Major Results from the MAARBLE FP-7 Space Project

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UNIVERSITY OF ALBERTA QUAECUMQUE VERA

UCLA

SEVENTH FRAMEWORK PROGRAMME

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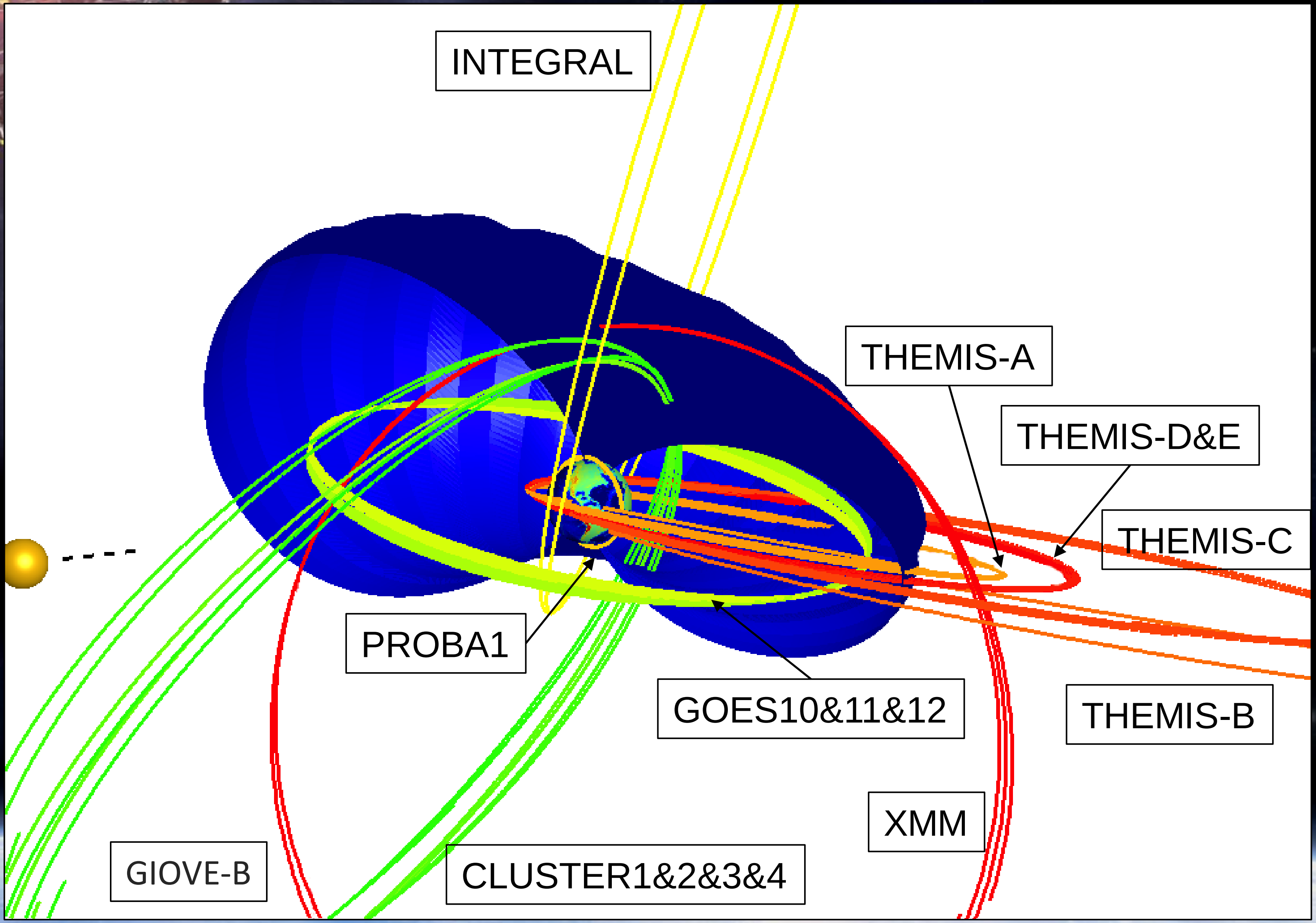
D. Turner

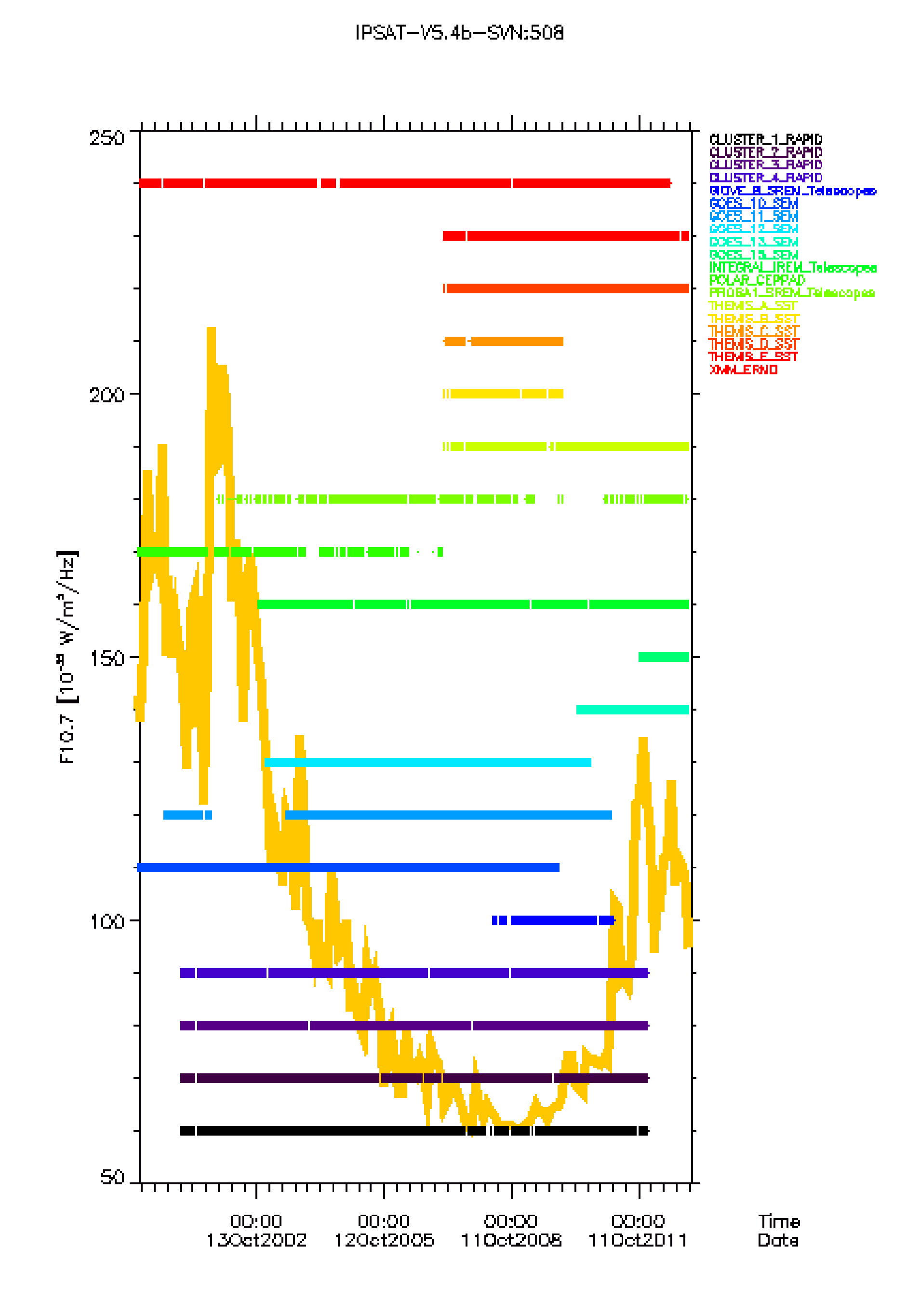
MAARBLE Work

- Monitoring, Analyzing & Assessing Radiation Belt Loss & Energization (MAARBLE)
- Three year European Commission FP7-SPACE-2011-1 Collaborative Project
- Particle data cross calibration, processing, and data assimilation model development and use.
- New waves and particle database available at the Cluster Science Archive (formerly at CAA).
- Scientific research and discovery.

Particle Database



Temporal Data Coverage



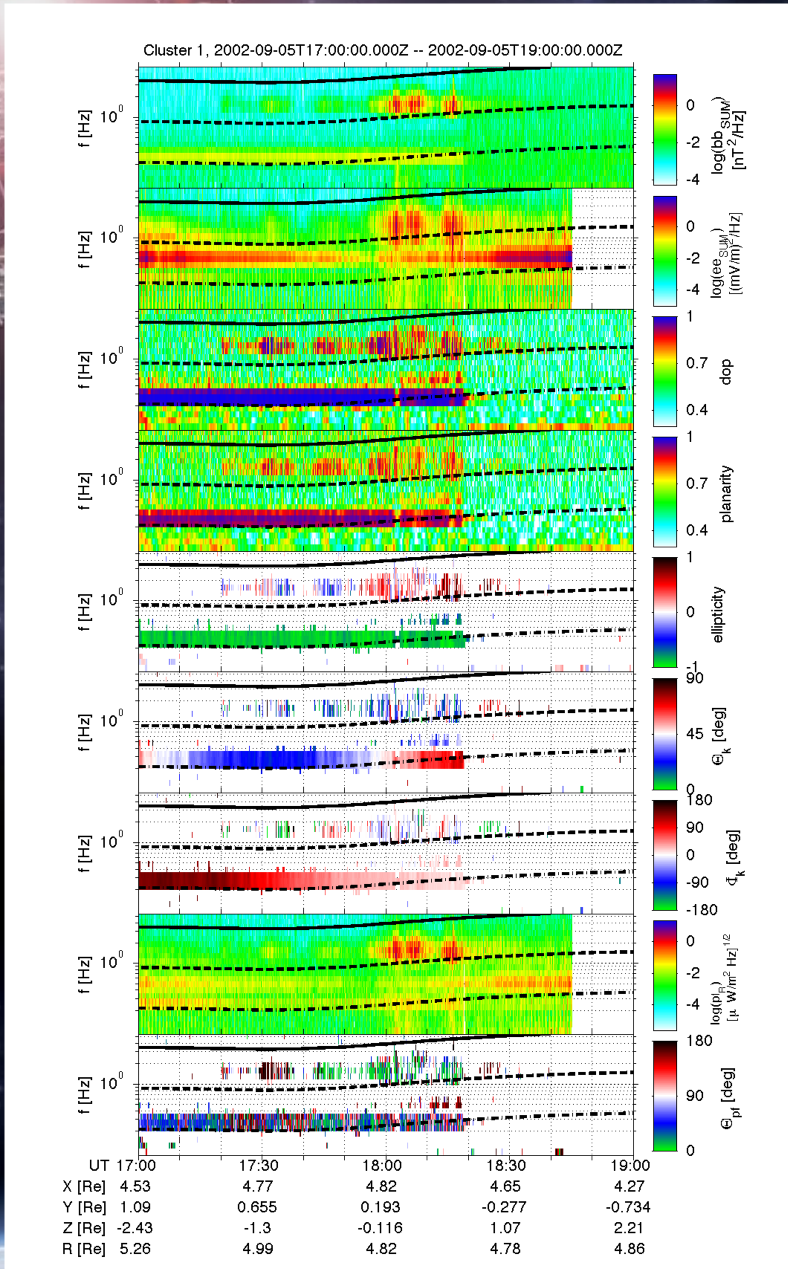
Ground and Satellite Wave Database

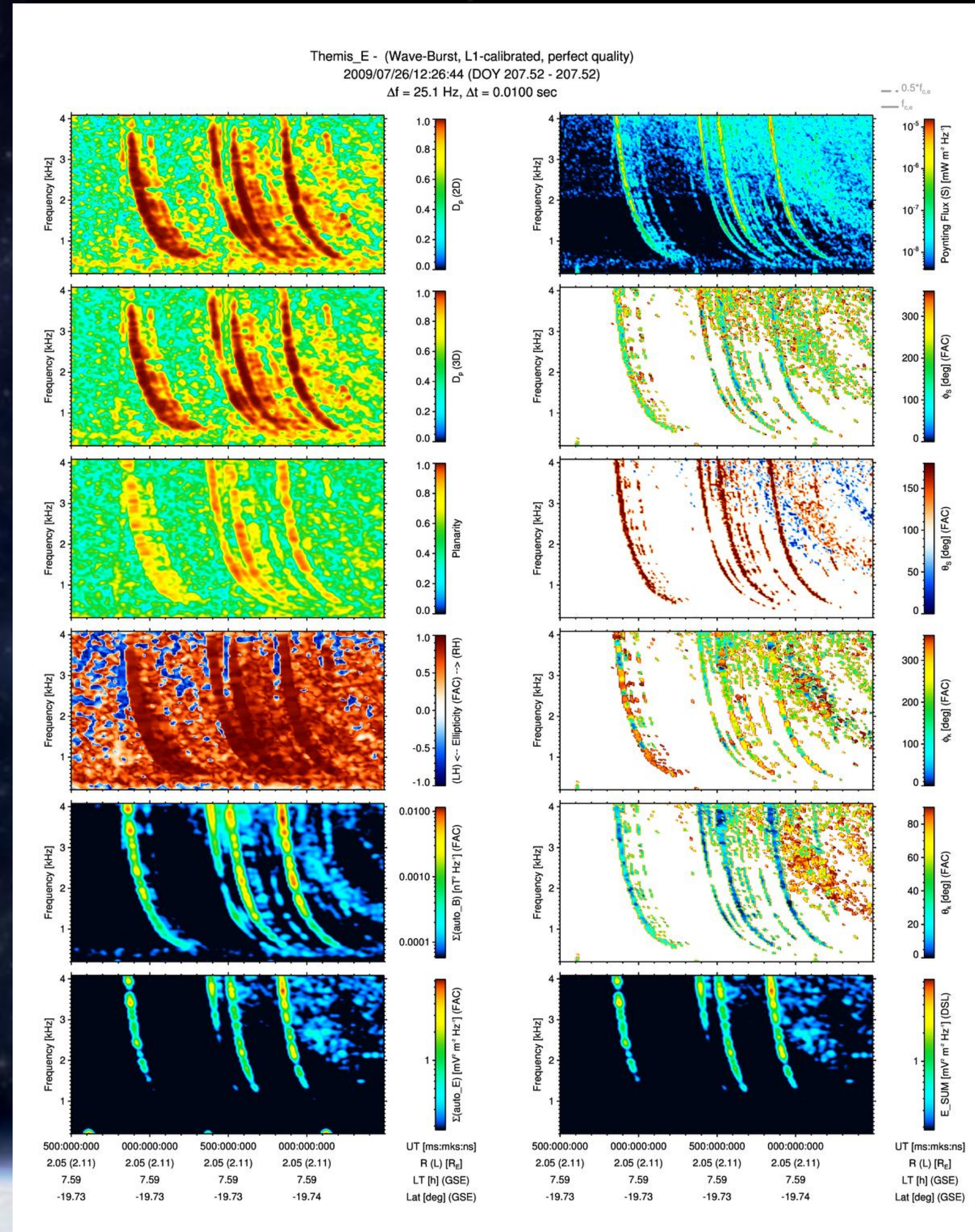
- Example: Spacecraft Wave Power and Polarisation

Table: Wave parameters

Name	Units	Description
Time	ISO time	Time tags
Frequency	Hz	Interval centred frequency tag
Frequency_BHW	Hz	Frequency bin half widths
BB_xxyyzz_fac	nT^2 Hz^-1	B Power spectral density
KSVD_fac	deg, deg	Direction of propagation (SVD) : polar and azimuthal angles.
ELLSVD	Unitless	Ellipticity of the polarization (SVD). Range: -1..1.
PLANSVD	Unitless	Planarity of polarization (SVD). Range: 0..1.
POLSVD	Unitless	Degree of polarization in the polarization plane (SVD). Range: 0..1.
DOP	Unitless	3D degree of polarization defined in Samson (1973).
BMAG	nT	Magnitude of the DC magnetic field.
EE_xxyyzz_fac	mV^2 m^-2 Hz^-1	E Power spectral density
EESUM_xxyy_isr2		Sum of E Power spectral density in two measured components in the spacecraft spin plane
PV*,**	W/m^2/Hz, deg, deg	Poynting vector : amplitude, polar and azimuthan angles

*subject to availability of E measurement.


Cluster 1, 2002-09-05T17:00:00.000Z -- 2002-09-05T19:00:00.000Z
f [Hz]
log(bb_SUM) [nT^2/Hz]
log(ee_SUM) [(mV/m)^2/Hz]
dop
planarity
ellipticity
Θ_k [deg]
Φ_k [deg]
log(p_R) [μ W/m^2 Hz]^1/2
Θ_pf [deg]
UT 17:00 17:30 18:00 18:30 19:00
X [Re] 4.53 4.77 4.82 4.65 4.27
Y [Re] 1.09 0.655 0.193 -0.277 -0.734
Z [Re] -2.43 -1.3 -0.116 1.07 2.21
R [Re] 5.26 4.99 4.82 4.78 4.86


Themis_E - (Wave-Burst, L1-calibrated, perfect quality)
2009/07/26/12:26:44 (DOY 207.52 - 207.52)
Δf = 25.1 Hz, Δt = 0.0100 sec
Frequency [kHz]
D_p (2D)
D_p (3D)
Planarity
(LH) <-- Ellipticity (FAC) --> (RH)
Σ(auto_B) [nT² Hz⁻¹] (FAC)
Σ(auto_E) [mV² m⁻² Hz⁻¹] (FAC)
Poynting Flux (S) [mW m⁻² Hz⁻¹]
φ_S [deg] (FAC)
θ_S [deg] (FAC)
φ_k [deg] (FAC)
θ_k [deg] (FAC)
E_SUM [mV² m⁻² Hz⁻¹] (DSL)
UT [ms:mks:ns]
R (L) [R_E]
LT [h] (GSE)
Lat [deg] (GSE)
500:000:000 000:000:000 500:000:000 000:000:000
2.05 (2.11)
7.59
-19.73 -19.73 -19.73 -19.74

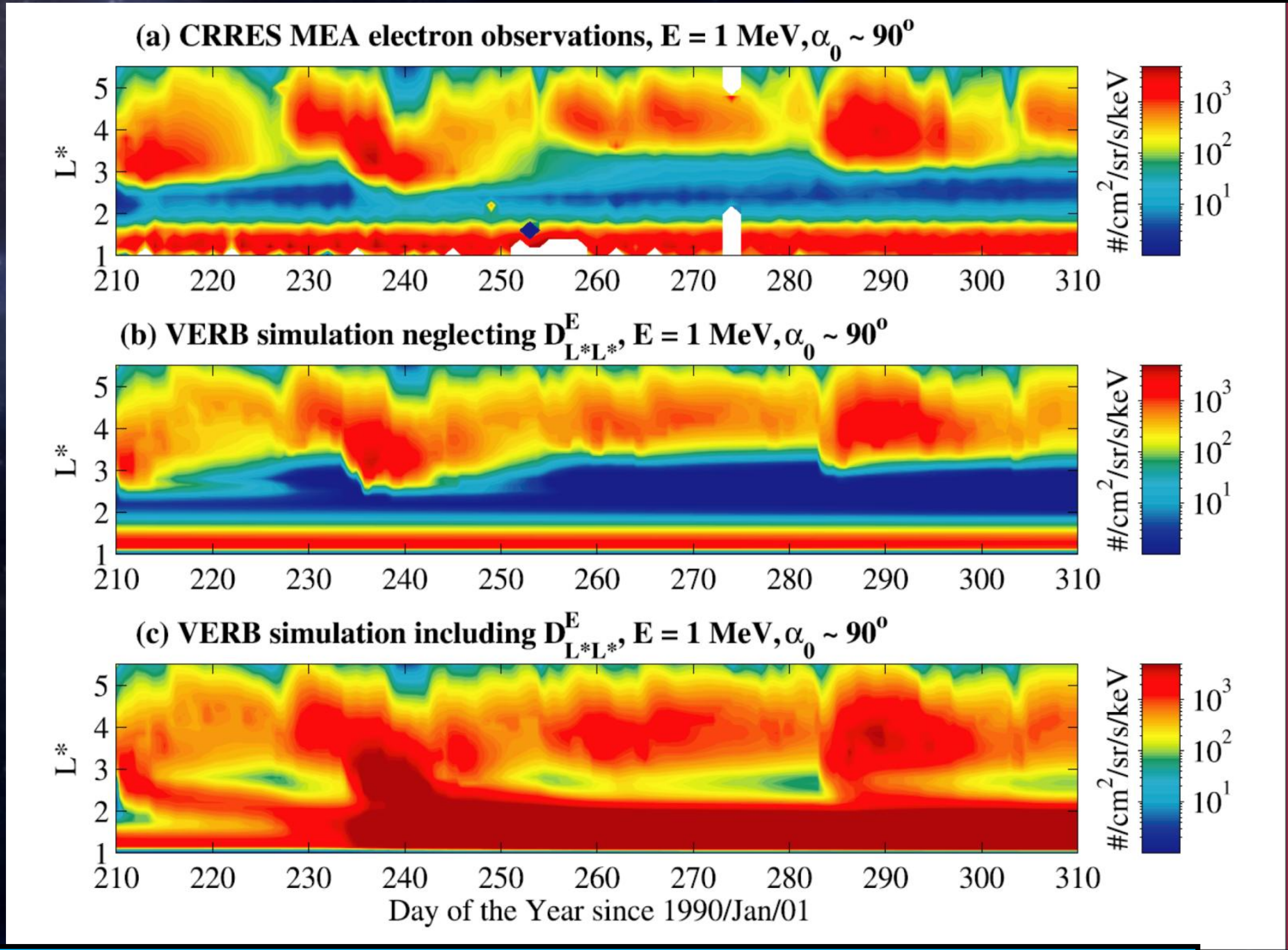
Pc5 ULF Wave Radial Diffusion

Motivation

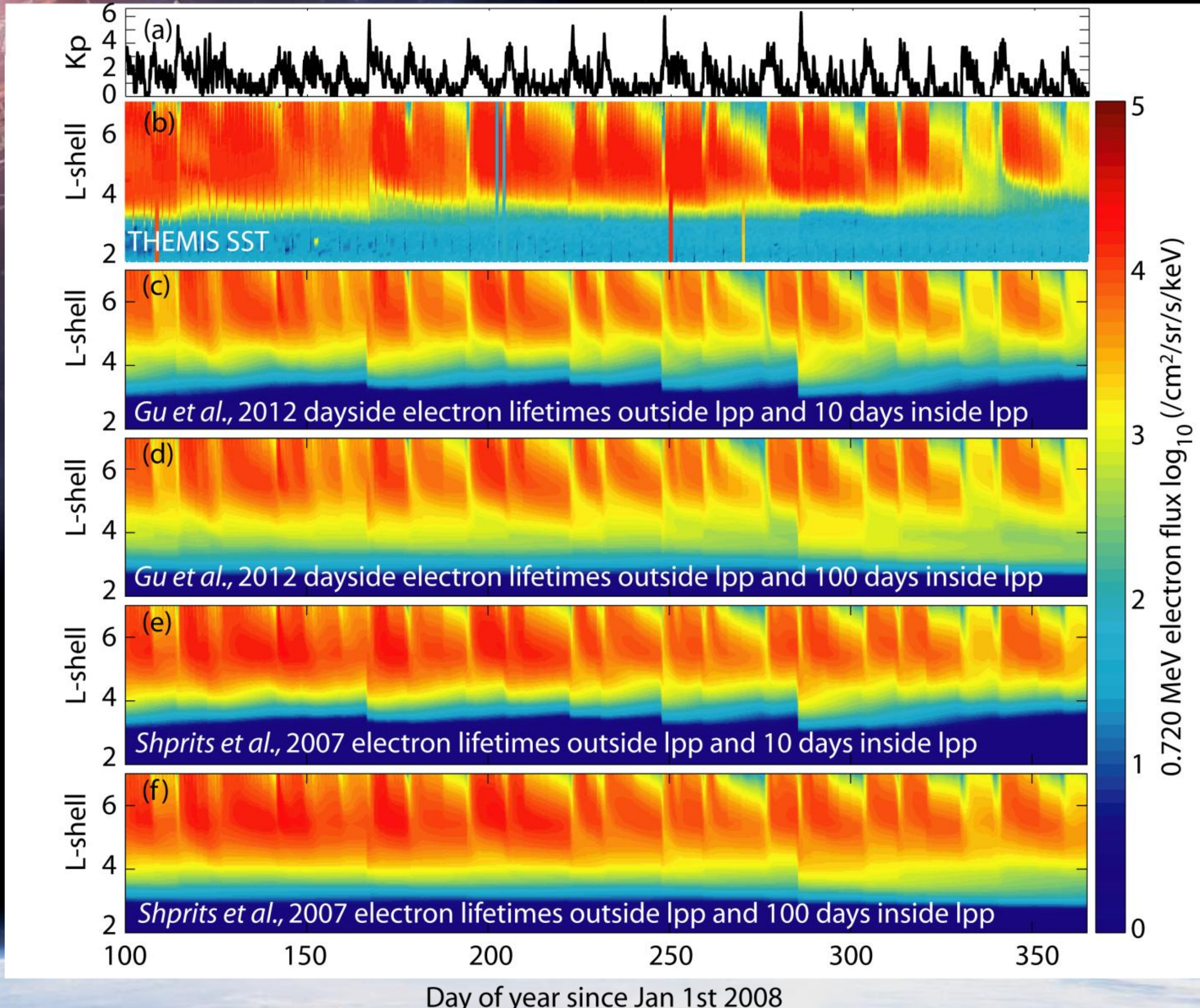
VERB model runs with Brautigam & Albert, JGR, 2000 diffusion coefficients

EM ULF waves only

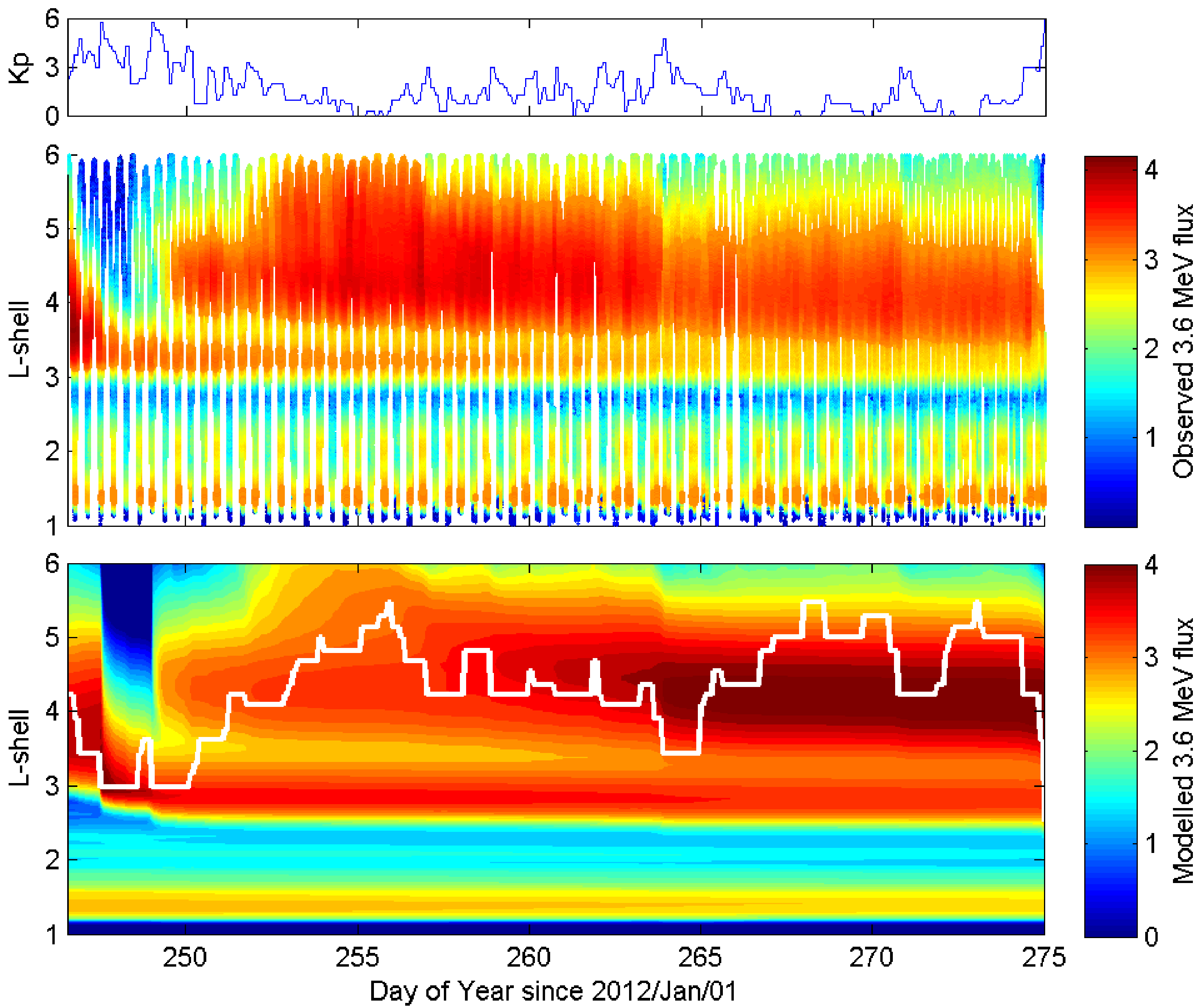
EM + electrostatic ULF fluctuations

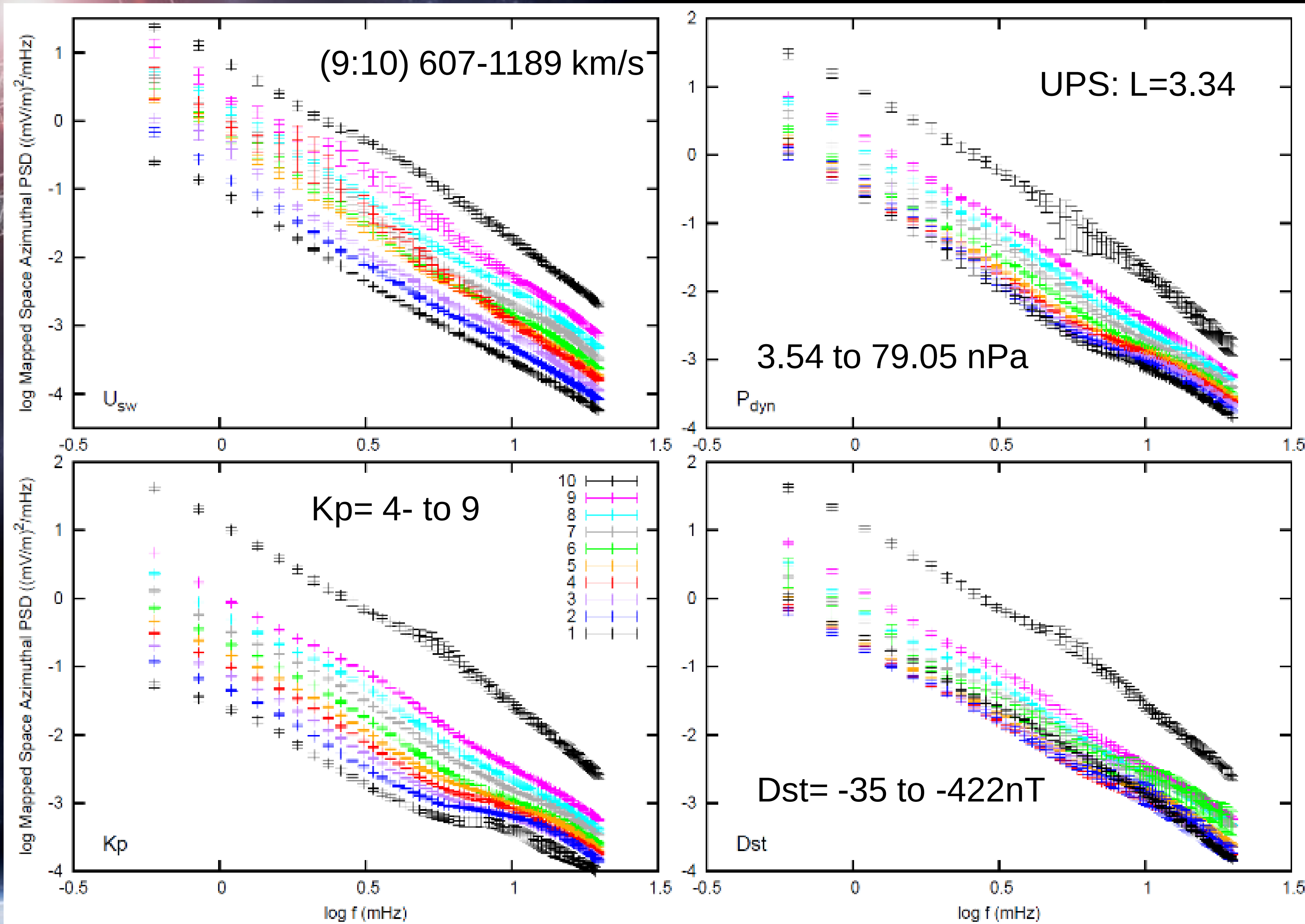


"More accurate models of radial diffusion rates should be determined in future studies and will require more accurate observations of electrostatic and electromagnetic fluctuations at low L-shells."- Kim et al

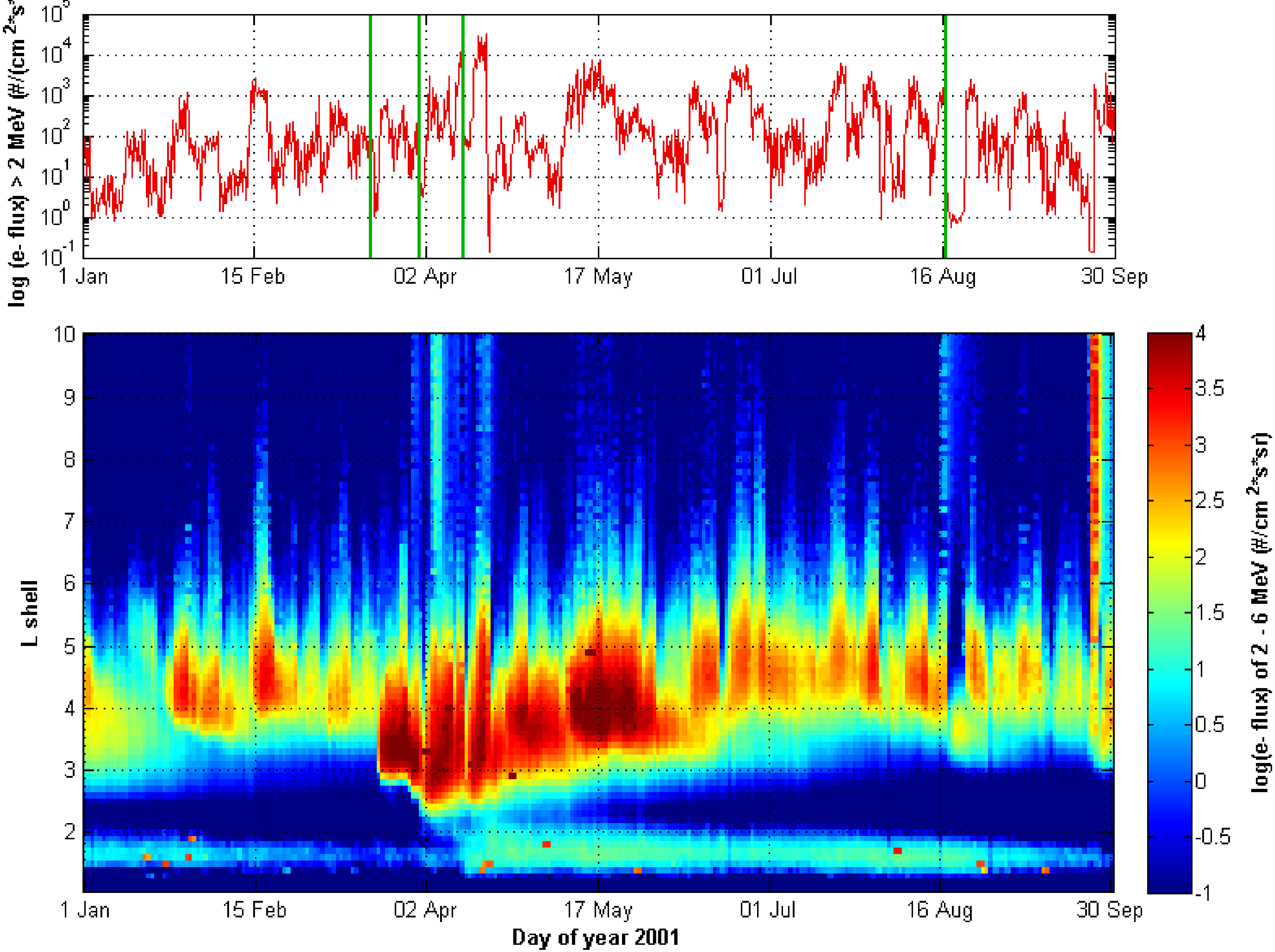


Kp
(a)
(b)
L-shell
THEMIS SST
(c)
Gu et al., 2012 dayside electron lifetimes outside lpp and 10 days inside lpp
(d)
Gu et al., 2012 dayside electron lifetimes outside lpp and 100 days inside lpp
(e)
Shprits et al., 2007 electron lifetimes outside lpp and 10 days inside lpp
(f)
Shprits et al., 2007 electron lifetimes outside lpp and 100 days inside lpp
100 150 200 250 300 350
Day of year since Jan 1st 2008
0.720 MeV electron flux log10 (/cm2/sr/s/keV)


Kp
L-shell
L-shell
Observed 3.6 MeV flux
Modelled 3.6 MeV flux
Day of Year since 2012/Jan/01

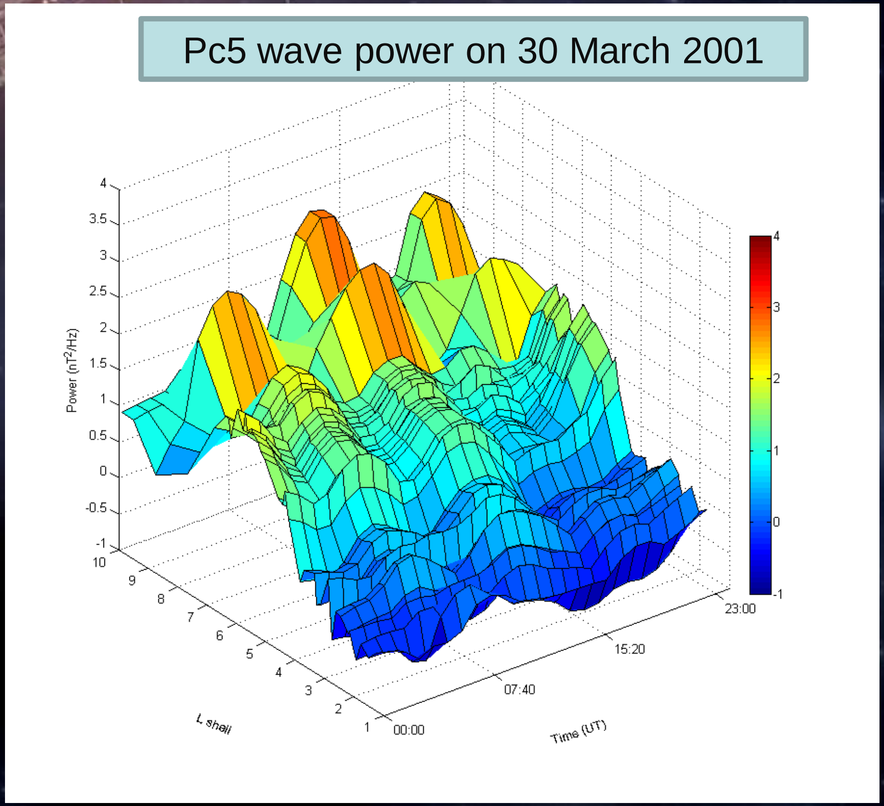


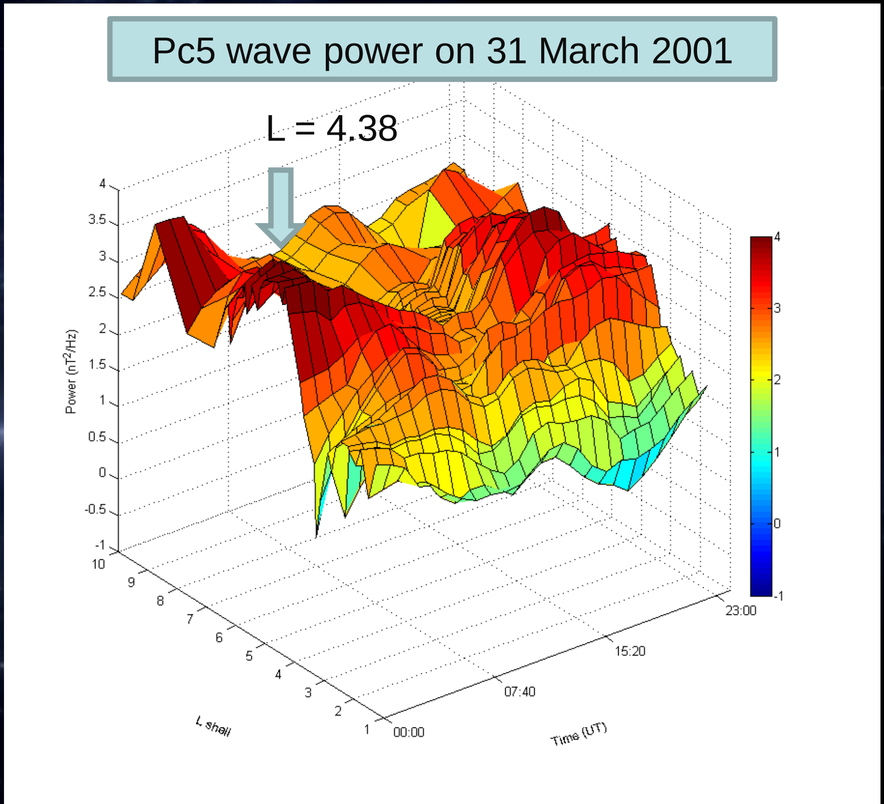
Dimitrakoudis et al.



log (e- flux) > 2 MeV (#/(cm 2*s*sr))
1 Jan
15 Feb
02 Apr
17 May
01 Jul
16 Aug
30 Sep
L shell
log(e- flux) of 2 - 6 MeV (#/cm 2*s*sr)
Day of year 2001

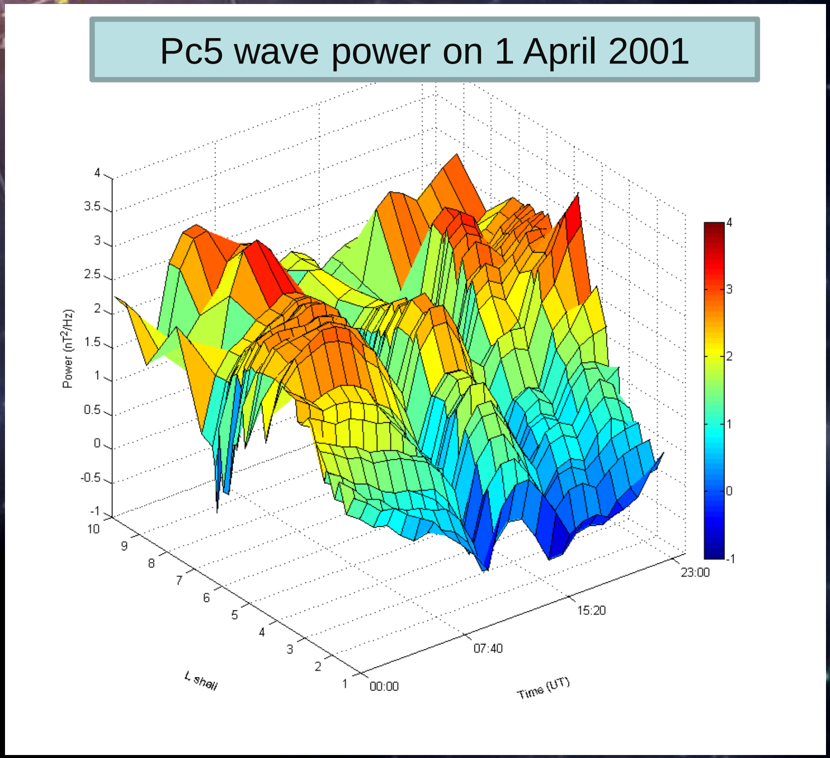
Electron acceleration in the Van Allen belts

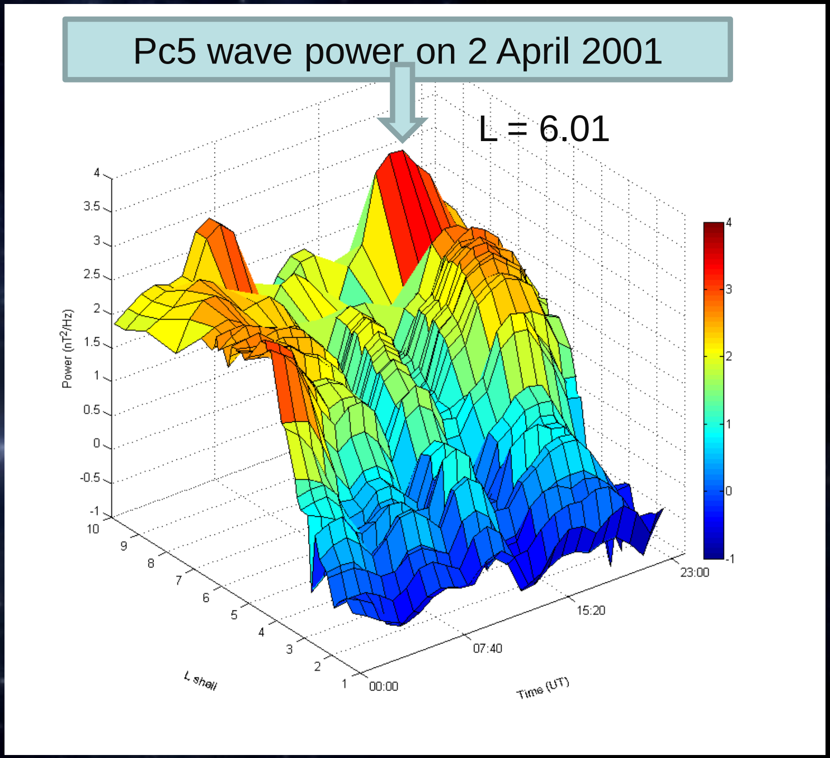




Inward penetration of Pc5 wave power
during the magnetic storm of 31 March 2001

Electron acceleration in the Van Allen belts

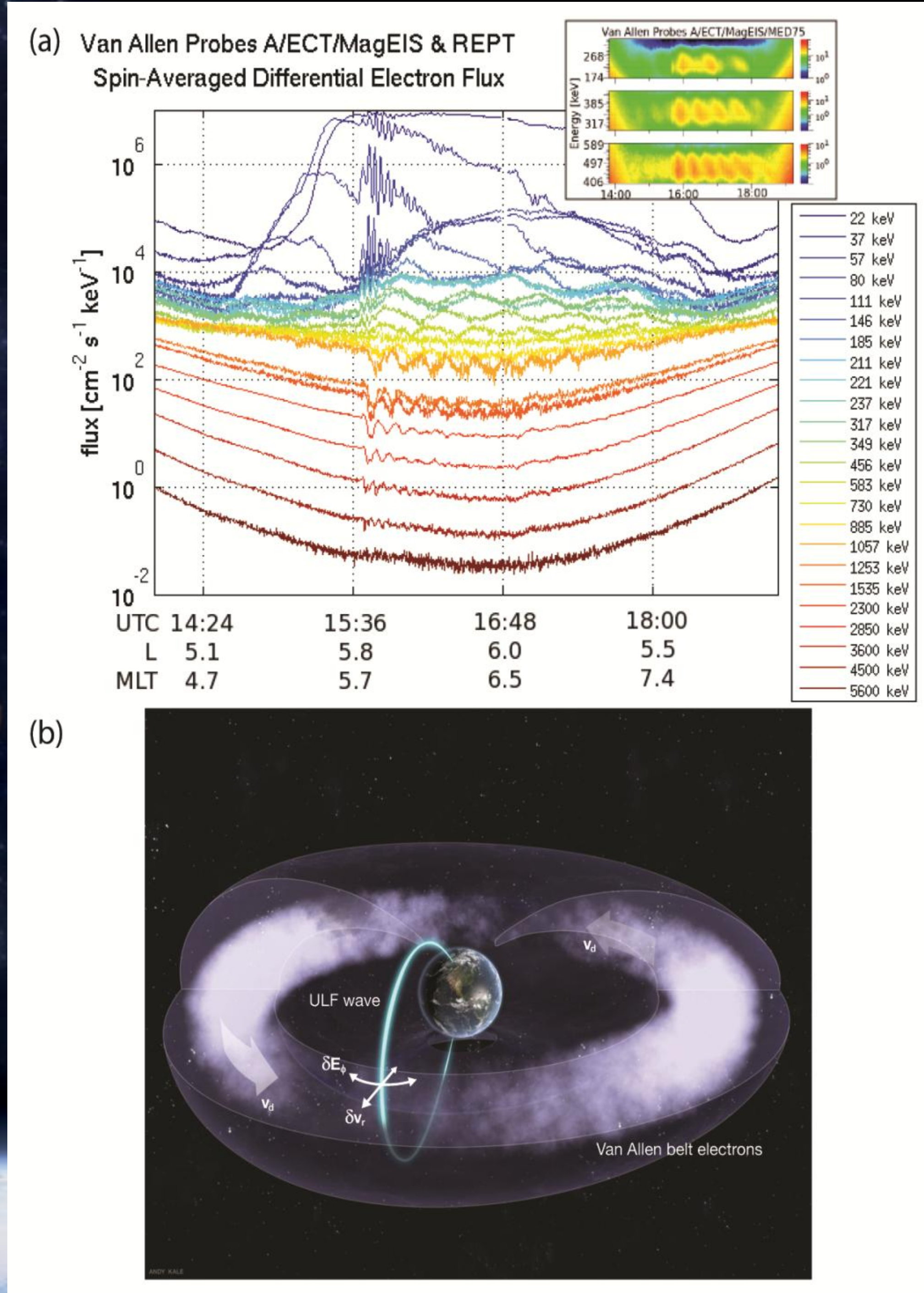




Pc5 wave power vary >5 orders of magnitude as a magnetic storm evolves and penetrate to lower L shells during the main phase

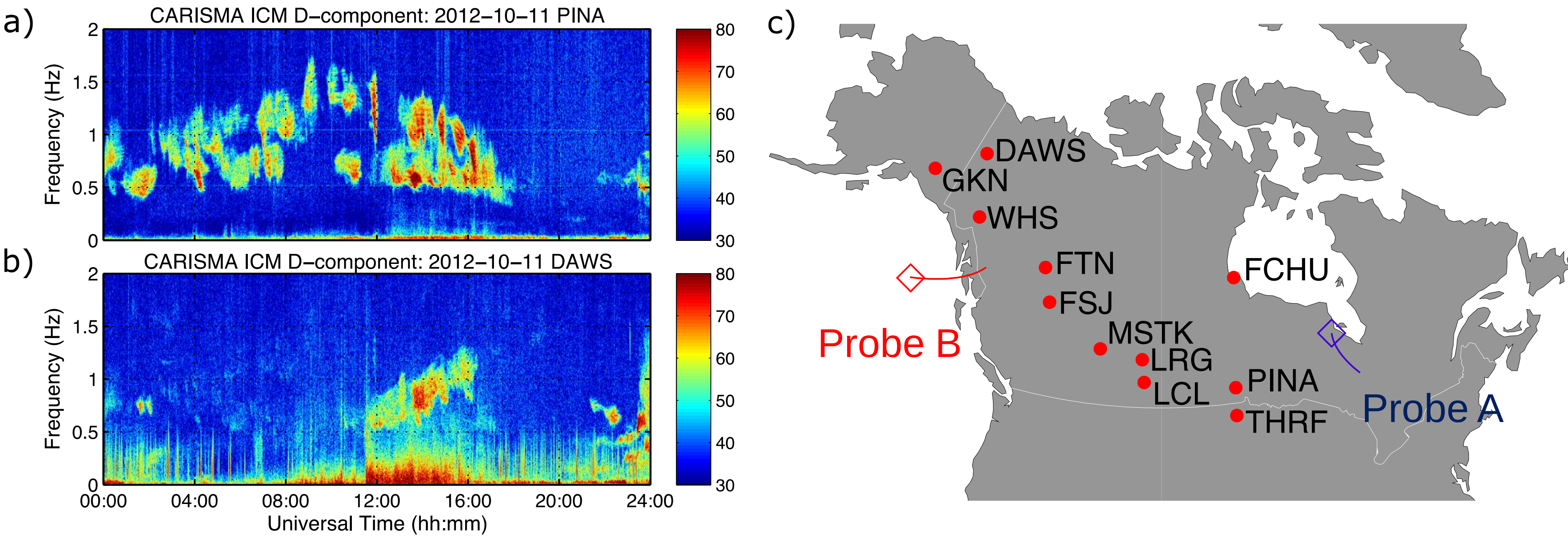
Multi-point Coherent Pc5 ULF Wave Interactions and Transport

- Propose alternative use of multi-point NASA Van Allen Probes data – unrivalled data quality and energy resolution.
- Mann et al. paper published in Nature Communications in September 2013.
- See also Claudepierre et al., GRL, 2013.



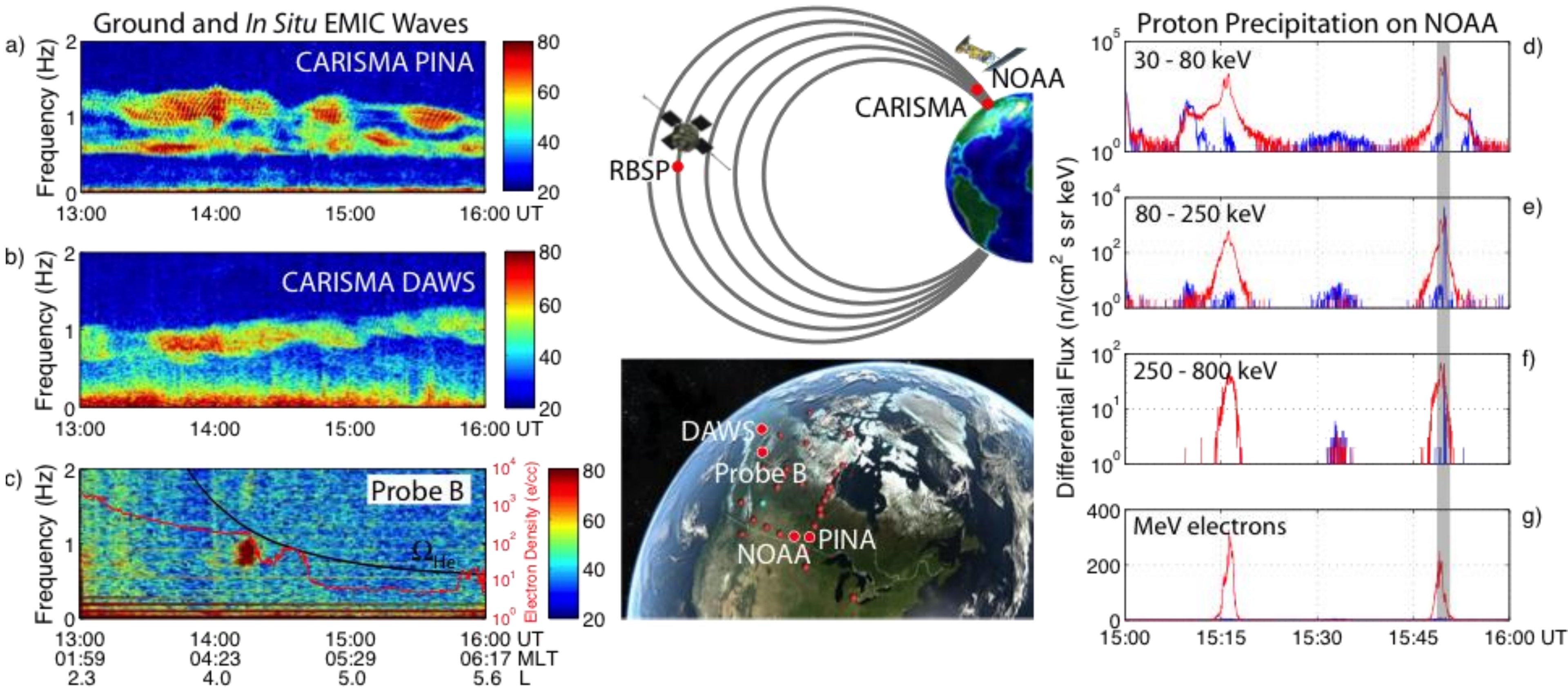
Excitation and Characterisation of EMIC and VLF Waves and Impacts on MeV Electrons

Long-lasting EMIC Event from October 11, 2012



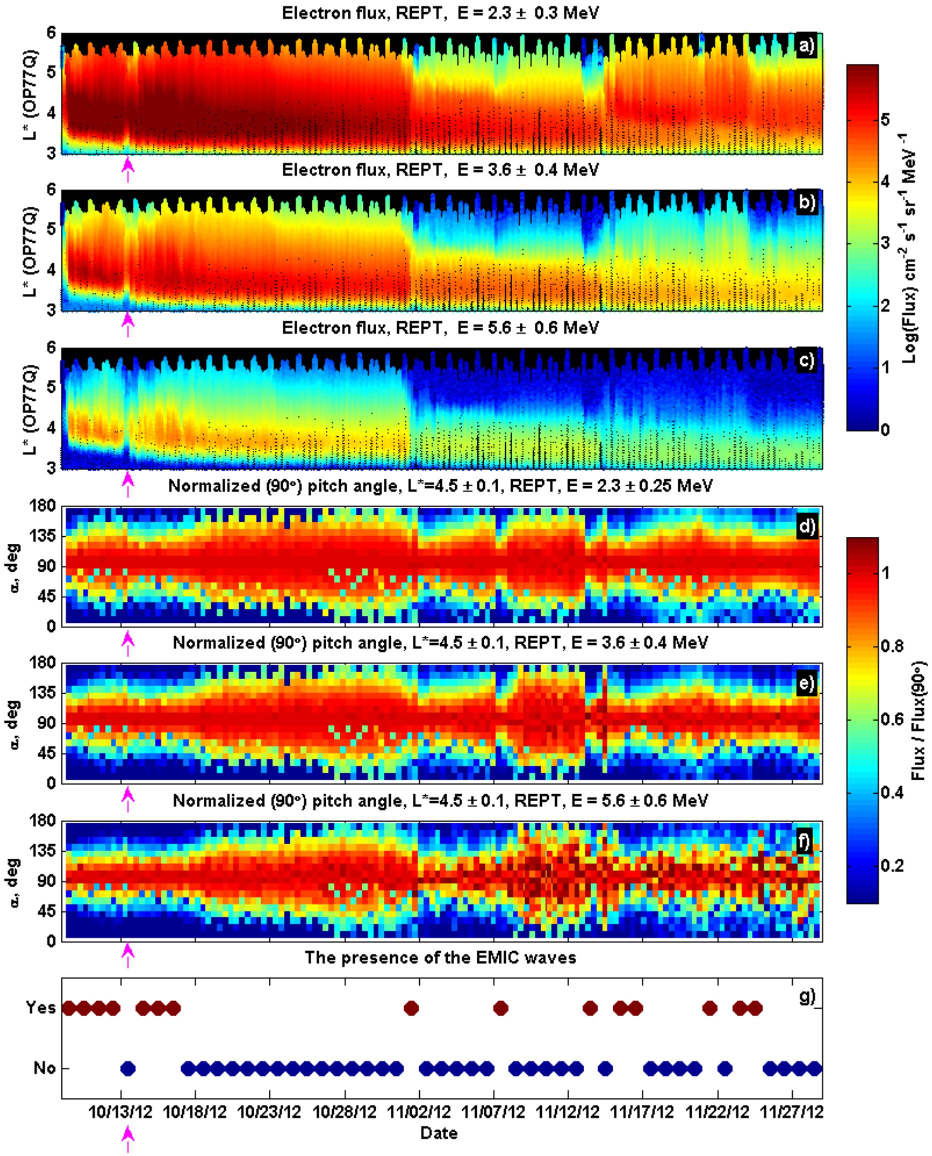
Magnetic field spectrogram from the CARISMA Pinawa station (L~4) and Dawson (L~6) on October 11, 2012.
This event resulted in two companion papers to Van Allen Probes GRL: Mann et al. GRL, 2014; Usanova et al., 2014.

Ground and Van Allen Probe EMICs: Impacts on MeV Electrons



Conjugate EMIC wave observations from the CARISMA magnetometers and the Van Allen Probes together with proton loss on the LEO-orbit NOAA POES satellite on October 11, 2012. (Mann et al., GRL., 2014; Usanova et al., GRL, 2014)

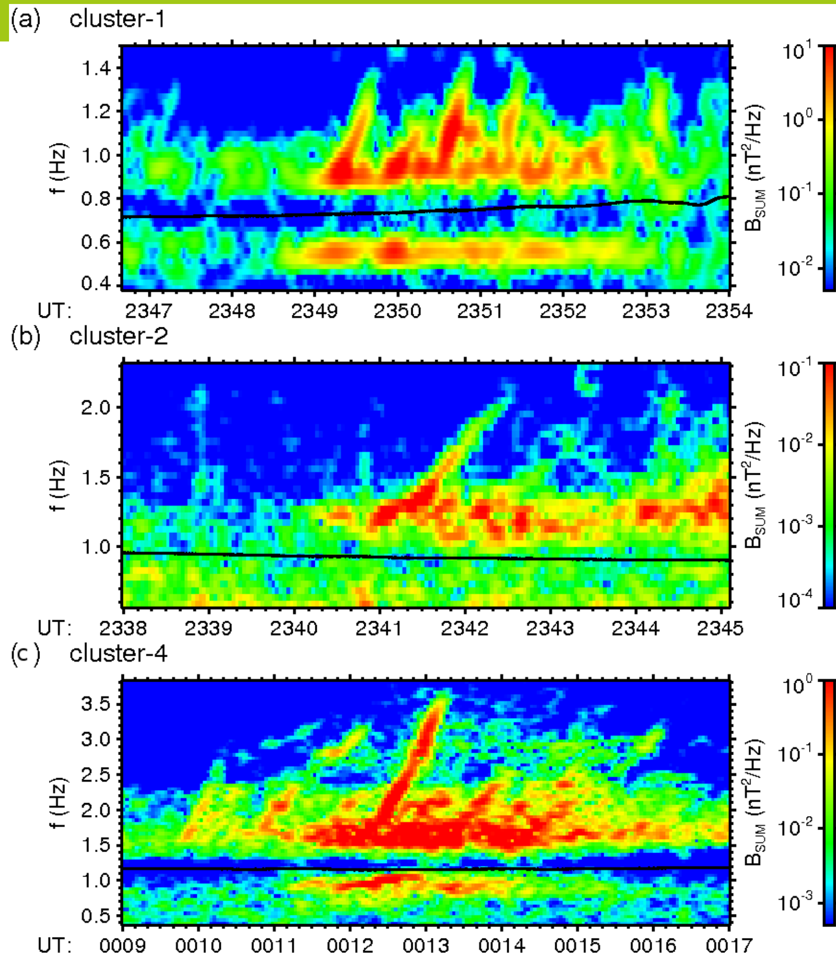
Electron Pitch-Angle Scattering



Differential electron flux as a function of L* (a-c), and differential flux as a function of PA, normalized by the 90-degree PA flux, at L*=4.5 (d-f) in the 2.3, 3.6, and 5.6 MeV energy channels,, and EMIC wave occurrence from L~4-4.5 on the ground (g)

between October 9 – November 29, 2012.

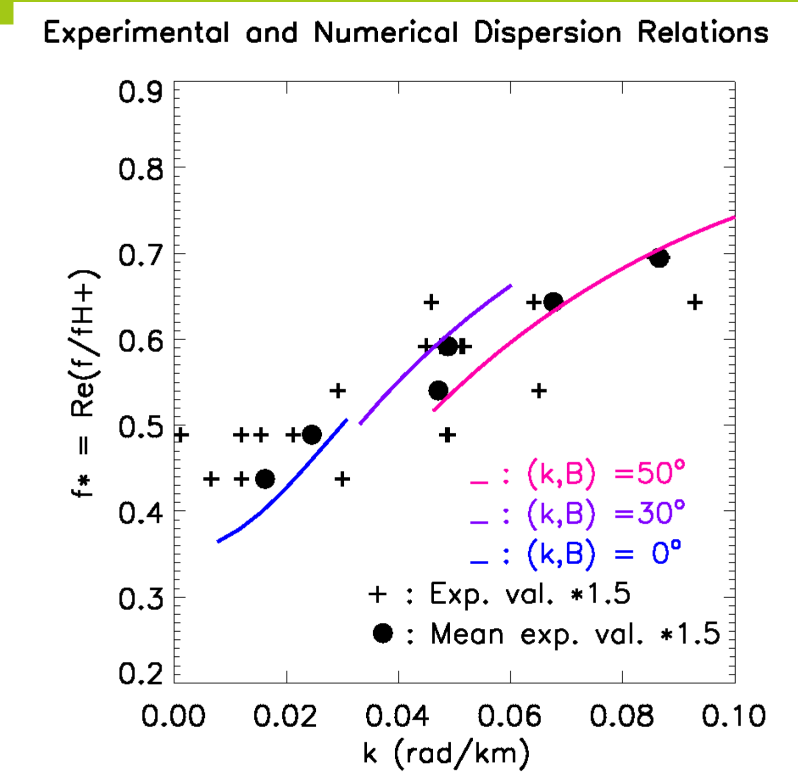
The purple arrow indicates the time of the minimum Dst in the consequent storm at 11 UT on October 13, 2012.



Cluster C1, C3 and C4 spacecraft observe EMIC triggered emissions with various frequency extents and various sweep rates within 20 minutes.

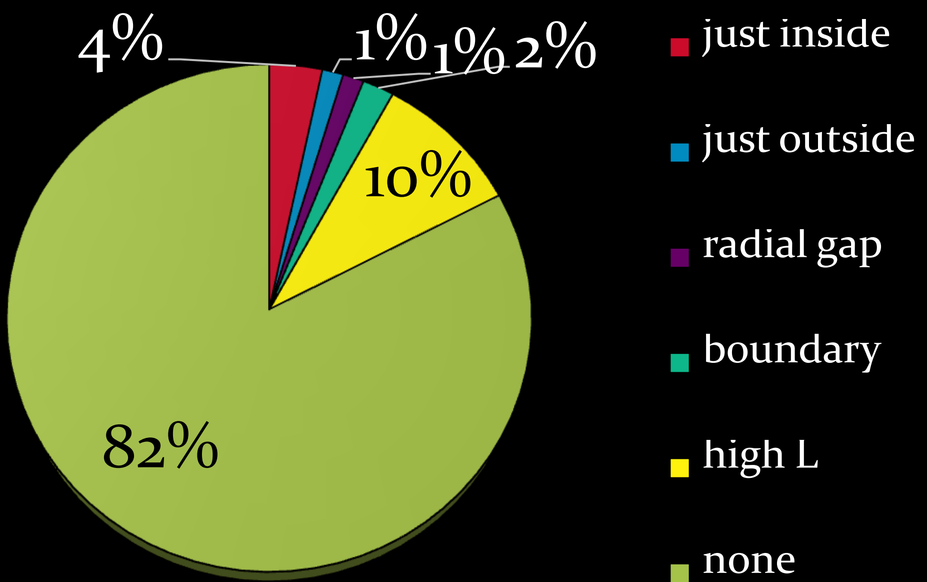
The location is the plasmapause nightside (26-27/03/2002). Energetic ring current ions were observed at the same time.

Such events permit to establish the in situ properties of EMIC triggered emission (*Grison et al*., JGR, 2013)



The observed dispersion of a rising tone (EMIC triggered emission) is obtained after direct estimation of the wavenumber (via a technique validated in *Grison et al*. JGR, accepted).

EMIC Waves at the Plasmapause?



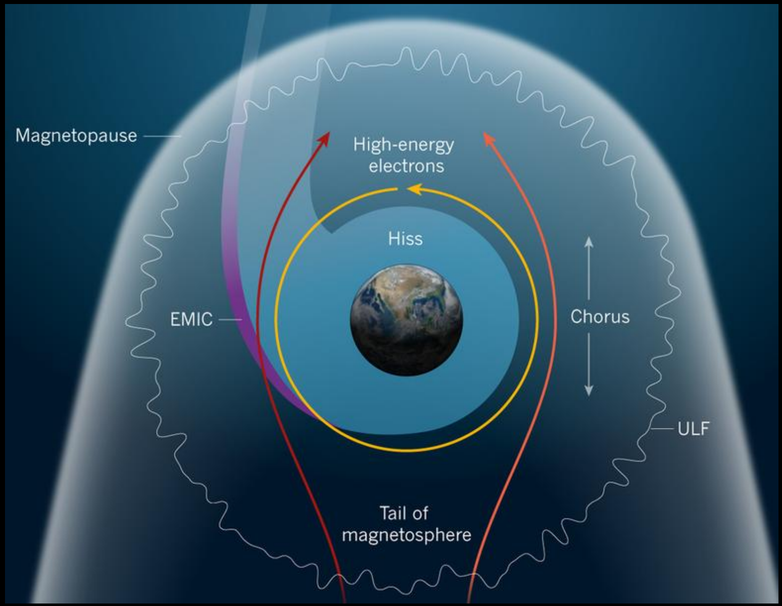


Figure taken from *Hudson [2013]*.

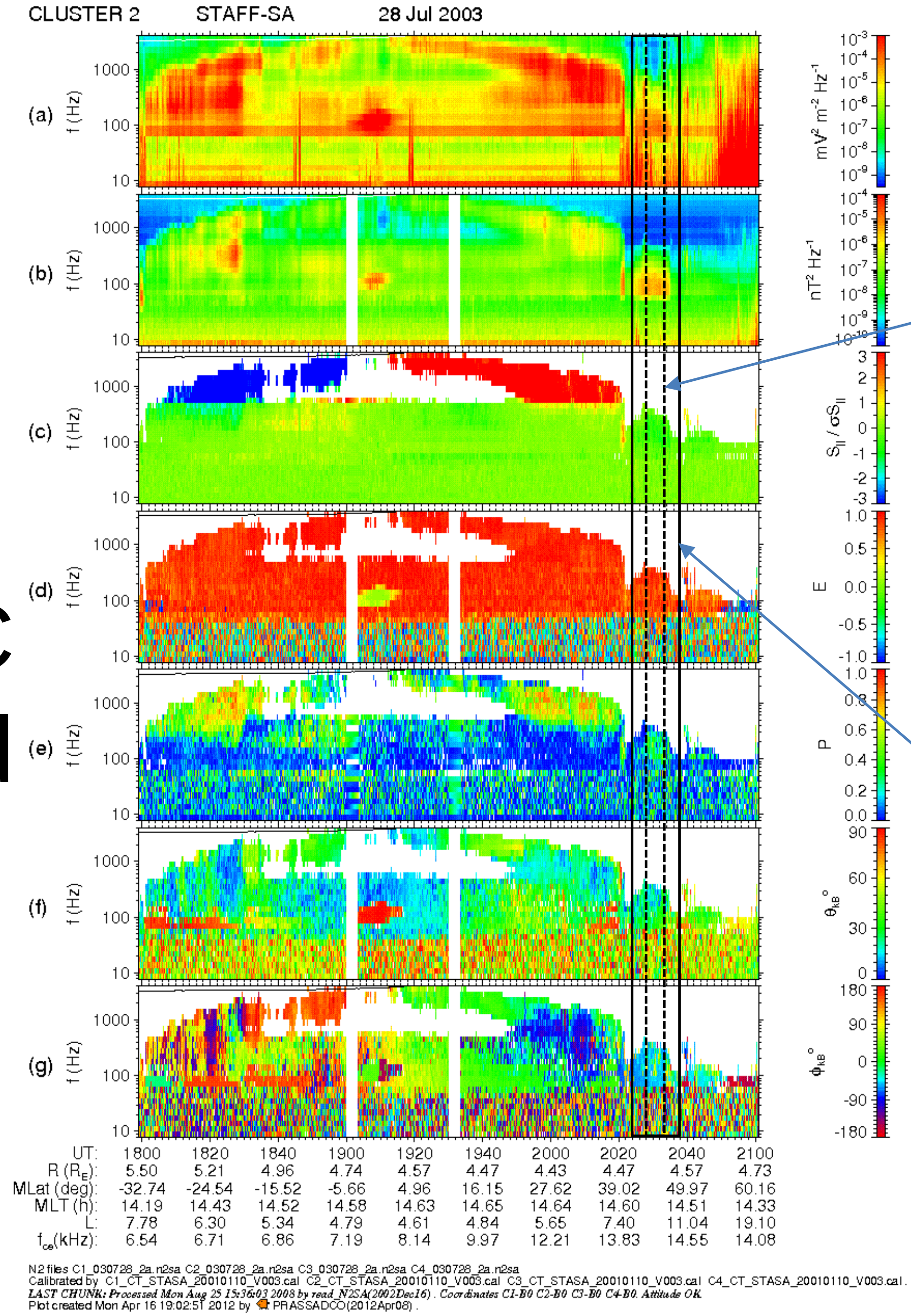
EMIC waves seen during 26 (18%) out of 148 plasmapause crossings.
Out of these 26 EMIC events

- 6 just inside;
- 1 just outside;
- 1 radial gap (outside and just inside);
- 3 at the boundary;
- 15 outside, at high L-shells.

- We observed 8 events just inside or at the boundary of the plasmapause in the duskside MLT sector (purple region).
- Average radial extent of these events was 0.8 R_E.

Usanova et al., 2014.

Link between VLF, EMIC waves and plumes?

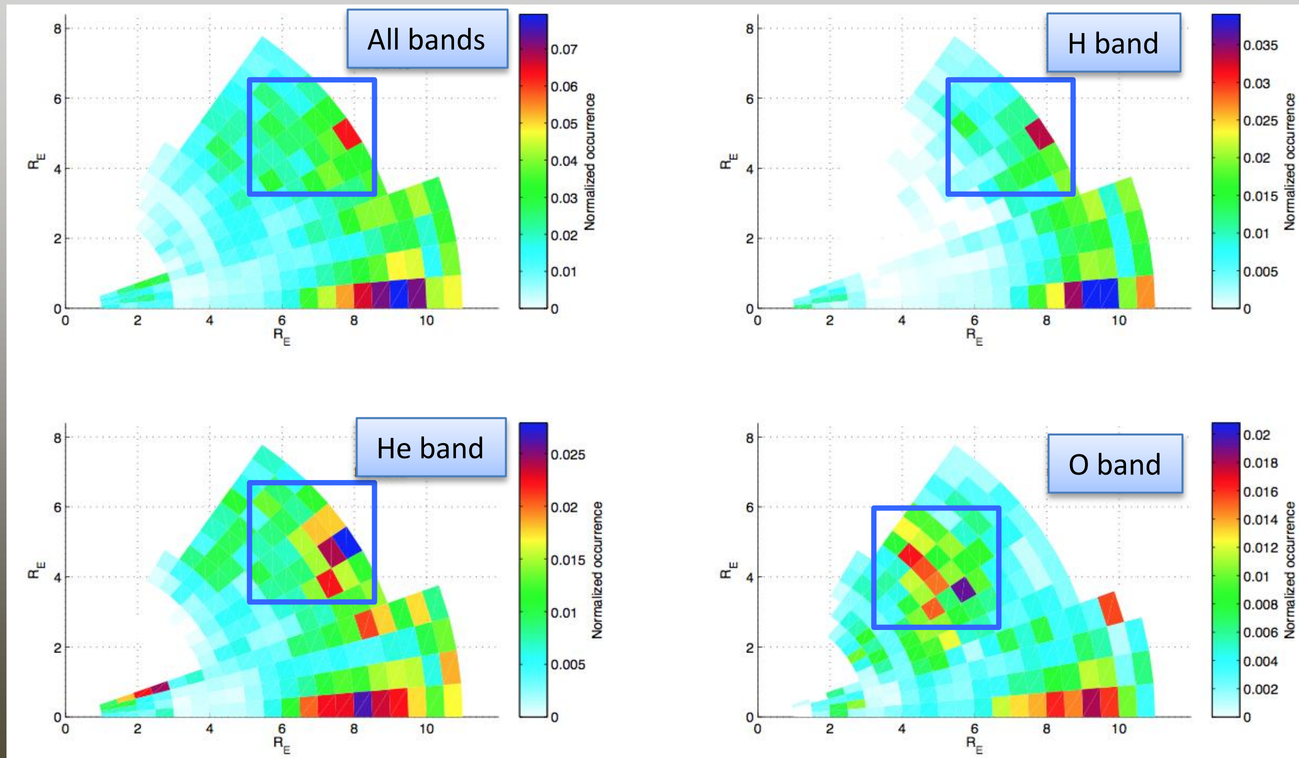


EMIC waves (Usanova et al. 2013).

Plume boundary: Darrouzet et al., (2010) Cluster statistics.

EMIC statistics from Cluster (polar) + THEMIS (equatorial)

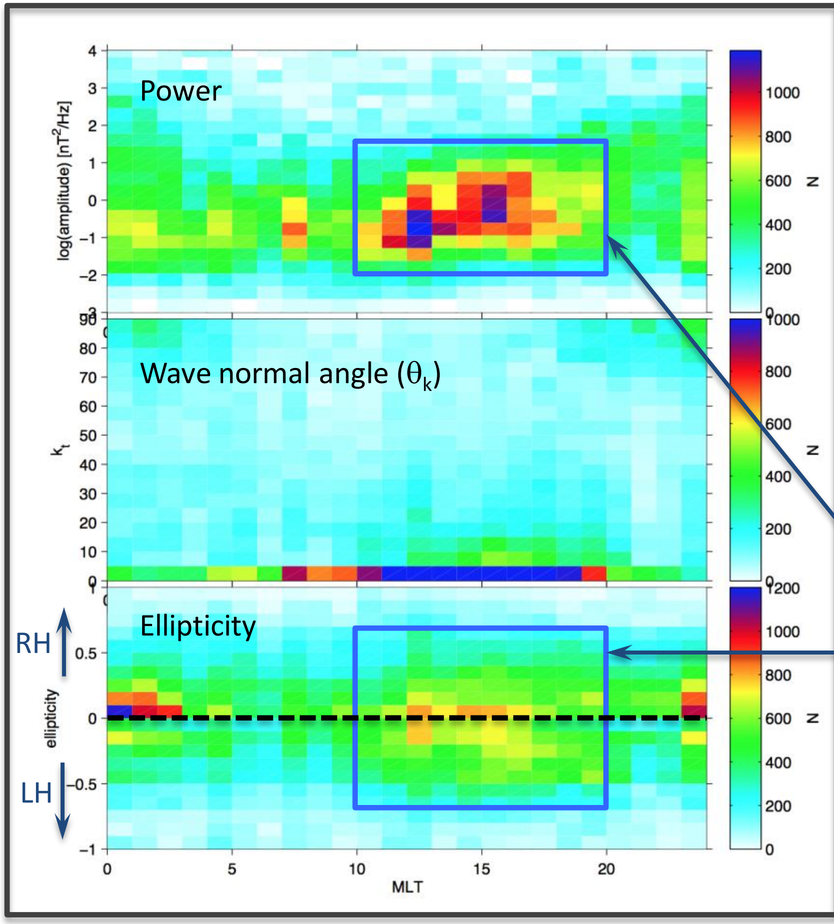
EMIC normalized occurrence in MLAT



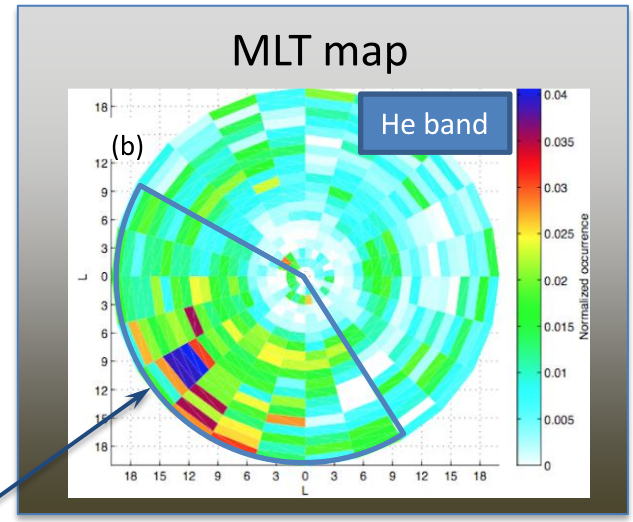
[Mella et al., 2014, in preparation]

An off-equatorial population of EMIC waves exists!

EMIC propagation and polarization properties



[Mella et al., 2014, in preparation]



EMIC Occurrence rate:

- Hydrogen band -> morning sector
- Helium band -> afternoon sector
- Oxygen band -> dusk sector

Typical range of <BB*> (magnetic power) is 1e-2 to 1e2 $nT^2\ Hz^{-1}$

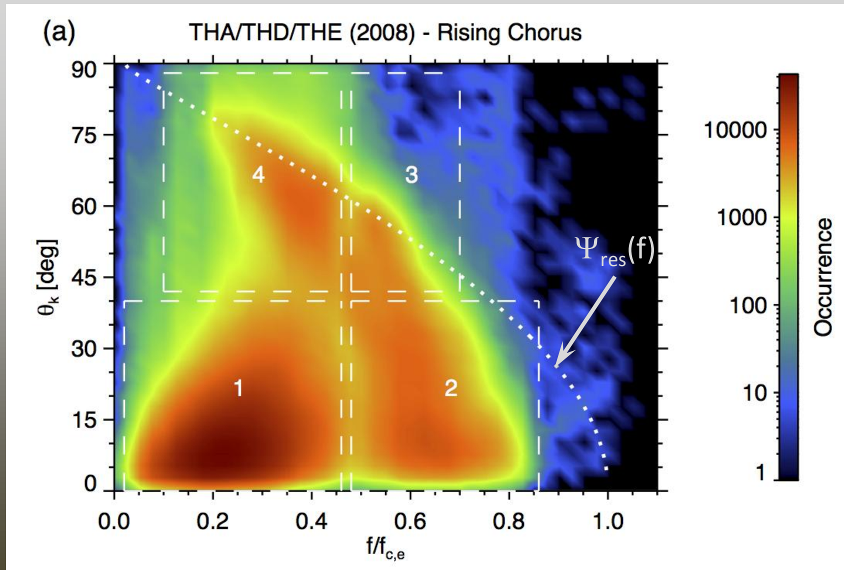
Most of the observed EMIC waves have wave normal angles very close to field aligned ($\theta_k < 5°$)

Ellipticity ranging from -0.5 to 0.5

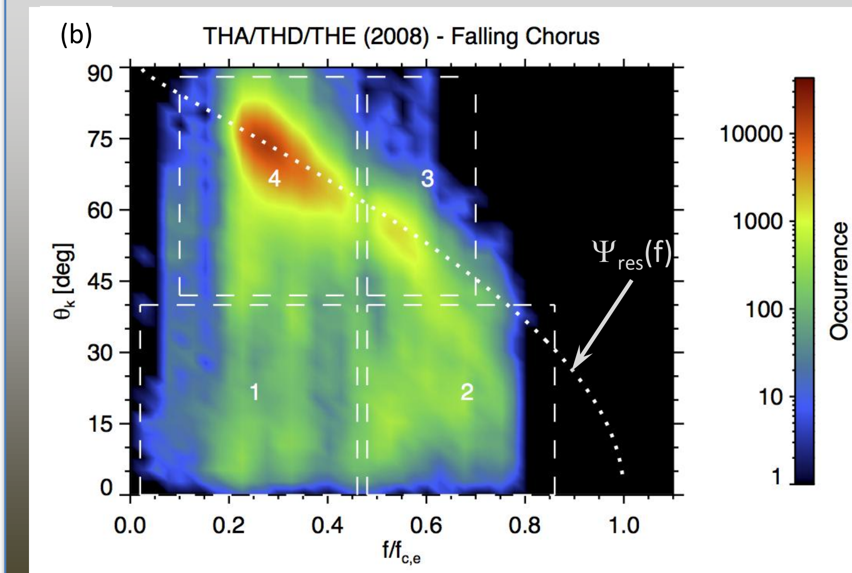
Chorus statistics from THEMIS - THA/THD/THE - year 2008

Normalized Frequency ($f/f_{c,e}$) vs. Wave normal angle (θ_k)

Rising-tone Chorus (spectral points)



Falling-tone Chorus (spectral points)



Most rising tone spectral points in lower band ($f < 0.5\ f_{c,e}$) with **k** quasi-parallel to $\mathbf{B_0}$ ($\theta_k < 30°$);

Also many scanned θ_k close to Ψ_{res} (Ψ_{res} ... resonance cone angle)

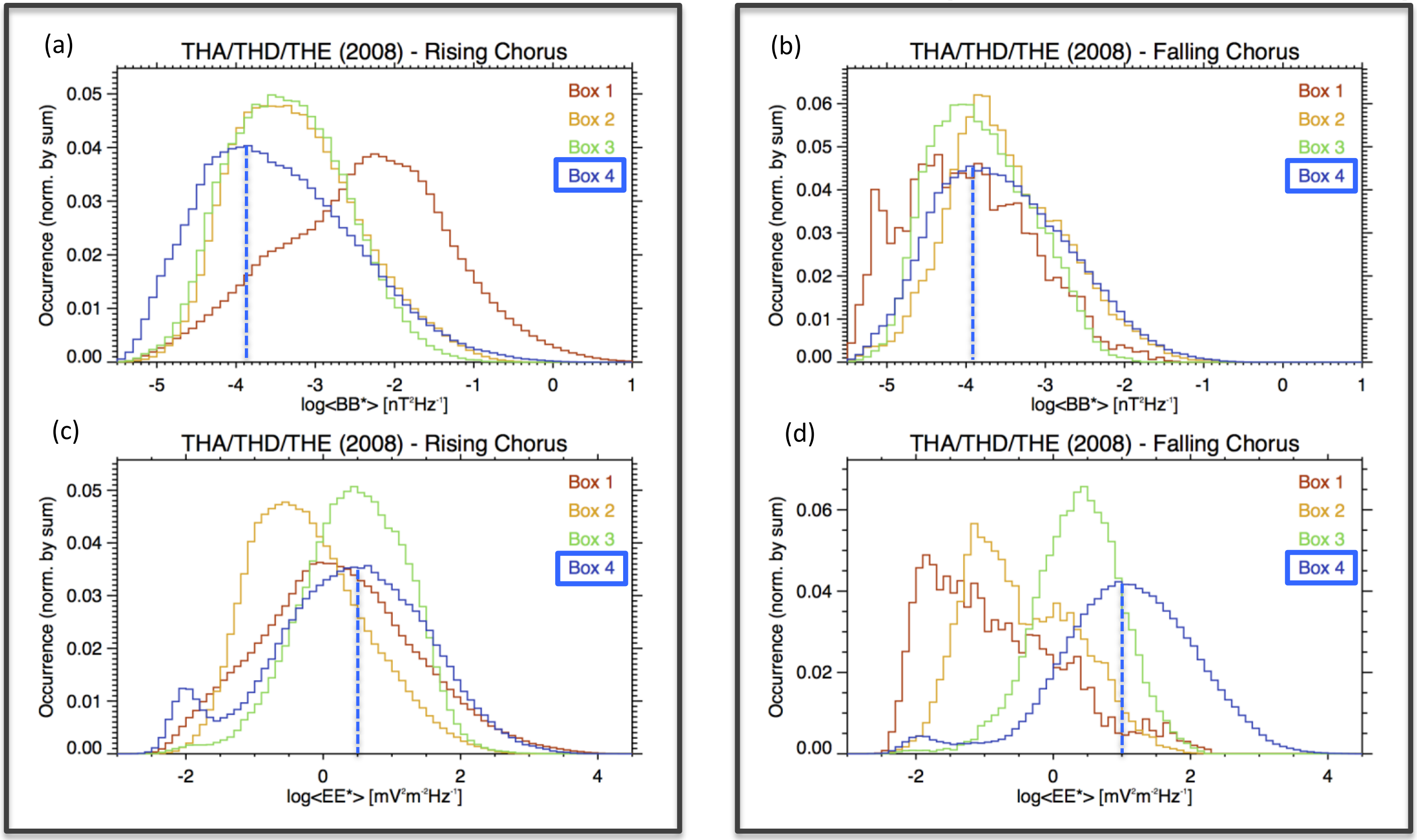
Most falling tone spectral points in lower band ($f < 0.5\ f_{c,e}$) with θ_k close to Ψ_{res}; (Ψ_{res} ... resonance cone angle)

High θ_k is generated already close to equatorial plane (source region);
THEMIS at $-16° < MLAT < +10°$

[Taubenschuss et al.,2014, submitted]

Comparison
Rising tones – Falling tones

[Taubenschuss et al.,2014, submitted]



Only Box 4 (lower band; $\theta_k > 40°$) contains enough data points from both groups for a direct comparison

Mean <BB*> (magnetic power) and <EE*> (electric power) in Box 4 are at similar levels;

<BB*>: 1e-4 vs. 1e-4 $nT^2 Hz^{-1}$

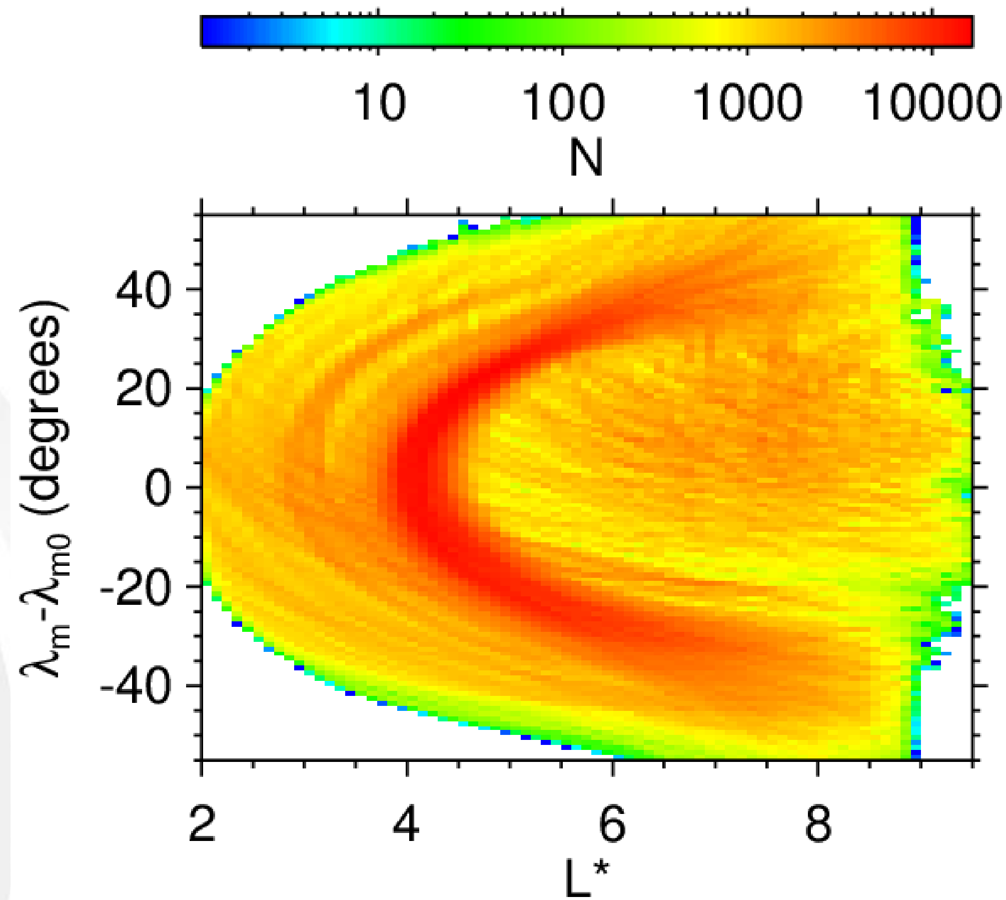
<EE*>: 5e-1 vs. 10e-1 $mV^2 m^{-2} Hz^{-1}$

Risers and Fallers in Box 4 are ~electrostatic (cB/E < 5) ... same type of wave, just different spectral drift

11 years of CLUSTER measurements 2001-2011

- $2\ R_E < R < 11\ R_E$
- $-60^o < \lambda_m < +60^o$
- L* (T89)
- λ_{m0} within $\pm 10^o$
- 4 spacecraft
- Total number of **16 × 10[6]** multicomponent (3B, 2E) spectra

Represented in bins $0.1\ L^* - 1^o\ \lambda_m - 0.5h$ MLT



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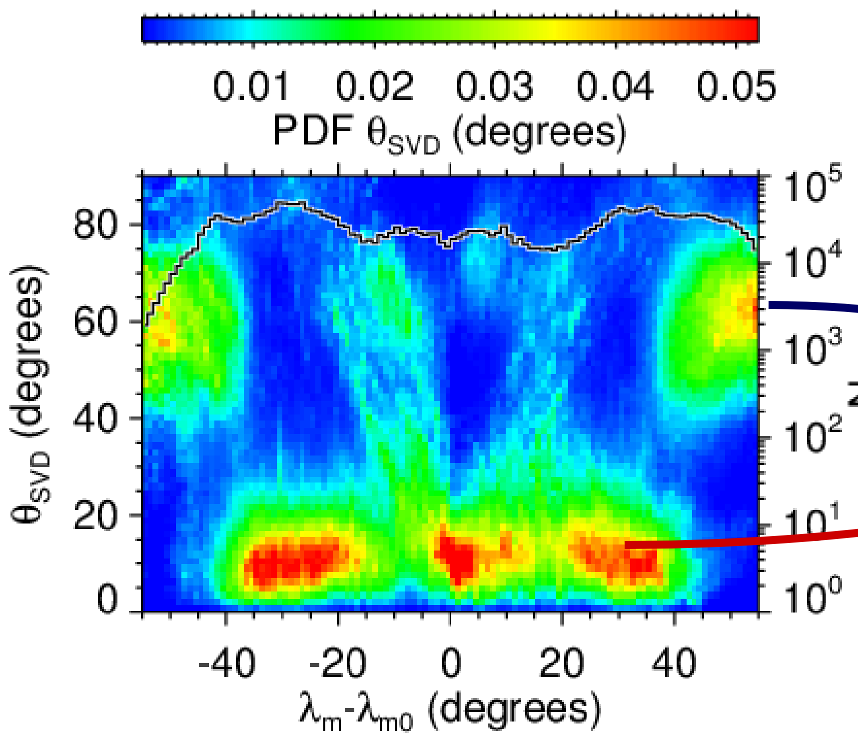
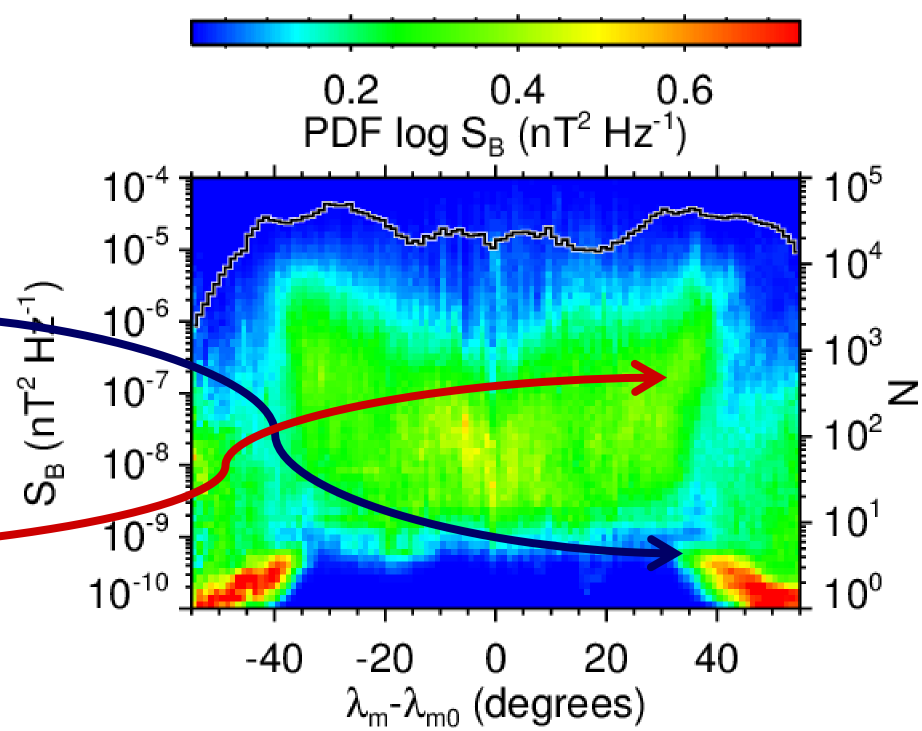
PDF of the wave-normal angle – SVD

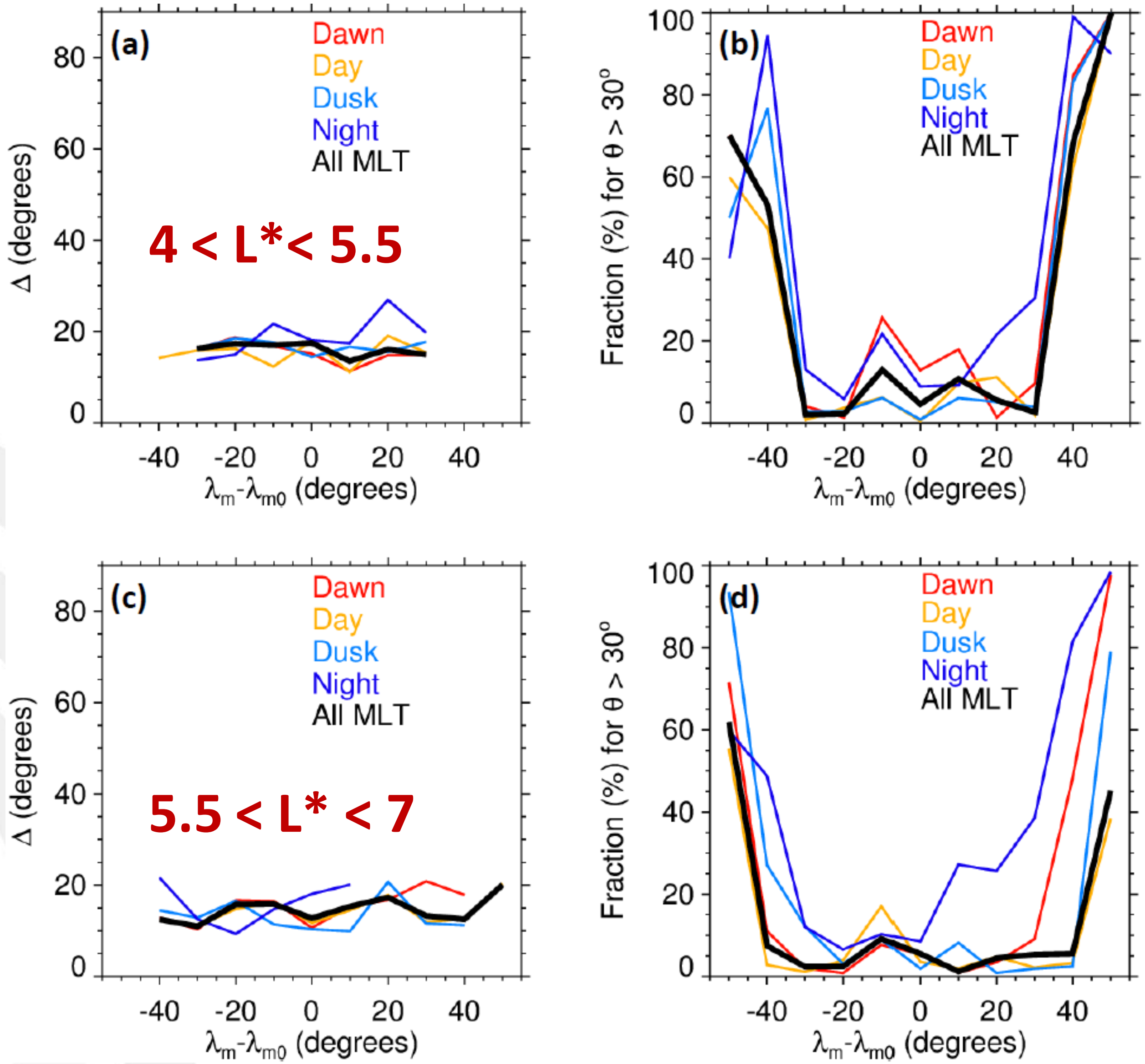
PDF of the magnetic field power-spectral density





Gaussian model of the probability density function of the wave vector angle

$A \exp(-\theta^2/\Delta^2)$



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Fine structure of chorus wave packets
EMFISIS Waves, Van Allen Probe A, 14 Nov 2012

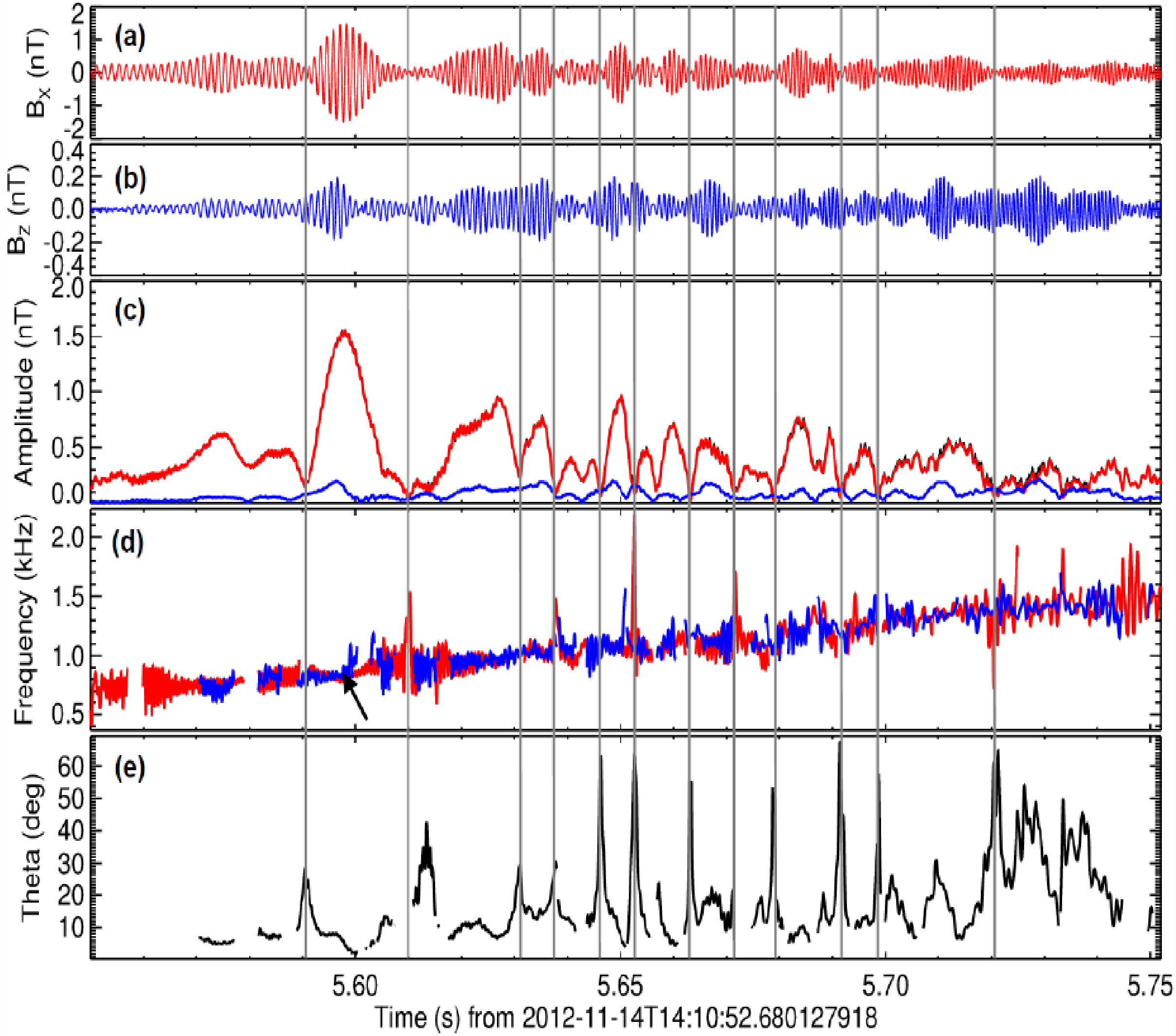
magnetic field perp. to B_0

parallel to B_0

instantaneous amplitude

instantaneous frequency

angle between the wave vector and B_0



Santolik et al., GRL, 2014.

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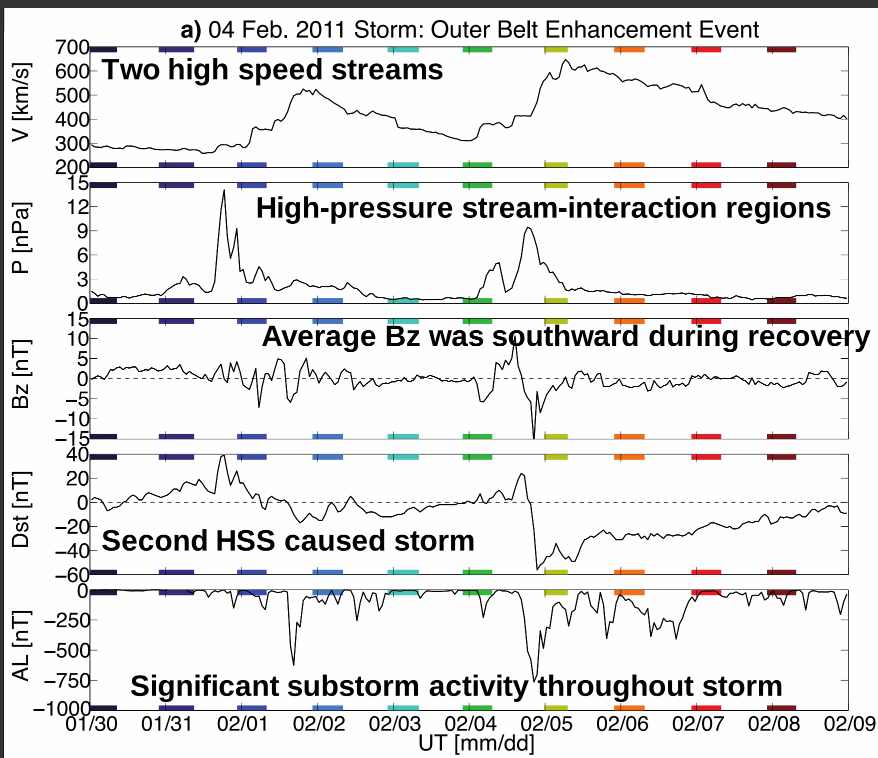
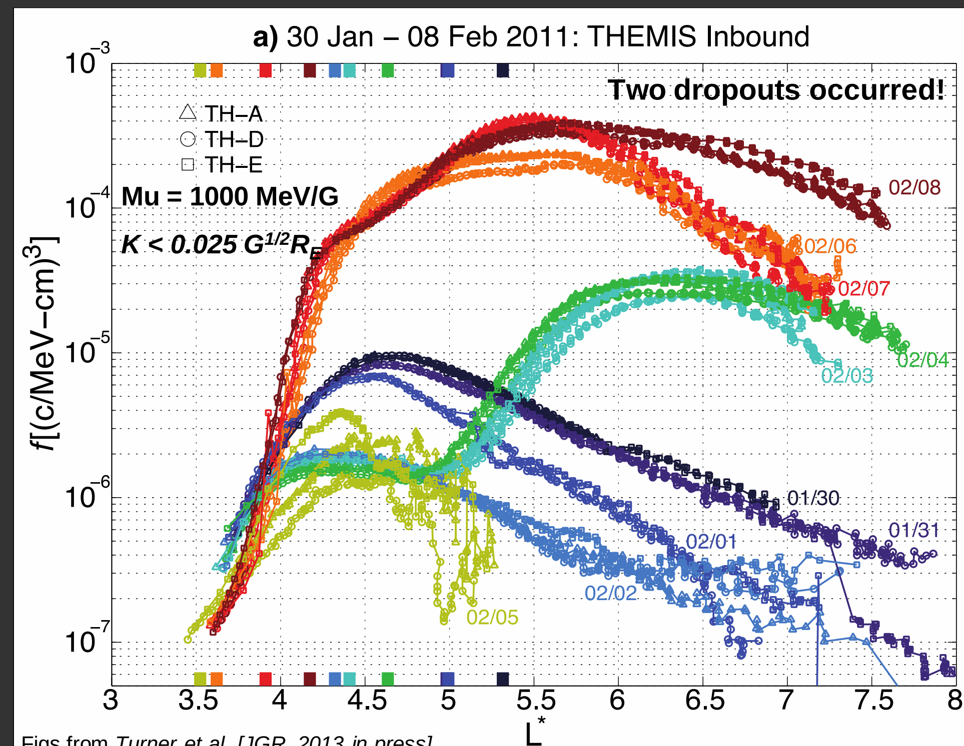
Case 1: 04 Feb. 2011 Storm

- Two dropouts occurred (02 and 05 Feb.) following two SIRs during this 10 day period
- After the first dropout, a remnant belt was still visible after the PSD was replenished at L*>5.5 on 03-04 Feb., leaving a double outer belt structure!
- The second dropout was much stronger, essentially eliminating the belt at L*>5
- The outer belt was replenished in less than 1-day during the early recovery phase

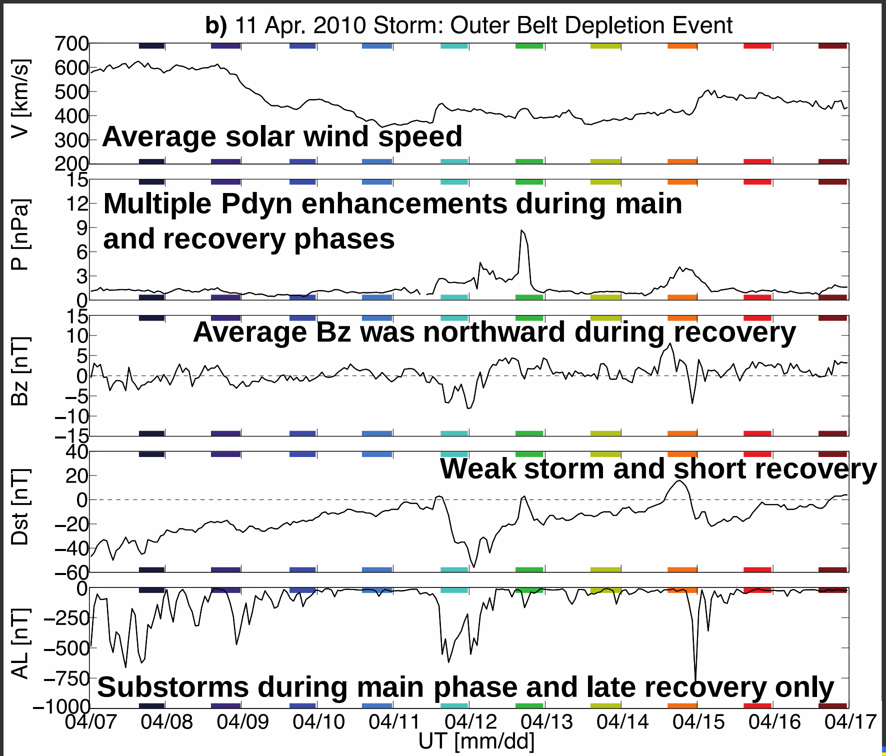


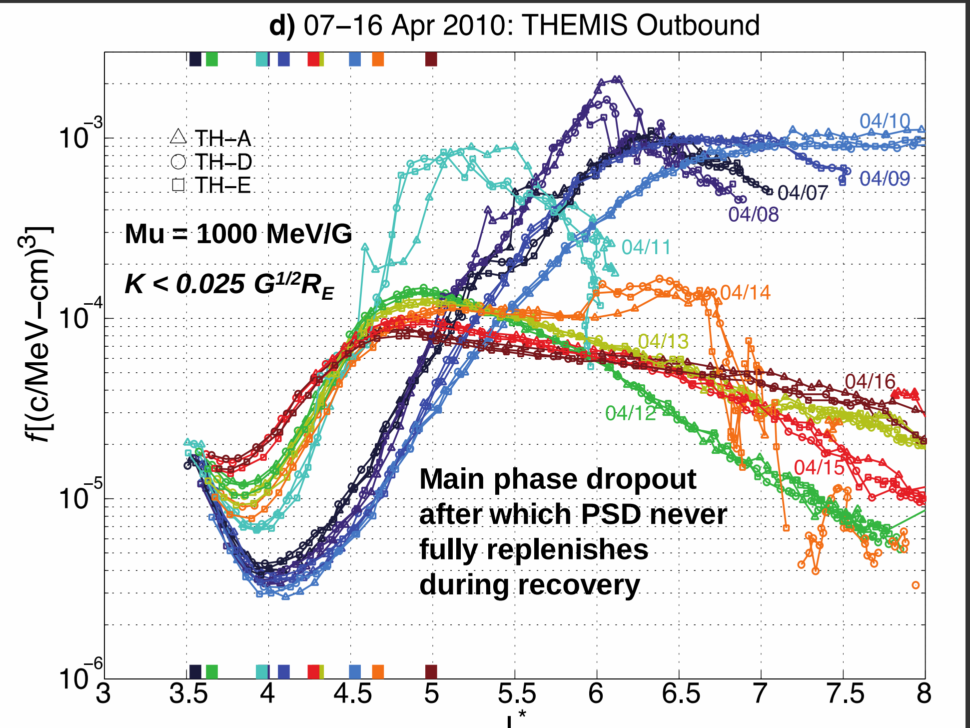


Figs from *Turner et al. [JGR, 2013 in press]*

Case 2: 11 Apr. 2010 Storm

- CME-driven storm following a much stronger storm (also CME-driven) on 05 Apr. that resulted in a strong outer belt enhancement
- Glancing CME (partial halo); magnetic cloud observed from 11-12 Apr. with stronger shock on trailing edge
- Precipitation loss was more significant, but only at L-shells < ~5; consistent with other storms examined that reveal main phase precipitation and *Bortnik et al. [JGR, 2006]*

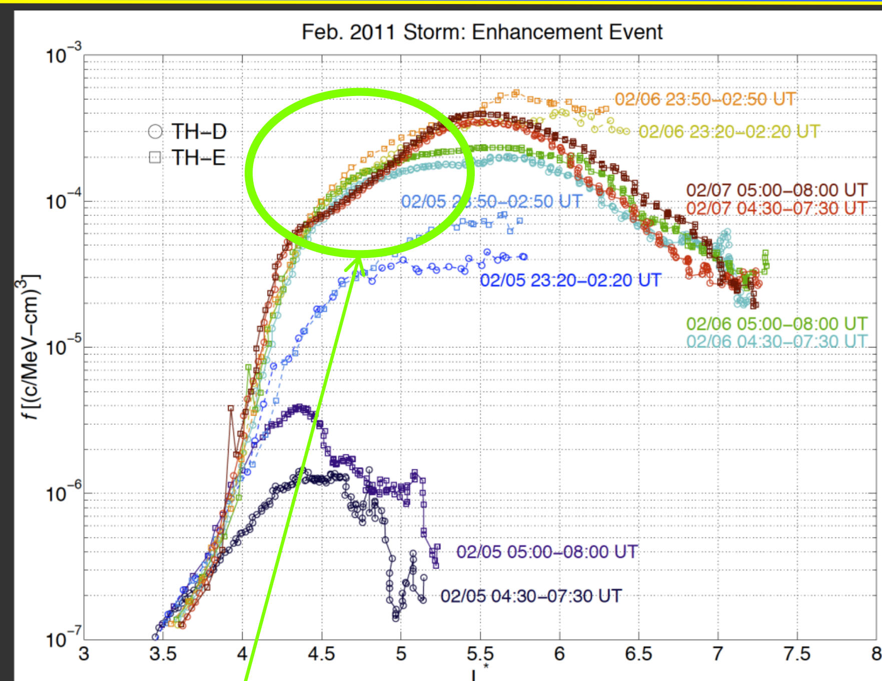


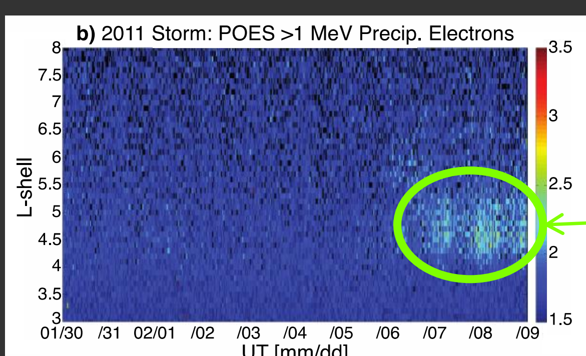


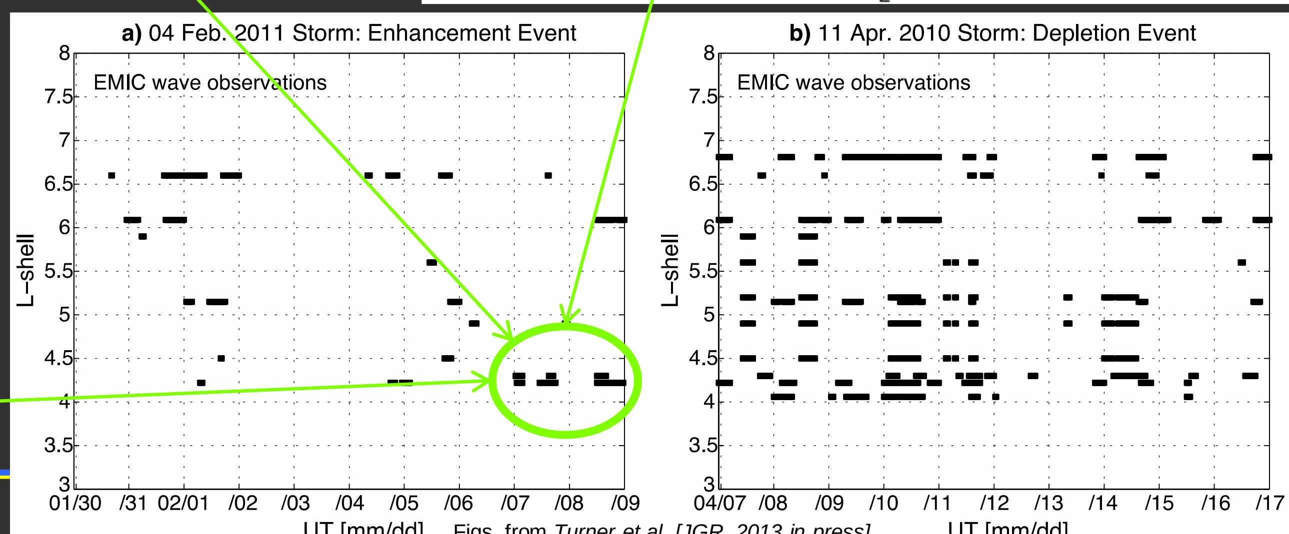
Figs. from *Turner et al. [JGR, 2013 in press]*

EMIC Waves

- Wave-particle interactions with EMIC waves may also result in loss from the system [e.g., *Horne and Thorne, GRL 1998;* Borovsky and Denton, JGR 2009]
- During the two storms: EMICs observed by GOES and THEMIS-GMAGs
- Compared to enhancement event, depletion event reveals more EMIC wave observations over broader ranges in L* and longer periods of time; *Few EMICs during main phase dropouts!*
- Maybe direct evidence of EMIC waves scattering >1 MeV electrons at 4<L*<5 on 07-08 Feb. 2011?



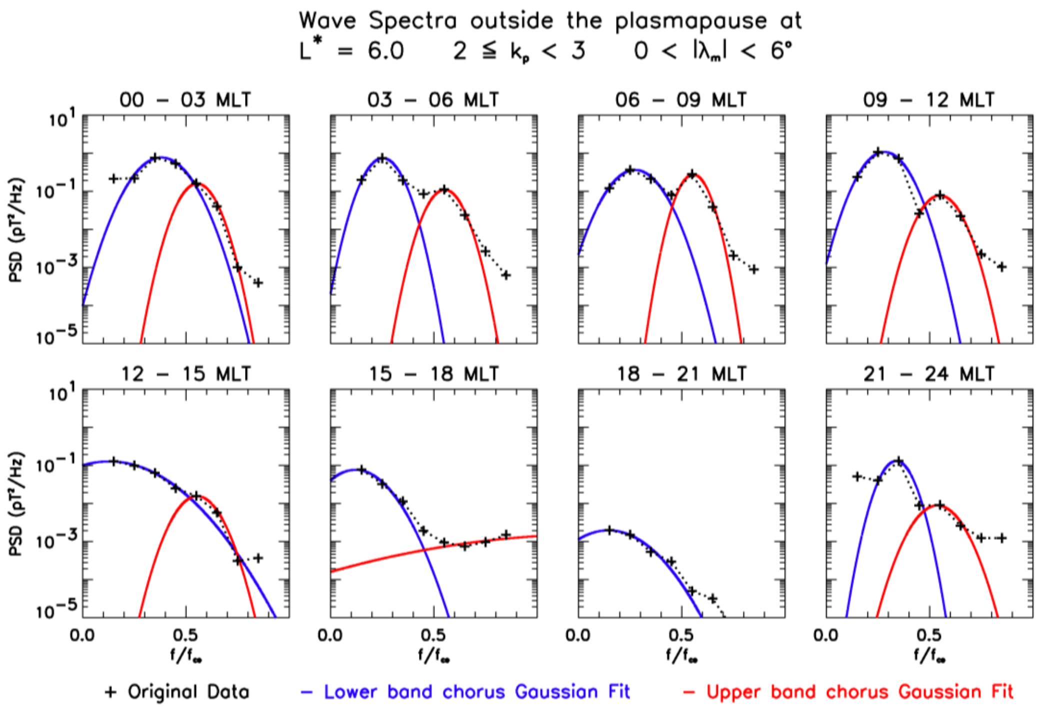




Figs. from *Turner et al. [JGR, 2013 in press]*

EMIC, Whistler and Hiss Wave Pitch Angle Diffusion Coefficients

Fitting the Power Spectra



- To calculate diffusion rates we need the wave power spectra as a Gaussian function
- Developed automatic procedure to fit data
- Captures >90% of wave power
- Example for chorus

British Antarctic Survey
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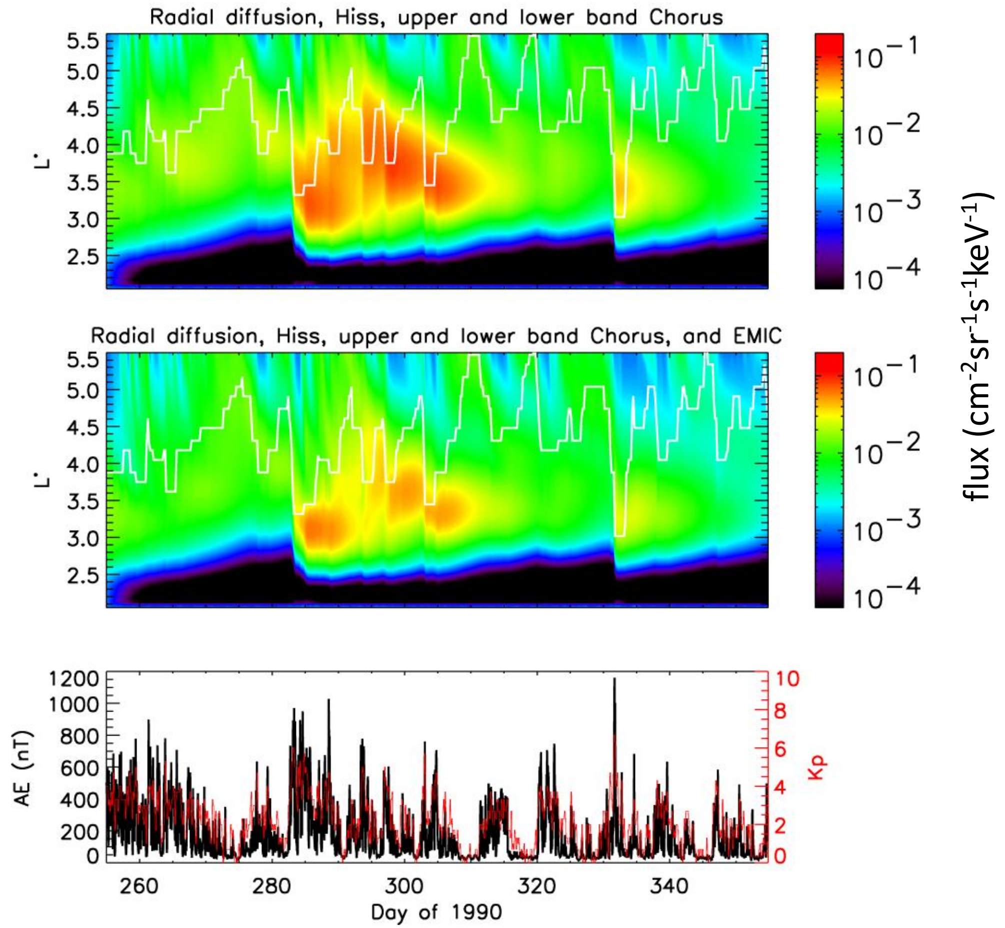
Electron flux: 100 day simulation – 45°

45° flux ($cm^{-2}sr^{-1}s^{-1}keV^{-1}$) for 6MeV electrons

Without EMIC

With EMIC



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Pitch-angle dependency: 100 day simulation

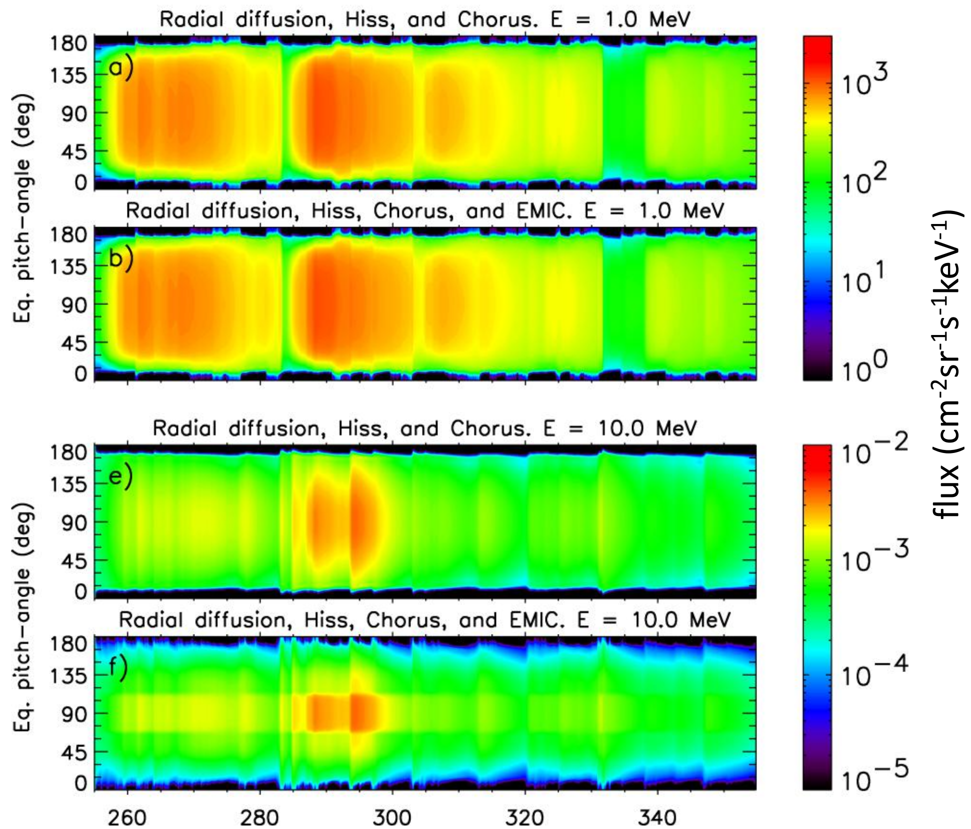
Electron flux ($cm^{-2}sr^{-1}s^{-1}keV^{-1}$) at L* = 4.5

Without EMIC

With EMIC

Without EMIC

With EMIC



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Conclusions

- MAARBLE FP-7 project is now nearing its conclusion.
  - Extensive scientific discovery relating to ULF waves, VLF, and EMIC waves and their impact on radiation belt dynamics.
  - New particle and waves data base available at Cluster Science Archive.
  - Within MAARBLE team this data base being successfully mined for new scientific discovery.
  - Encourage community to take advantage of this new public resource at Cluster Science Archive.

http://www.cosmos.esa.int/web/csa

esa

MAARBLE

Monitoring, Analyzing & Assessing Radiation Belt Loss & Energization

www.maarble.eu

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Ends