellite design (COSPAR PRBEM report)**
  - **Especially important at MEO altitudes**
  - **Data is critical from MEO regions**
- **MEO will be a key region for the next generation of commercial communication satellite constellations.**

Courtesy of Paul O'Brien.

Paul.OBrien@aero.org

THE AEROSPACE CORPORATION


Image U.S. Geological Survey
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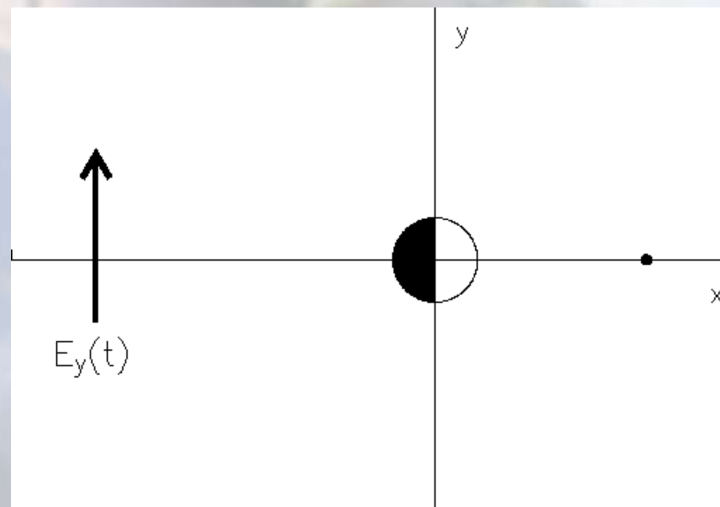
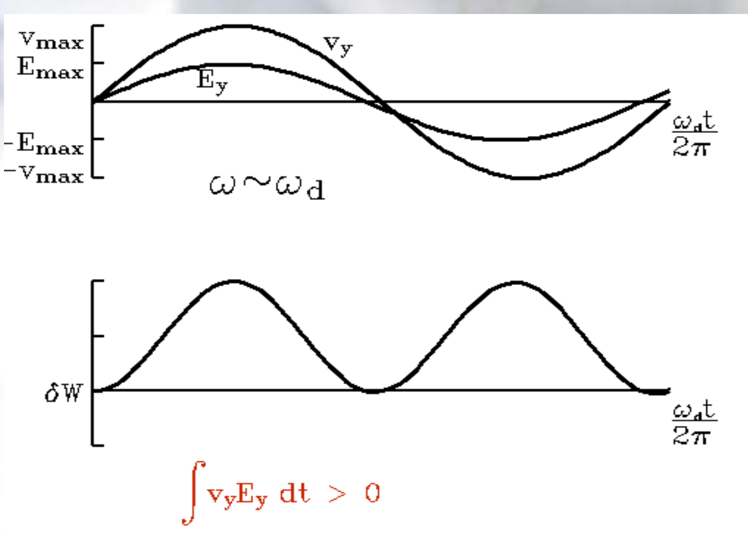
Google

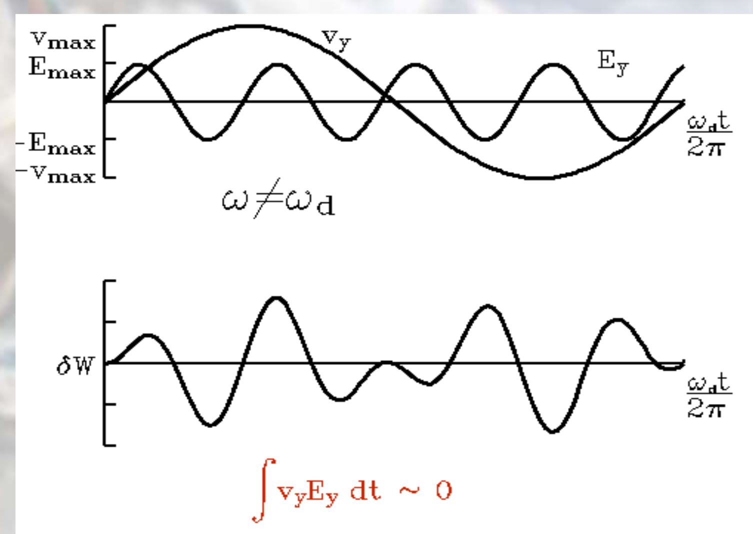
Electrons Influenced All Along Drift Path

Images courtesy of Scot Elkington, LASP.



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



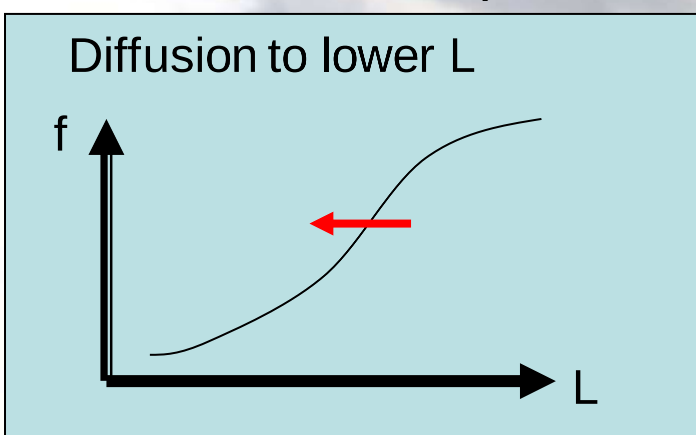


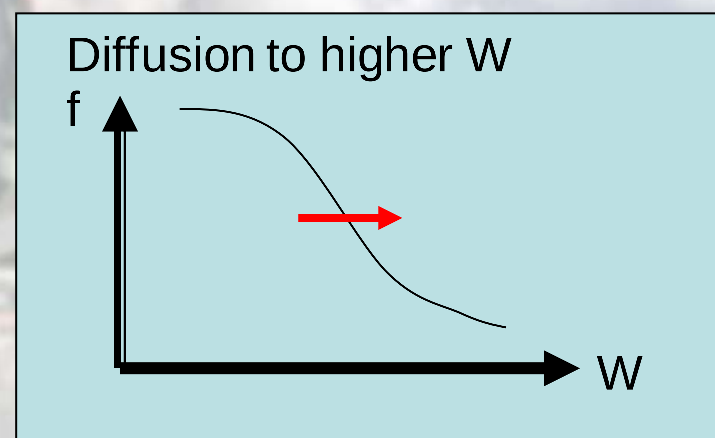
ULF Wave-MeV Electron Diffusion

- Rate of energy change due to ULF interactions:

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

- 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).





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

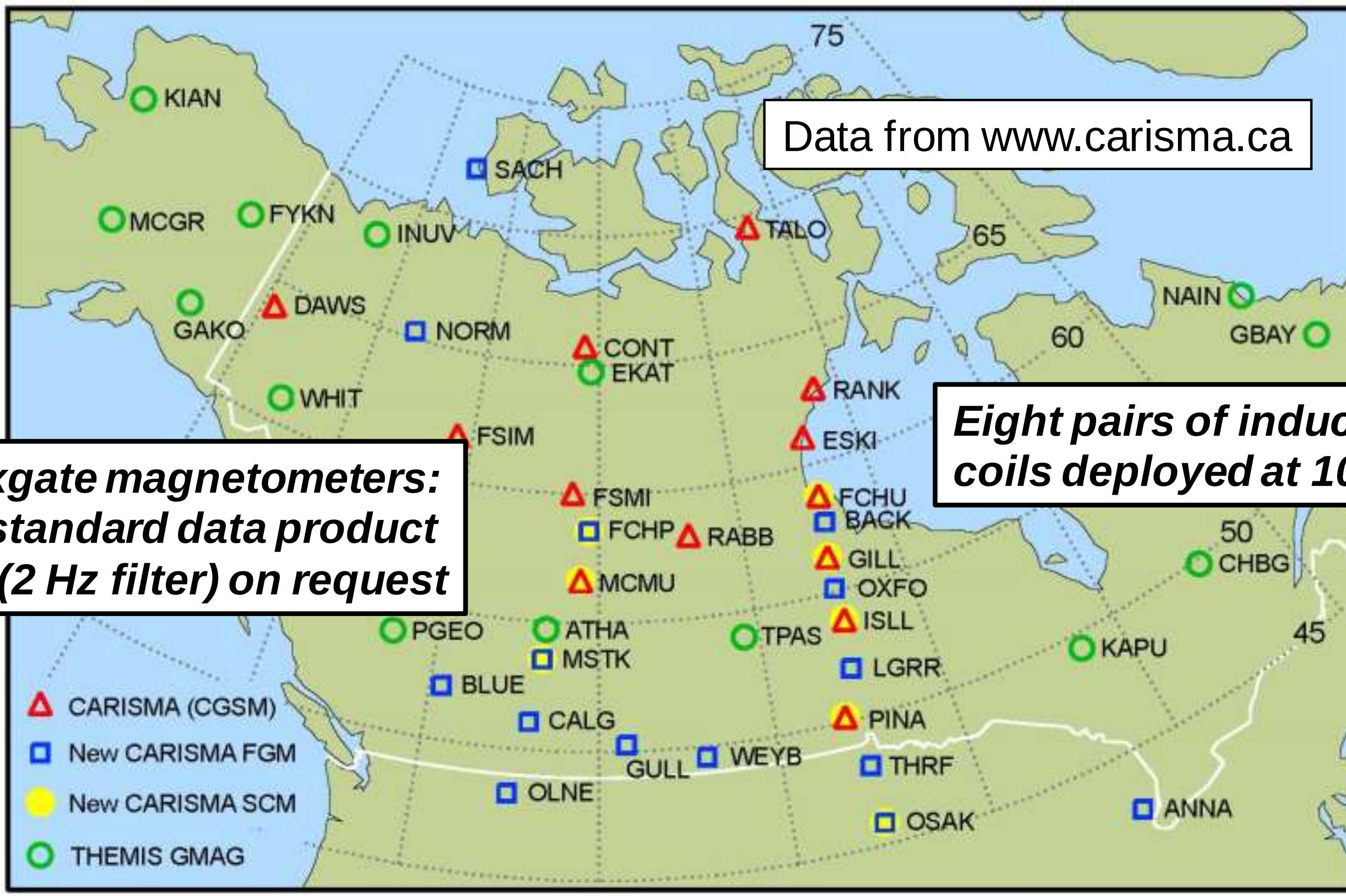
Energy dependence

Azimuthal Electric Field Power

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

Expanded CARISMA Magnetometer Array

Data from www.carisma.ca



28 fluxgate magnetometers:
- 1Hz standard data product
- 8 Hz (2 Hz filter) on request

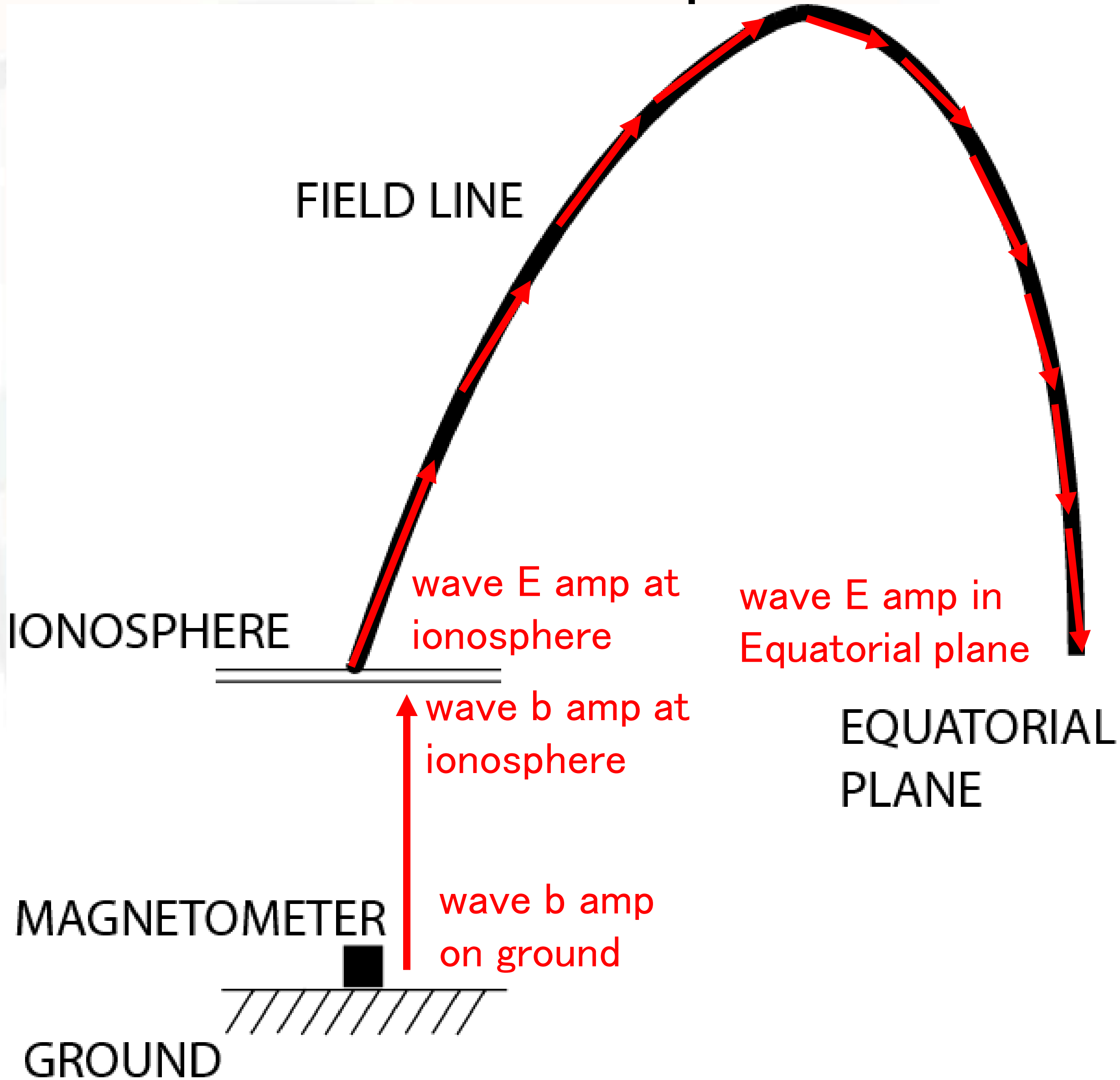
Eight pairs of induction coils deployed at 100 Hz.

Mapping Wave b Amplitude on the Ground to E in the Equatorial Plane

- Ground-based magnetometer measures wave b field on the ground.
- Hughes and Southwood, JGR,1976 model gives wave b amp at the ionosphere mapped from the ground.
- Ionosphere boundary condition gives E iono from b iono

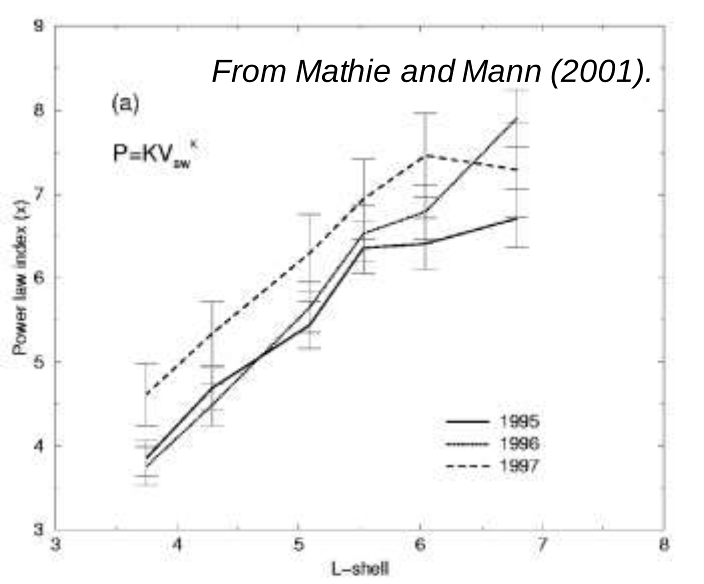
$$b_{iono}=\mu_0\Sigma_P E_{iono}$$

- Solution of guided Alfven wave equations gives E equatorial plane from E at the ionosphere Ozeke, et al JGR, 2009

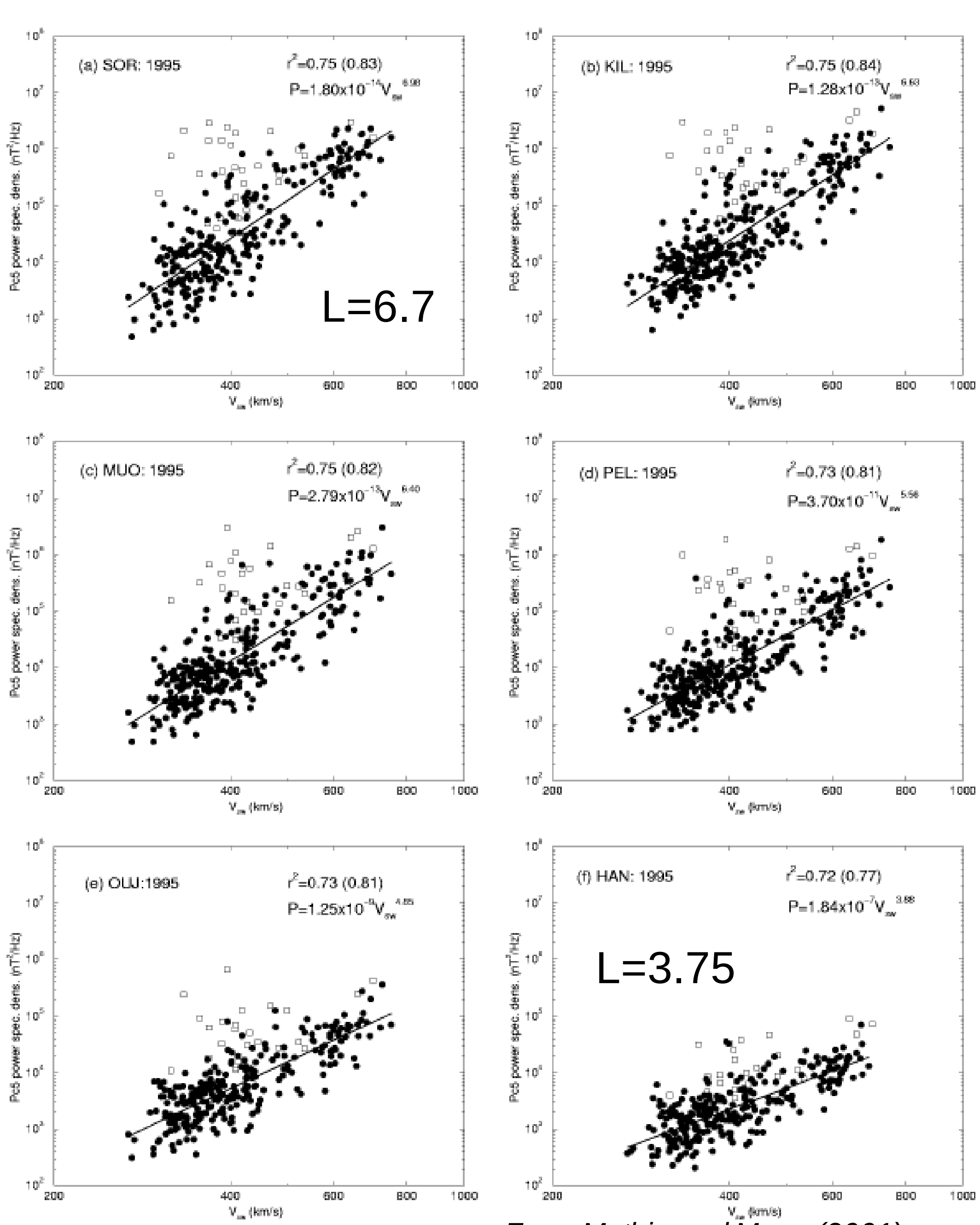


Solar Wind-ULF Wave Relation

- MeV electron flux correlated with (e.g., Paulikas and Blake, 1979; Kellerman and Shprits, 2012).
- Can ULF waves provide the physical mechanism for MeV electron acceleration?

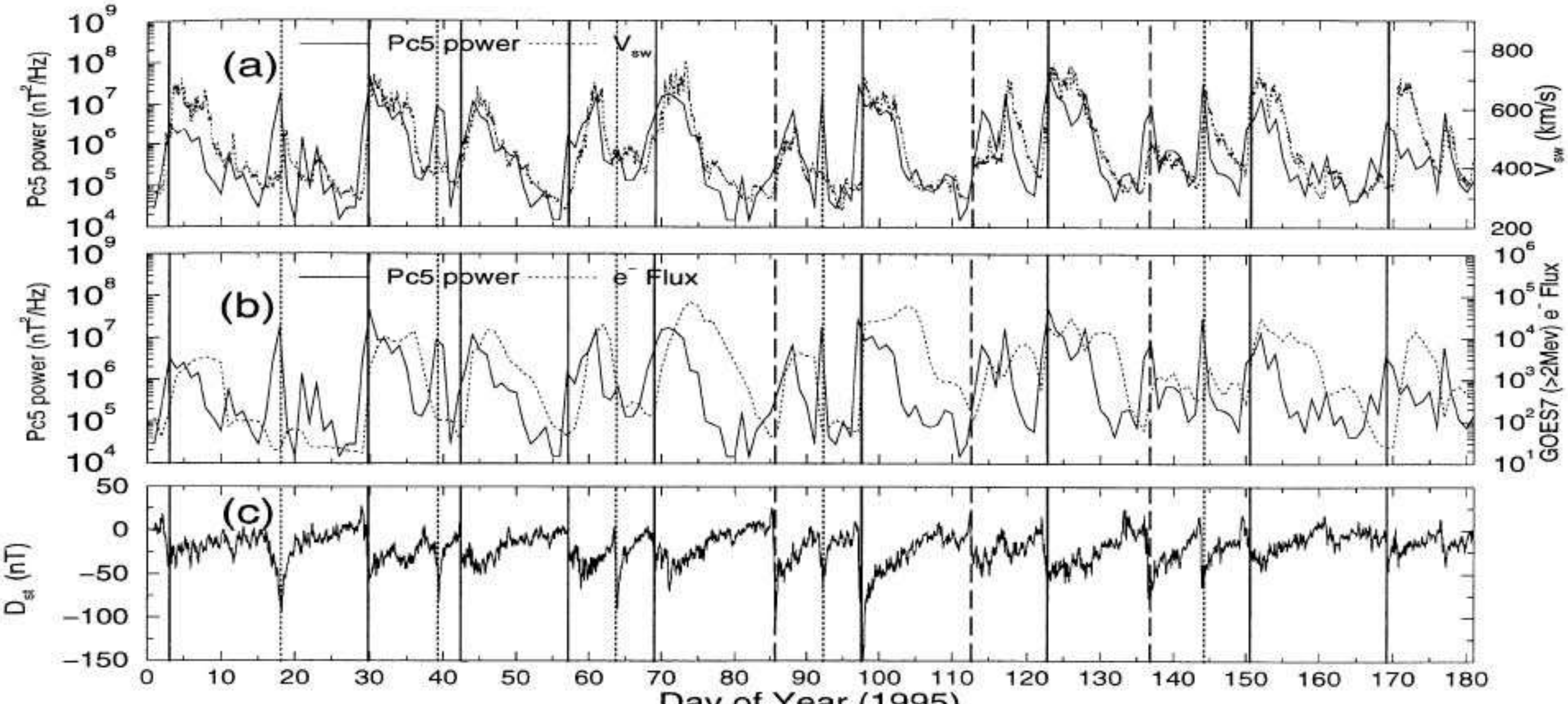


From Mathie and Mann (2001).



From Mathie and Mann (2001).

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

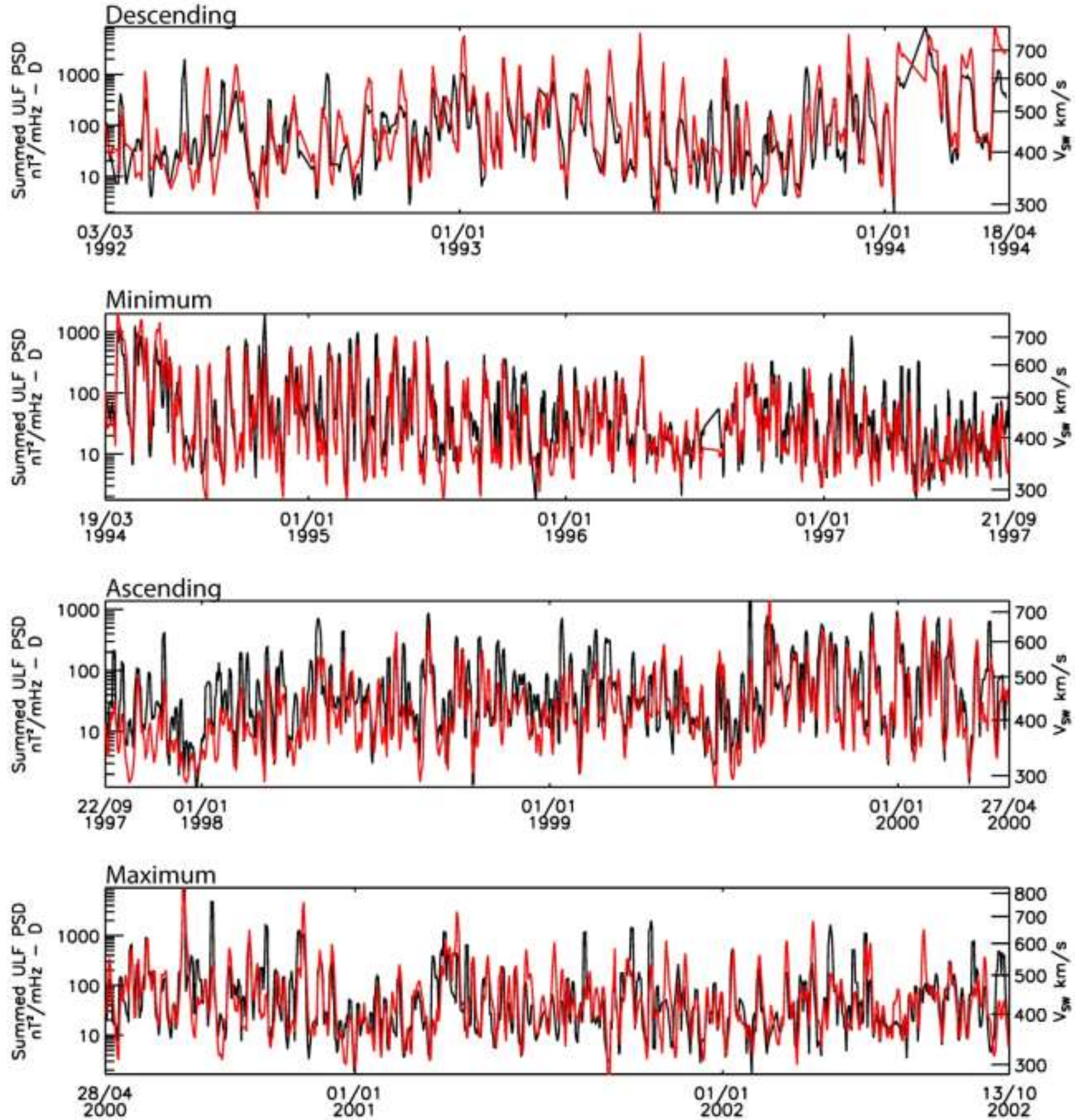


(From Mathie and Mann, GRL, 2000).

CARISMA

How robust is the ULF-Vsw relationship

- All L across outer zone.
- All solar cycle phases!



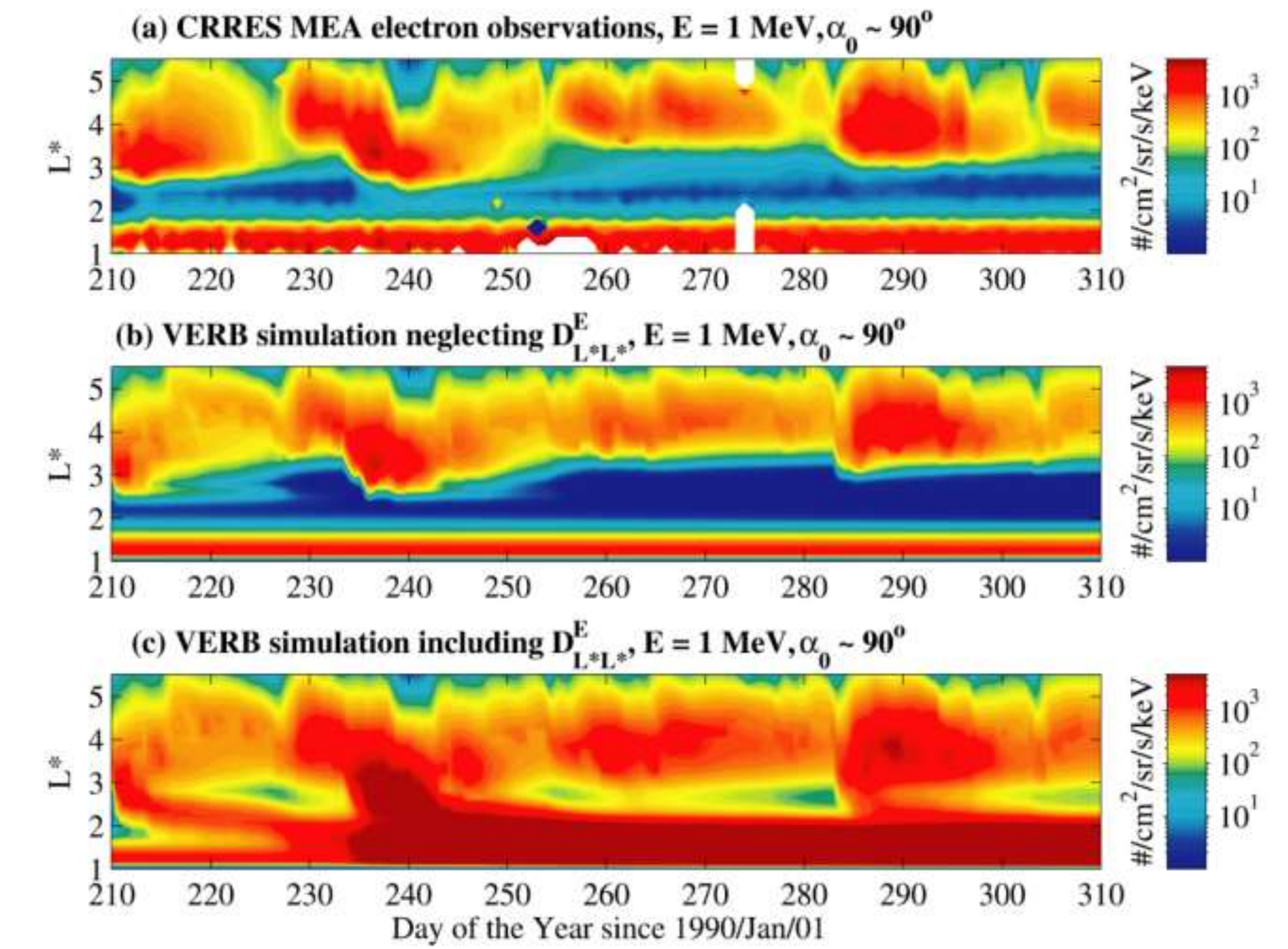
(From Mann et al, AGU Monograph, 2012).

Motivation

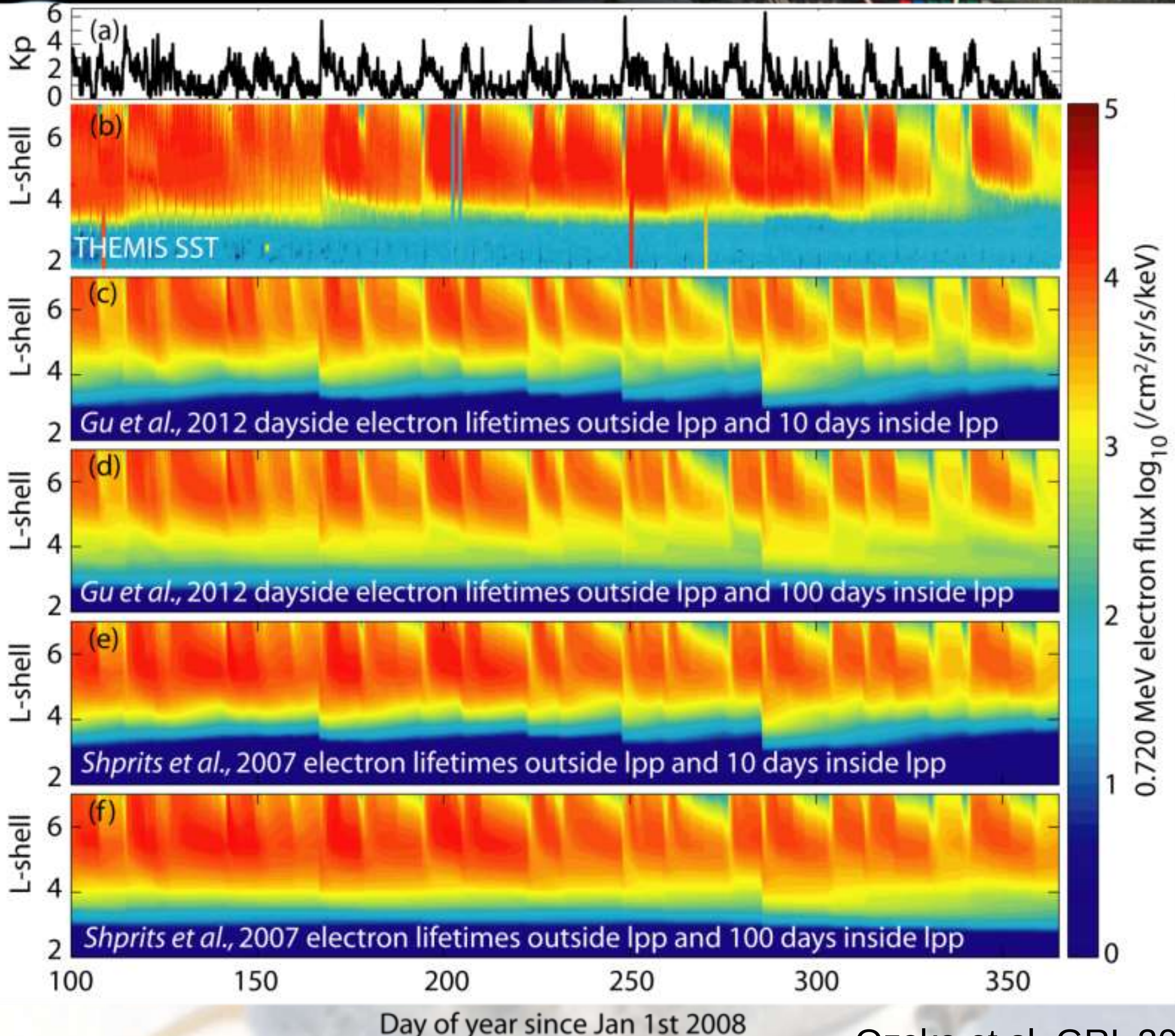
VERB model runs with Brautigam & Albert, JGR, 2000 diffusion coefficients

EM ULF waves only

EM + electrostatic ULF fluctuations

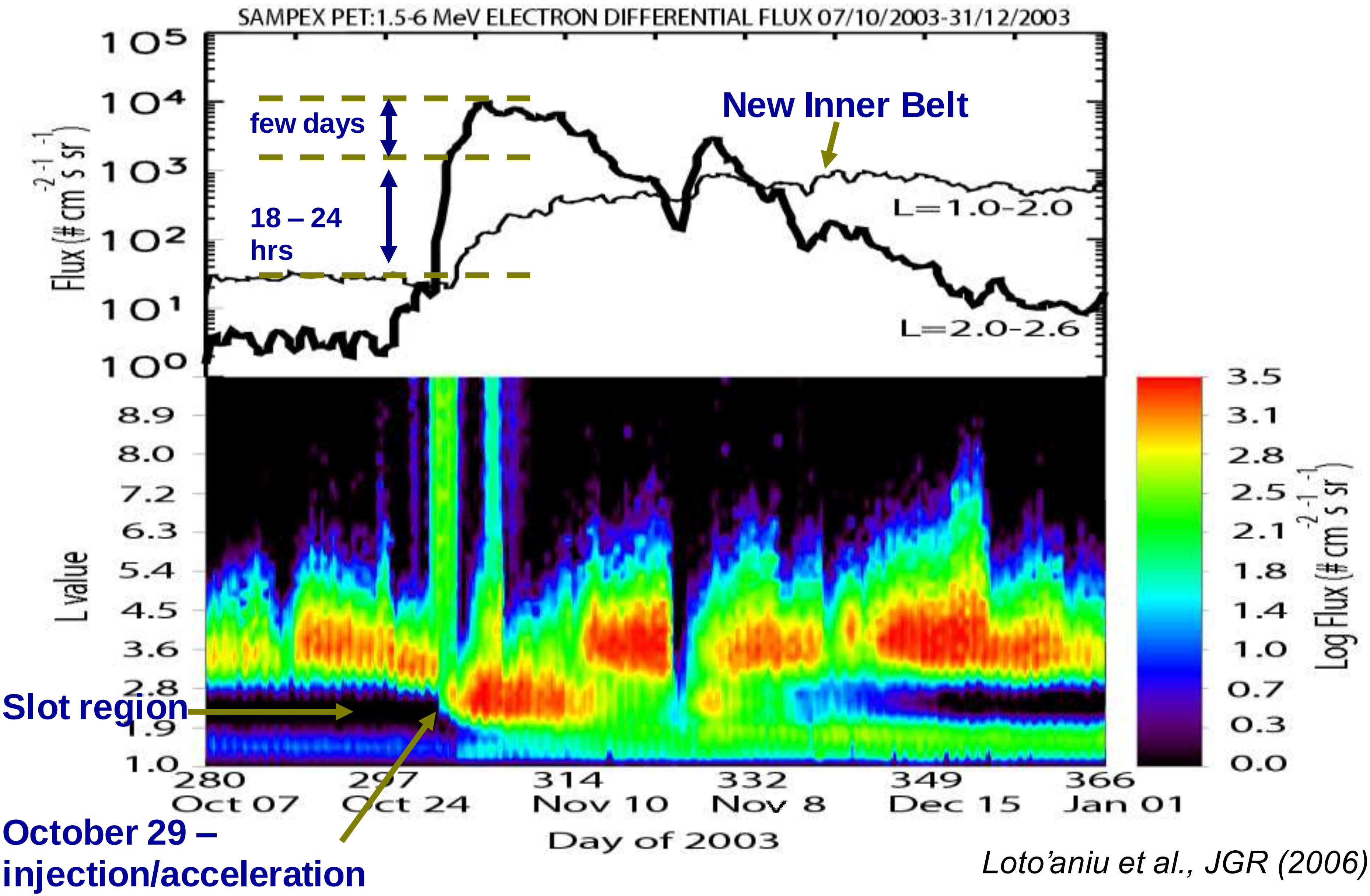


"More accurate models of radial diffusion rates should be determined in future studies and will require more accurate observations of electrostatic and electromagnetic fluctuations at low L - shells."- Kim et al JGR, 2011

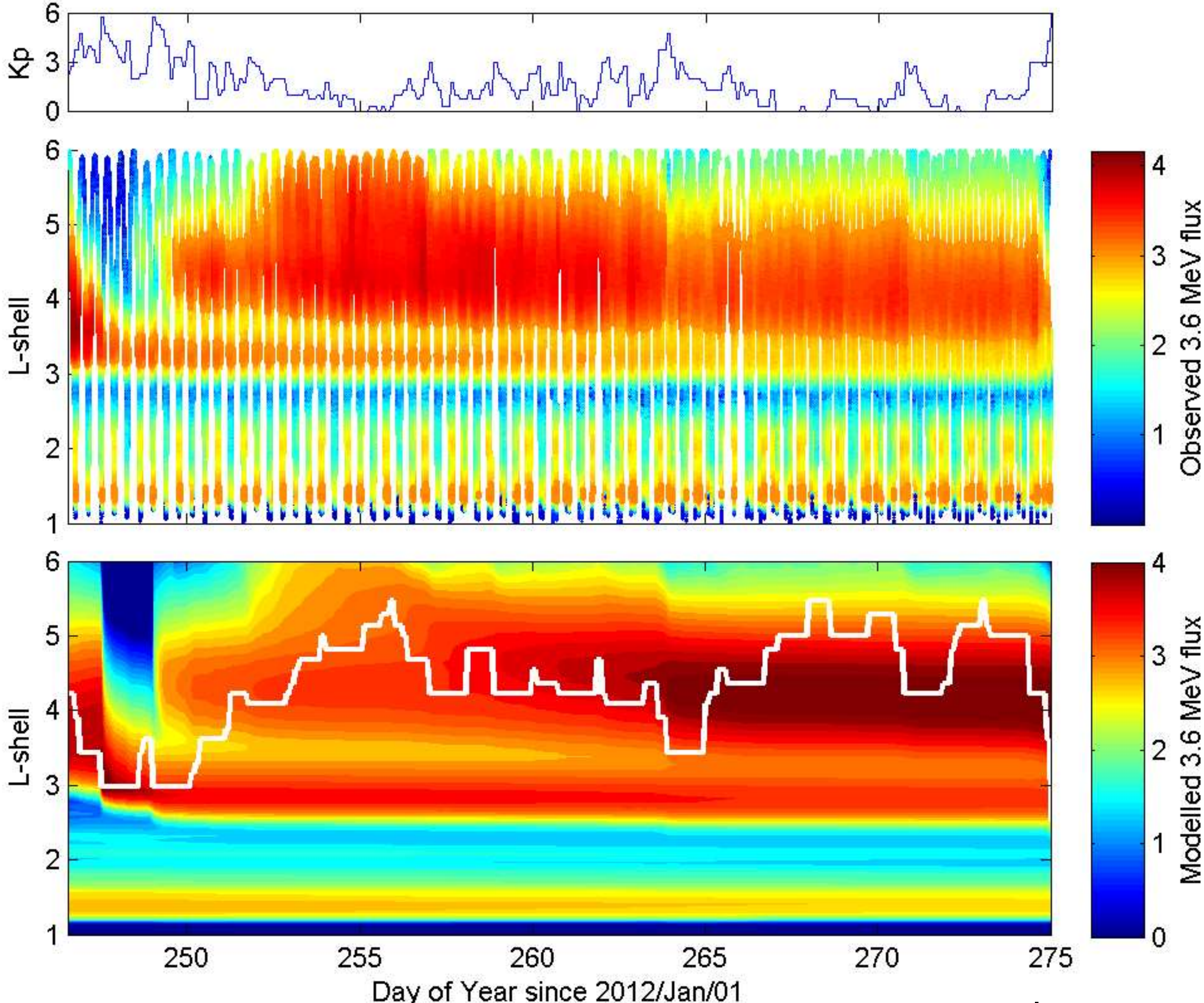


Ozeke et al. GRL 2014.

Halloween 2003 Superstorm



Loto'aniu et al., JGR (2006).



Mann et al., In prep., 2015.

Conclusions

- MeV electron dynamics are strongly linked to Vsw - cf. Paulikas and Blake (1979) – see more recently Kellerman and Shprits (2012).
- ULF wave power is similarly strongly dependent on Vsw.
- ULF waves play an important role in radiation belt dynamics, and in our opinion provide the intermediary for the Paulikas and Blake relation.
- Accurate specification of ULF waves power is critical for accurate modelling of the belt – both inward and outward transport.
- Accurate specification of outer boundary condition is also critical.
- Opportunity for ISWI – real-time magnetometer measurements for modelling transport of MeV electrons in the radiation belts.
- Low and mid-latitudes especially important for slot filling events.

Role for ISWI magnetometer data in space weather radiation belt data products – even though monitored from the ground!

Future operational space weather data product – collaborators welcome!