THE STUDY OF NON-LINEAR ACCELERATION OF PARTICLES DURING SUBSTORMS USING MULTI-SCALE SIMULATIONS

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Ion and Electron Acceleration During Substorms

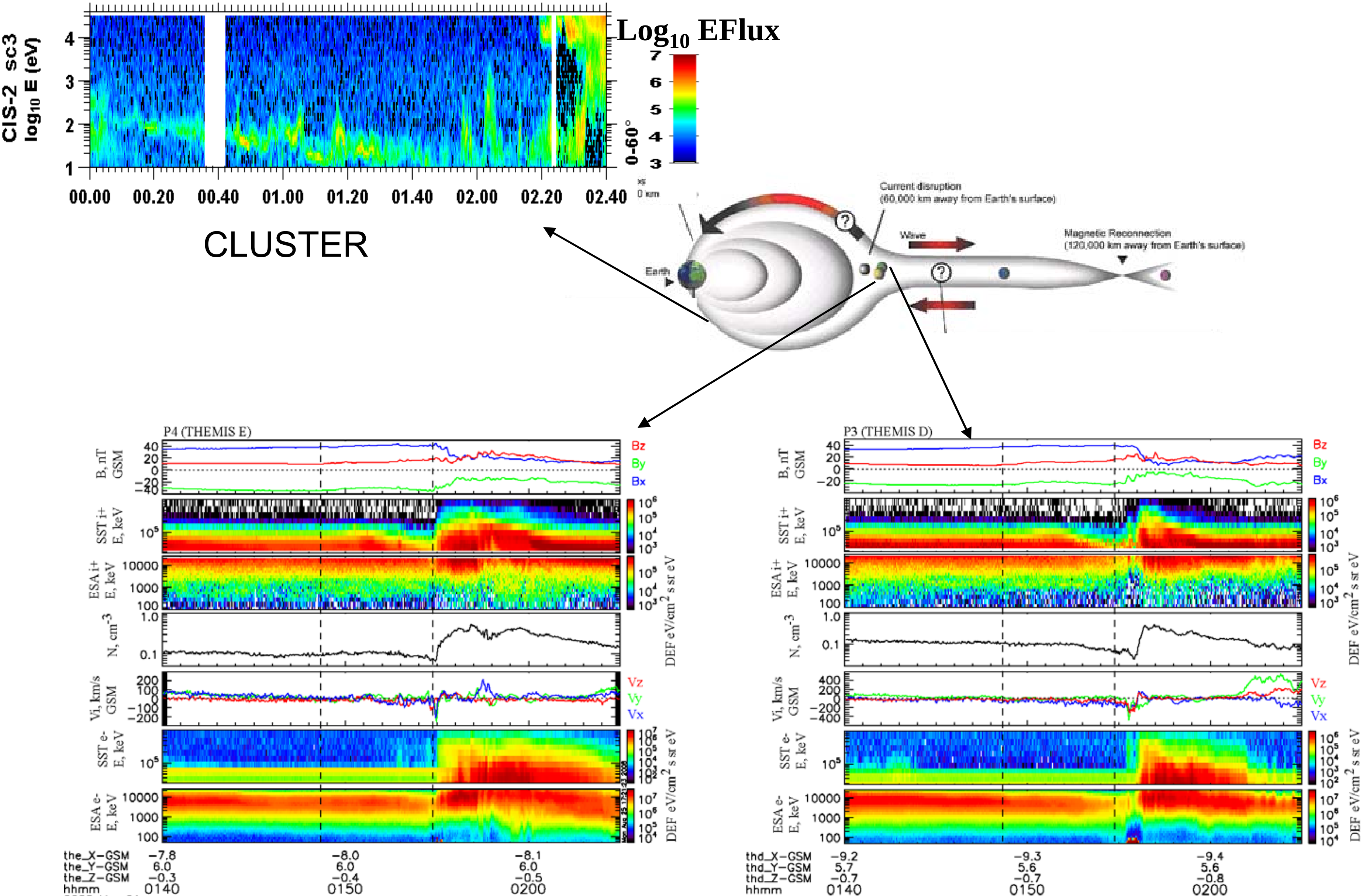
March 1, 2008

- Observations – large substorm with ion acceleration.
- Approach – data analysis, MHD simulations and large scale kinetic simulations.
- Energization – non-adiabatic motion in stretched tail fields

February 15, 2008

- Observations – substorm dipolarization with plasma waves and rapid electron acceleration.
- Approach – data analysis and MHD simulation.
- Energization – role of plasma waves.

March 1, 2008 THEMIS/CLUSTER Conjunction Event



THEMIS E (P4) THEMIS D (P3)

Goals and Approach

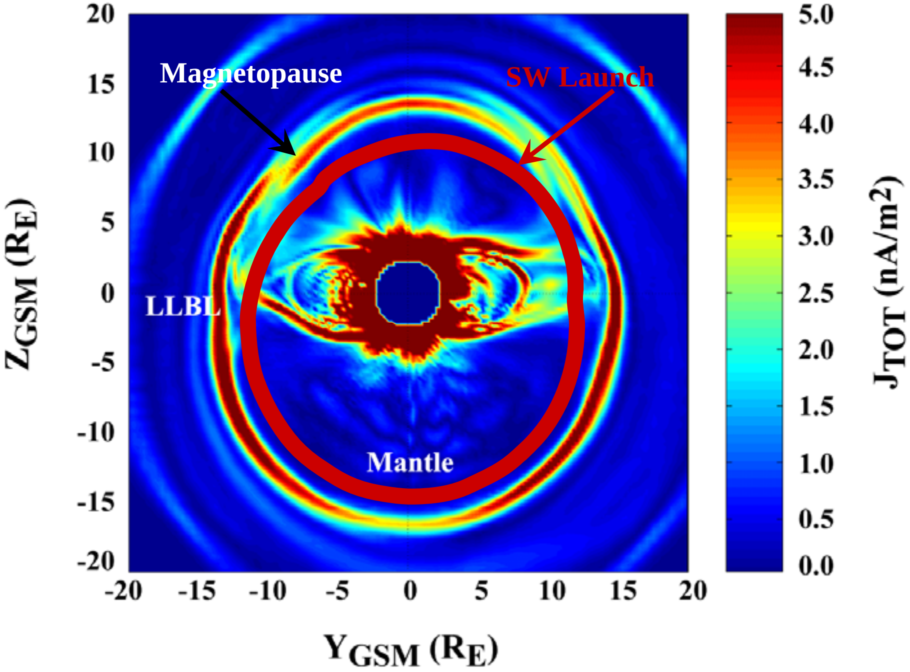
- Understand the energization of particles seen by THEMIS in the inner plasma sheet during the March 1, 2008 substorm.

- Follow trajectories of solar wind ions and ionospheric ions within the electric and magnetic fields from a global magnetohydrodynamic simulation of this substorm.

Magnetotail Ion Sources

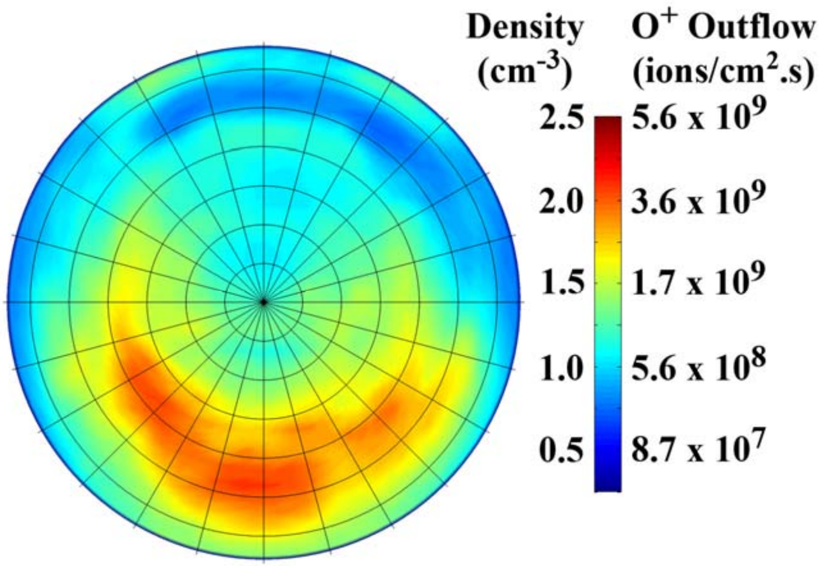
Solar Wind H^+

0130 UT

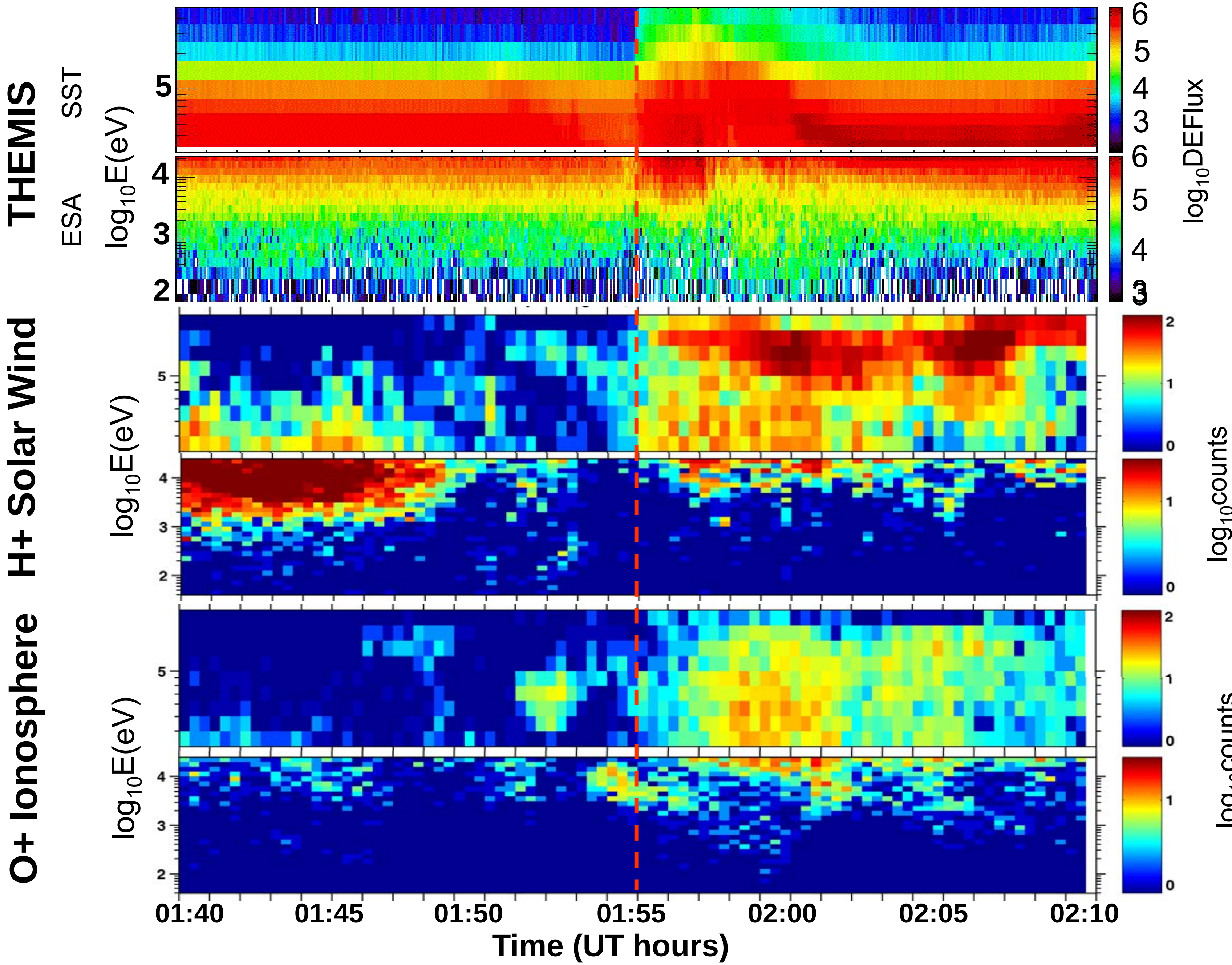


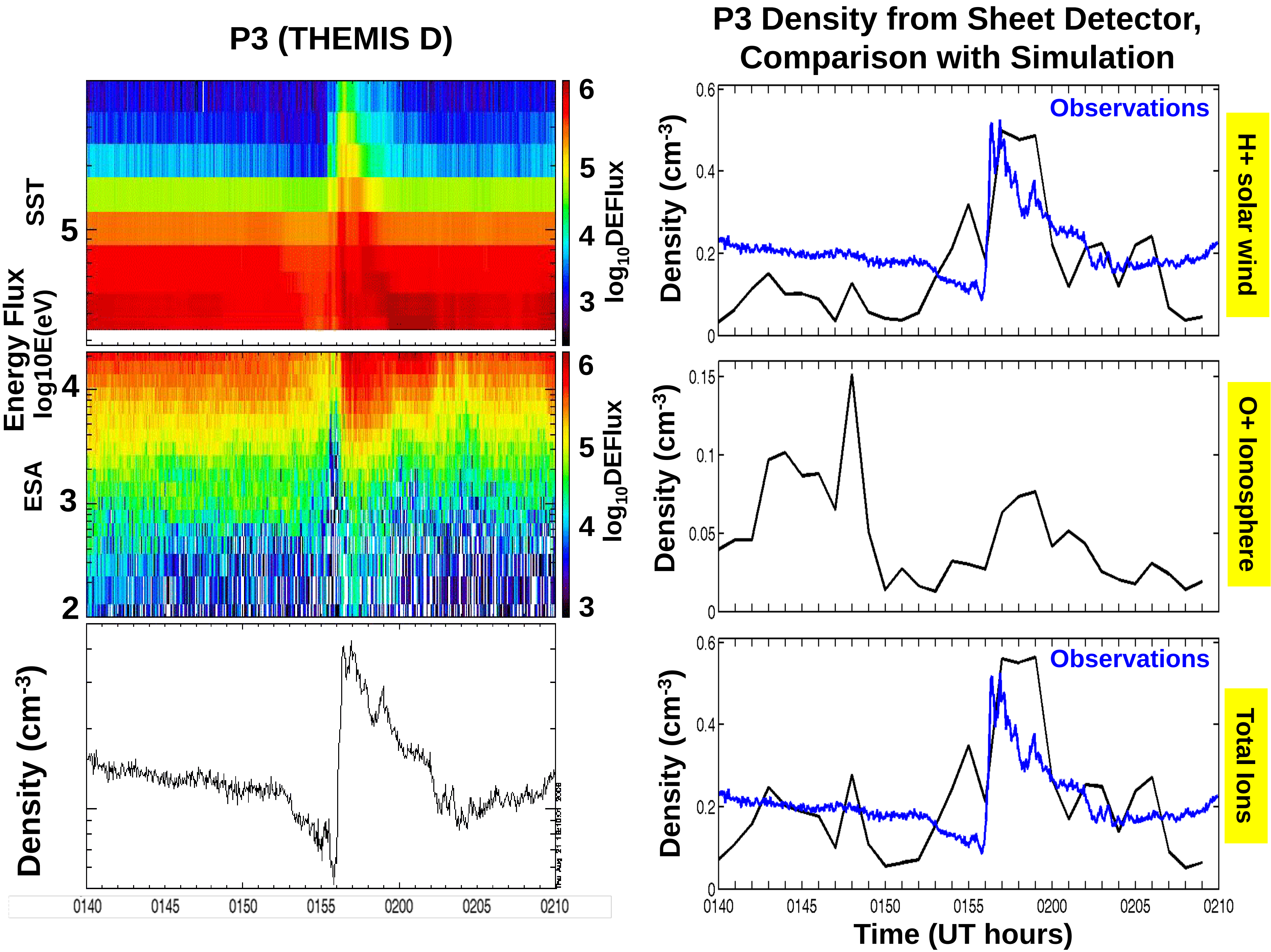
Ionospheric O^+

0155 UT



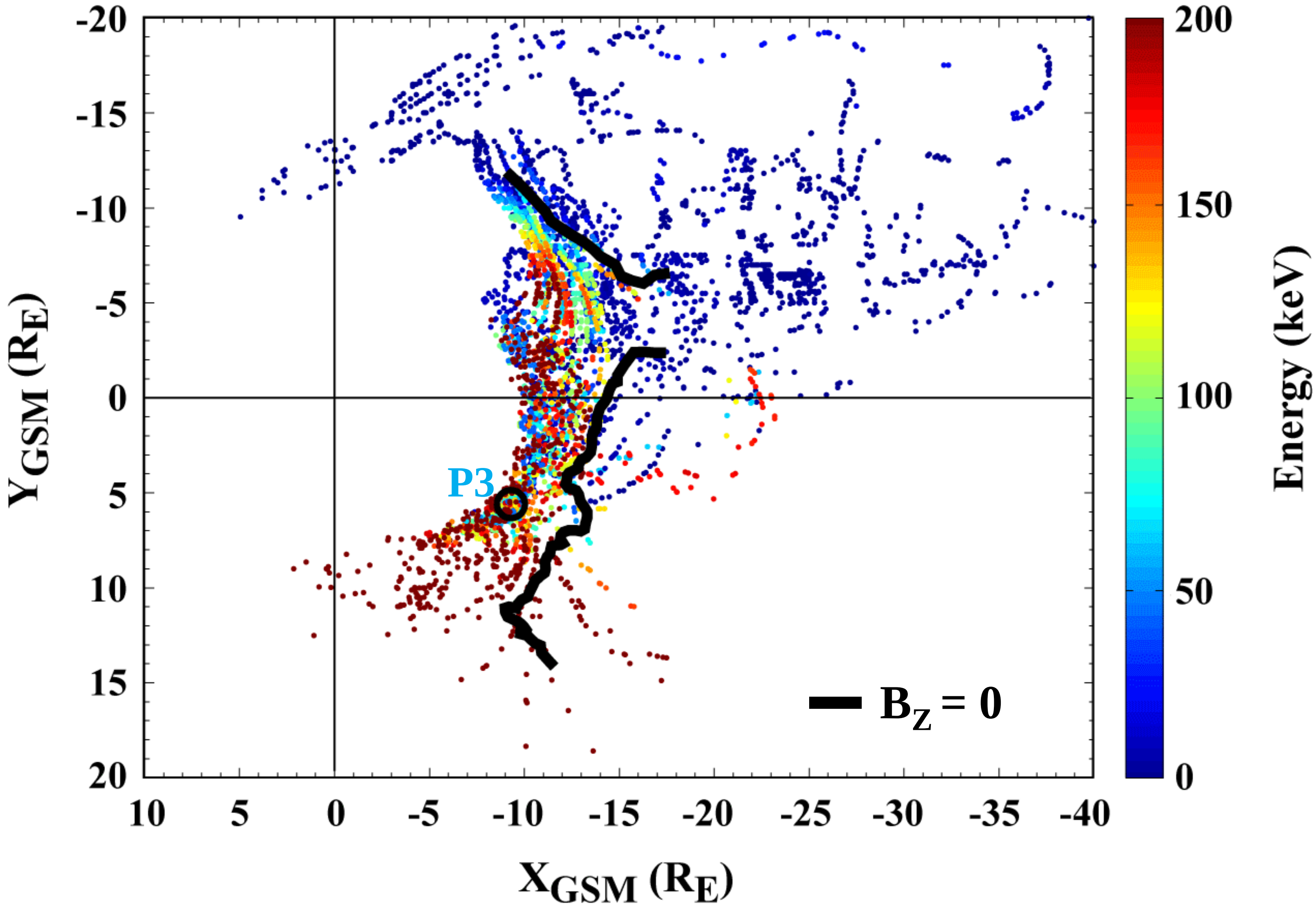
Observed and Simulated Ion Spectrograms at THEMIS E (P4)



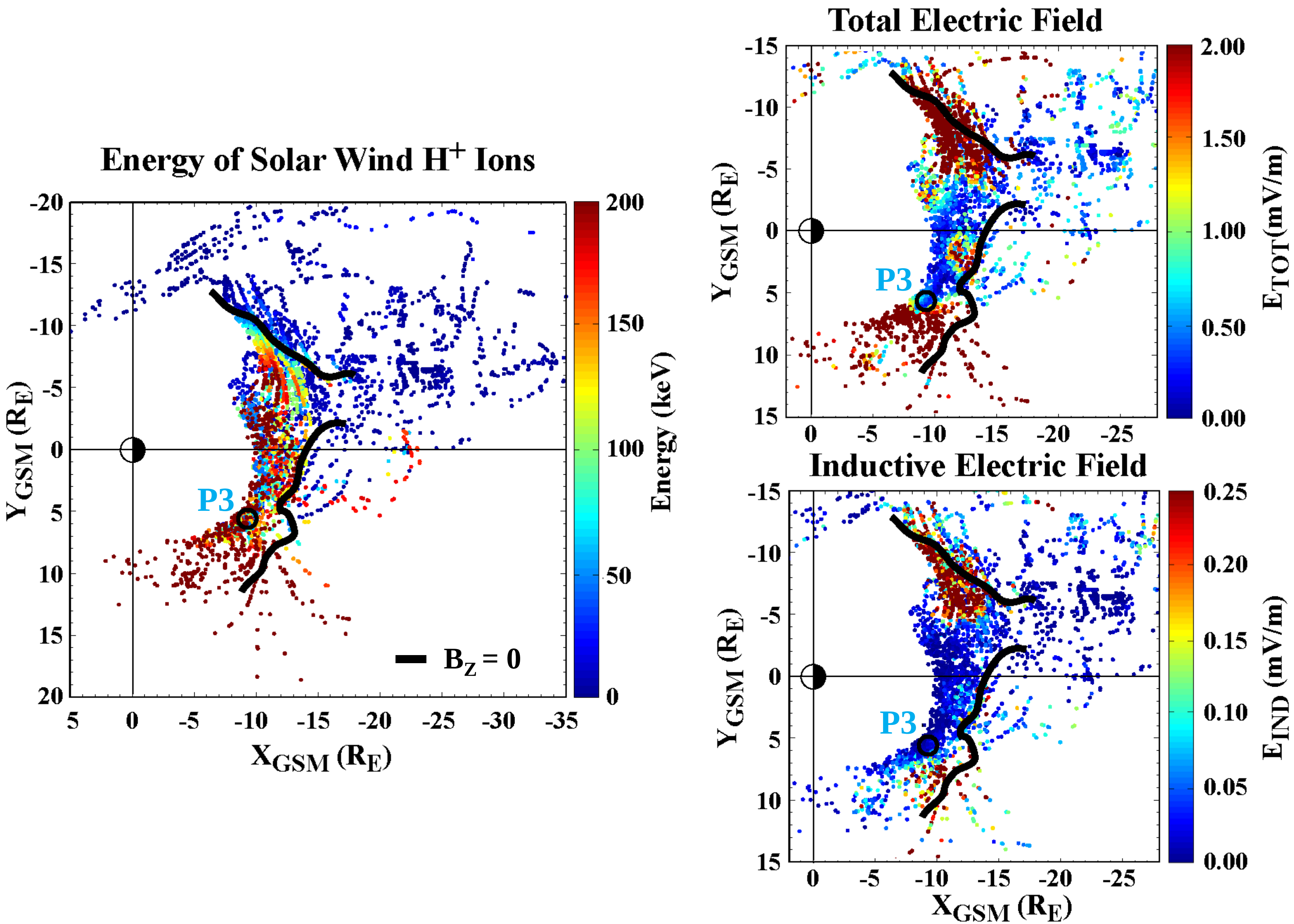


P3 (THEMIS D)
P3 Density from Sheet Detector, Comparison with Simulation
SST
ESA
Energy Flux
log10E(eV)
log10DEFlux
Density (cm-3)
Observations
H+ solar wind
O+ Ionosphere
Total Ions
0140
0145
0150
0155
0200
0205
0210
Time (UT hours)

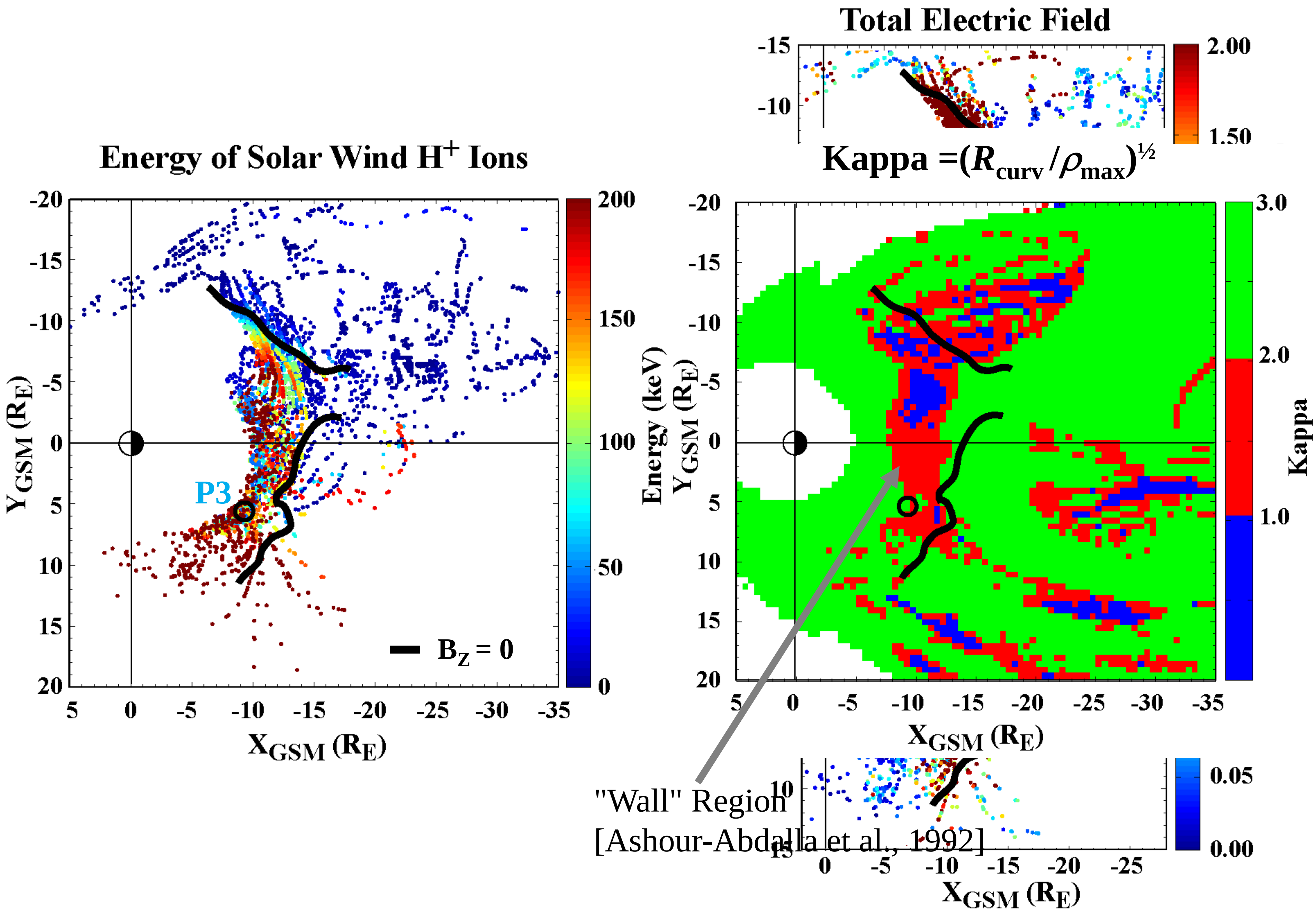
Energy of Solar Wind H^+ Ions in the Current Sheet

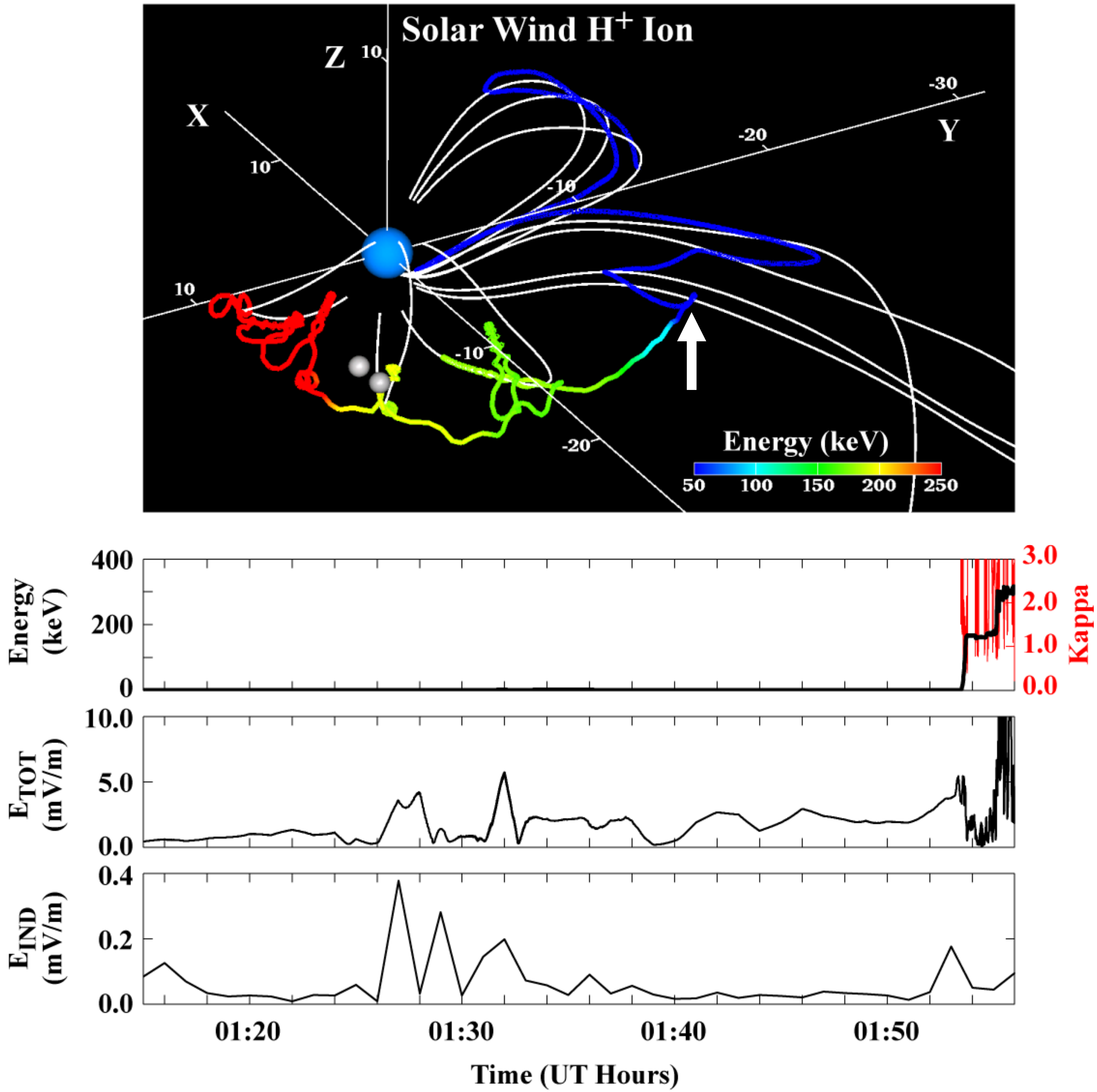


Particles and Fields P3 in the Current Sheet



Particles and Kappa P3 Solar Wind H+





Solar Wind H+ Ion
Z
X
Y
10
10
10
-10
-20
-30
-10
-20
Energy (keV)
50
100
150
200
250
Energy (keV)
400
200
0
Kappa
3.0
2.0
1.0
0.0
E_TOT (mV/m)
10.0
5.0
0.0
E_IND (mV/m)
0.4
0.2
0.0
01:20
01:30
01:40
01:50
Time (UT Hours)

Summary

- During March 1, 2008 substorm THEMIS observed high energies (~500keV) ions in the near-Earth tail.
- We used particle trajectory calculations in the electric and magnetic fields from a global MHD simulation and found that H^+ ions are accelerated to the observed values.
- Simulations indicate that O^+ ions contribute significantly to the particles observed by THEMIS.
- The most energetic H^+ ions were also accelerated in a region called the "wall" where $\kappa \approx 1$.
- The observed rapid energy gain requires both non-adiabatic motion and large total electric fields.

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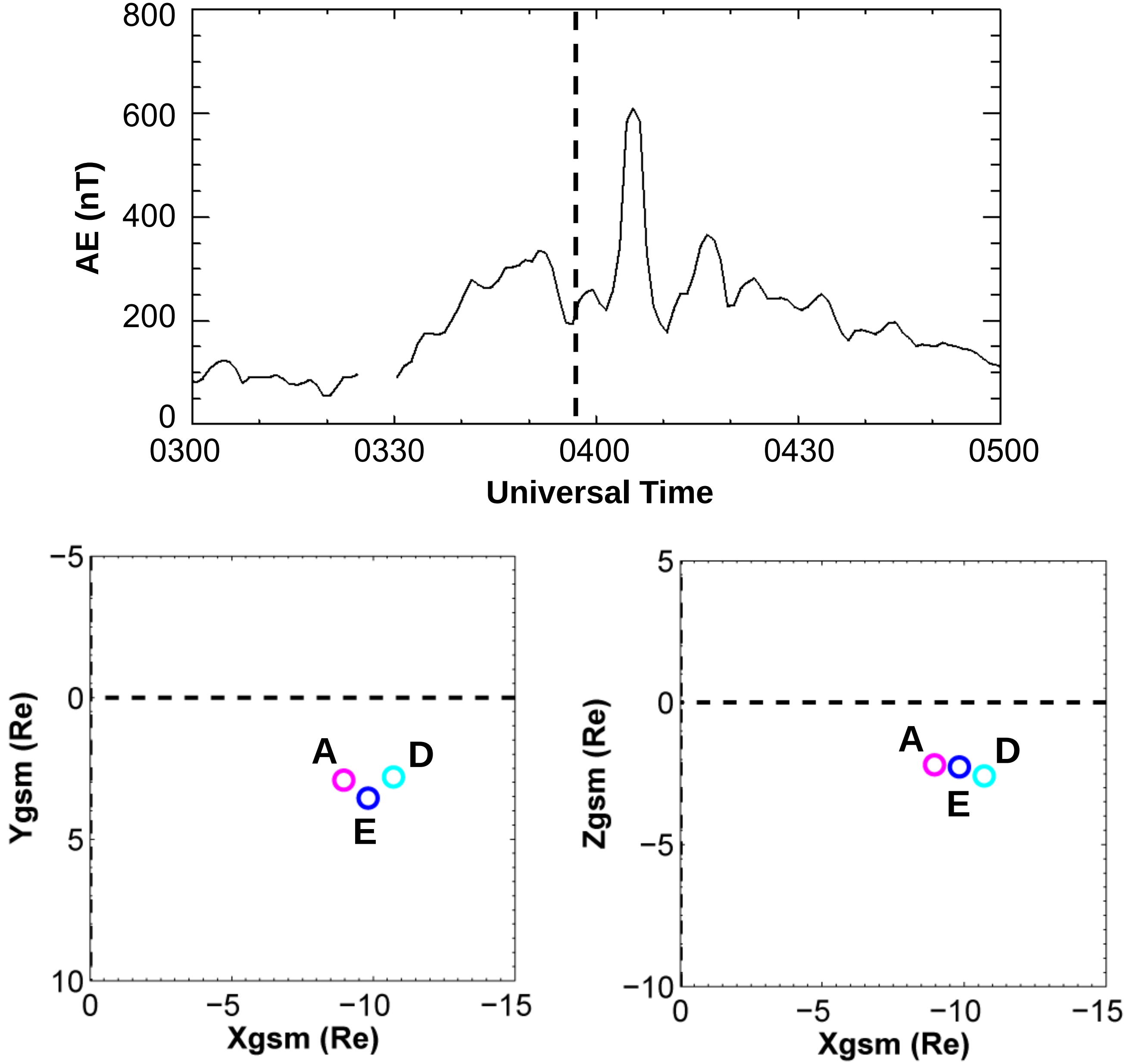
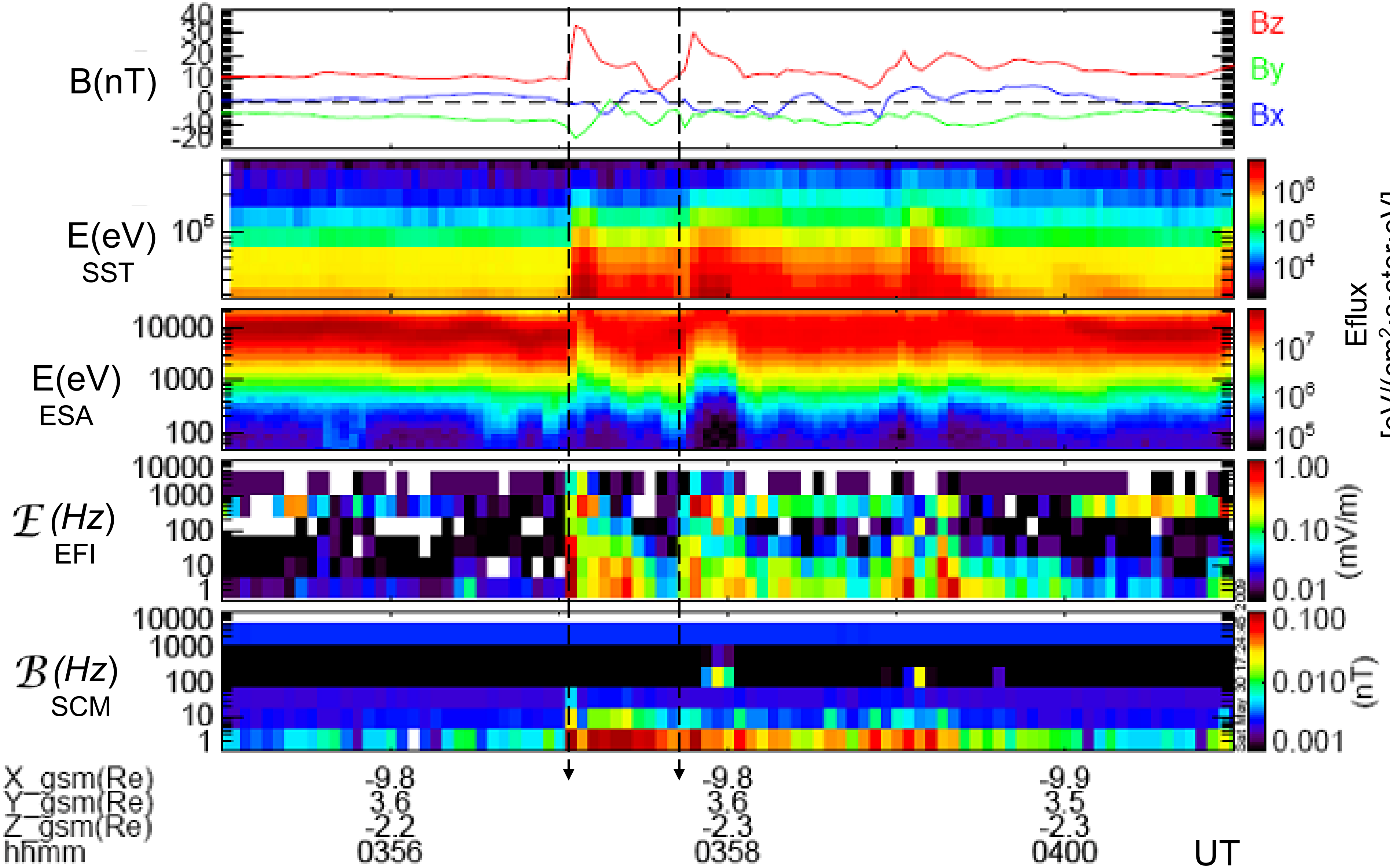
<u>February 15, 2008</u>

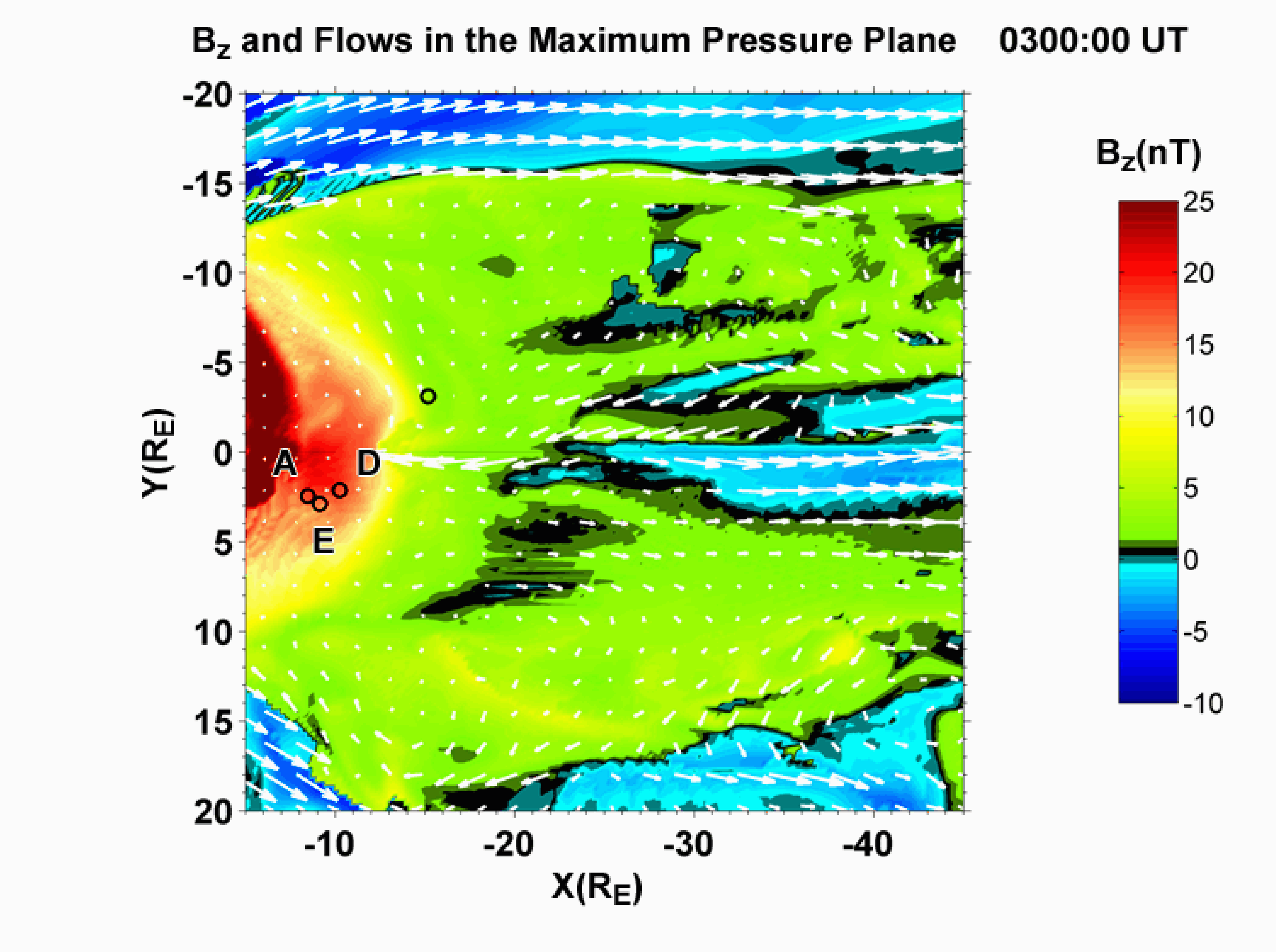
- Observations – substorm dipolarization with plasma waves and rapid electron acceleration.
- Approach – data analysis and MHD simulation.
- Energization – role of plasma waves.

AE Index and Spacecraft Positions on February 15, 2008



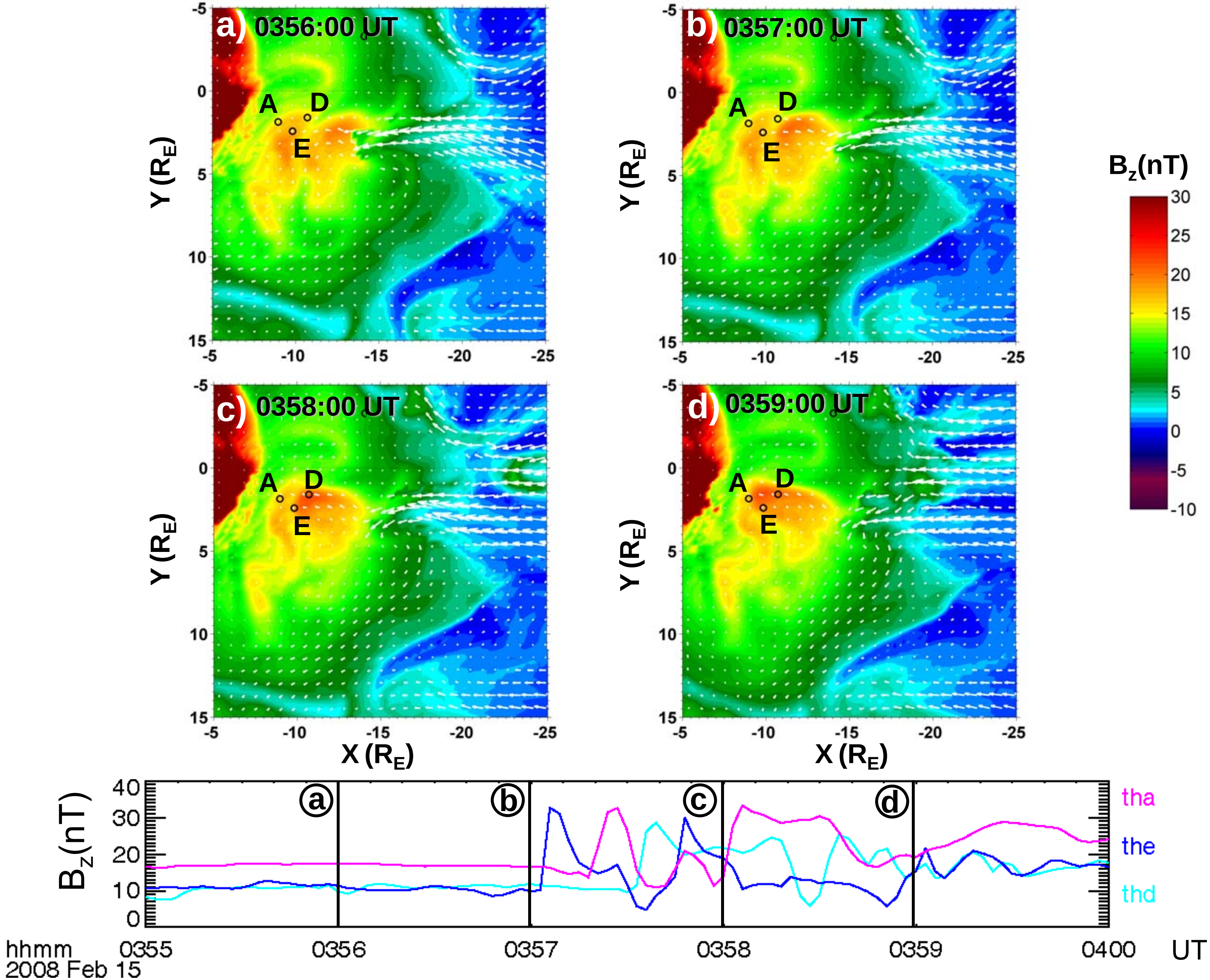
THEMIS E Data on February 15, 2008



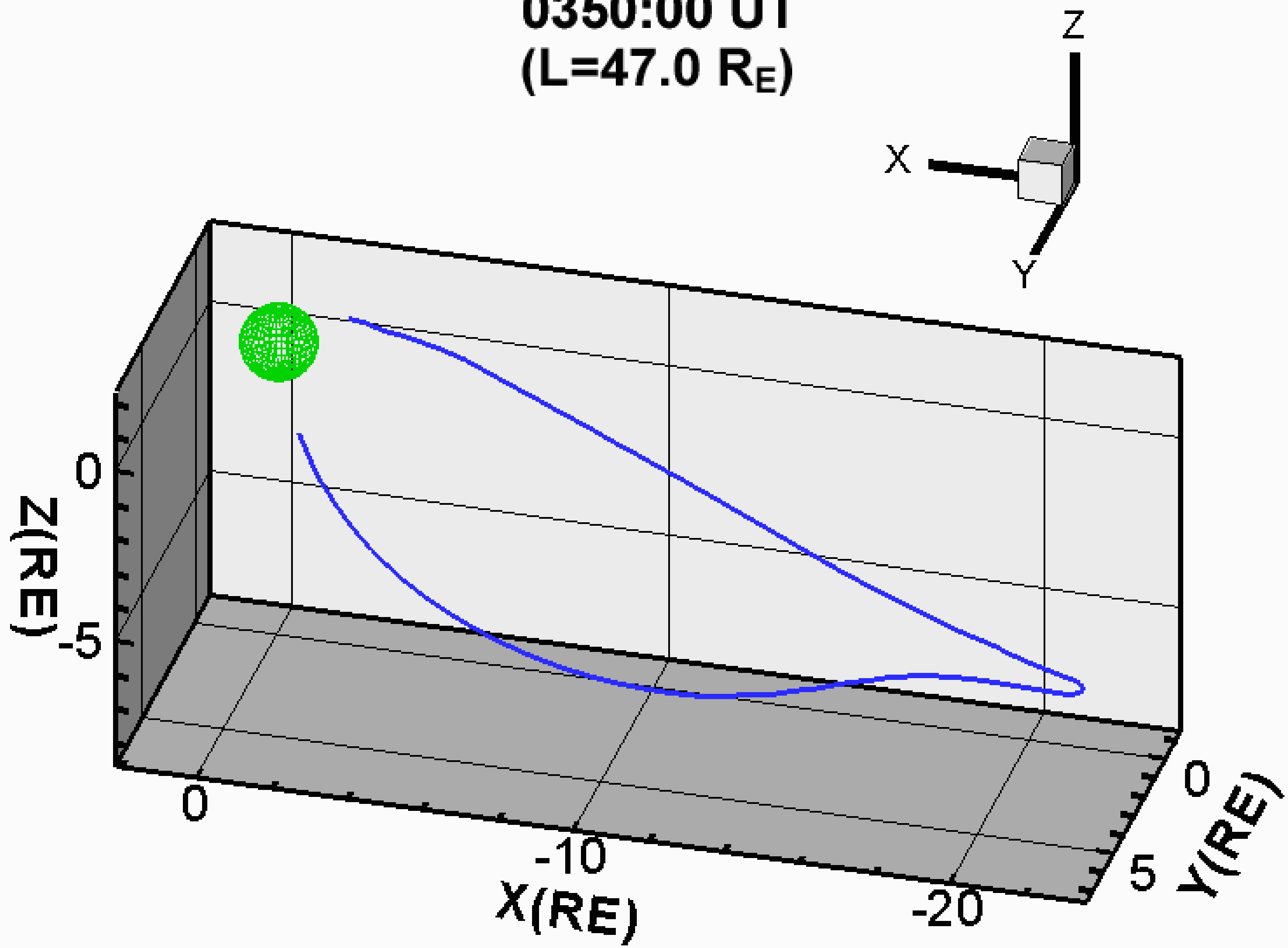


B_z and Flows in the Maximum Pressure Plane 0300:00 UT
B_z(nT)
25
20
15
10
5
0
-5
-10
-20
-15
-10
-5
0
5
10
15
20
$Y(R_E)$
-10
-20
-30
-40
$X(R_E)$
A
D
E

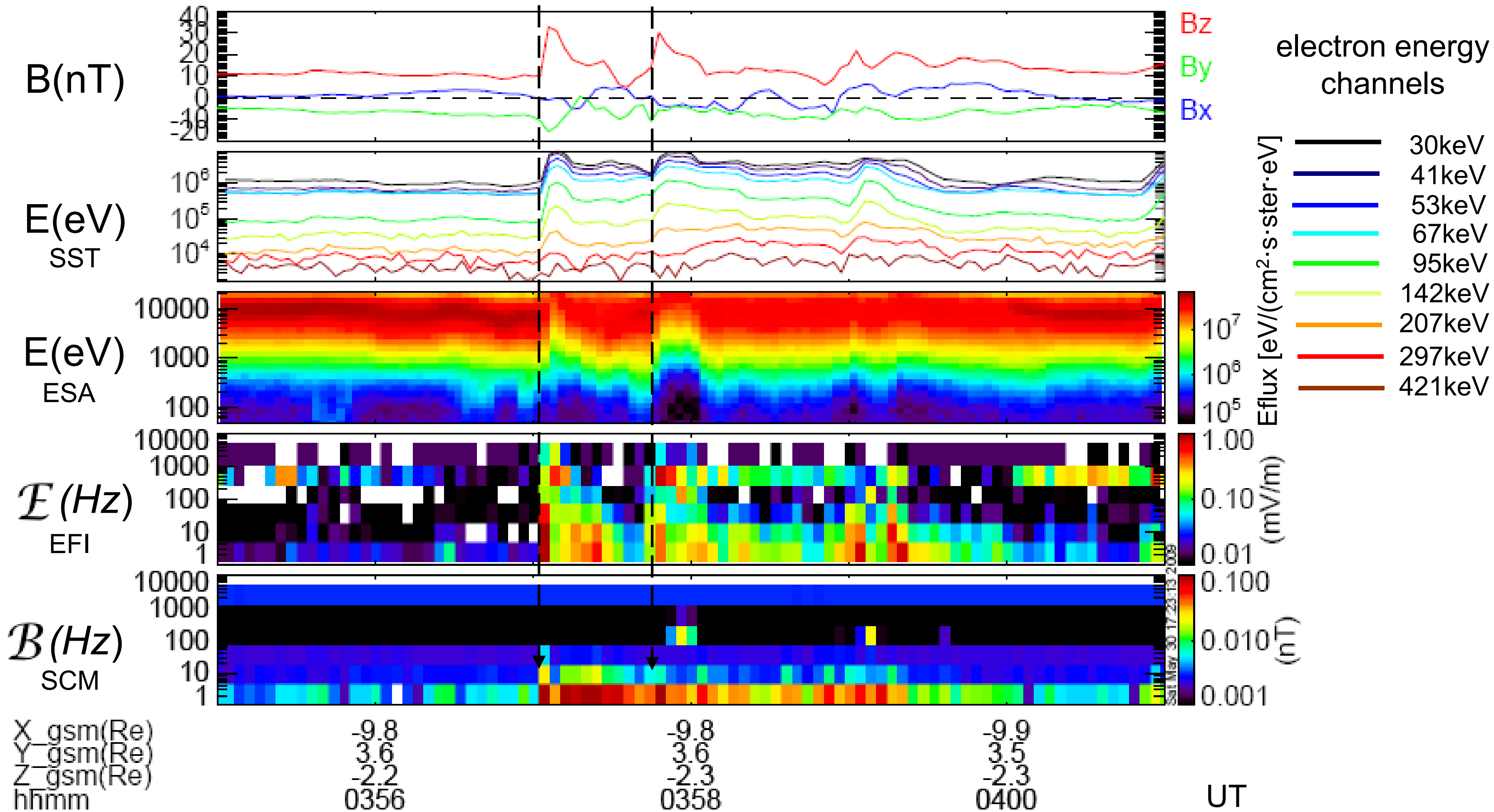
Snapshots of B_z and Flows in the Maximum Pressure Plane



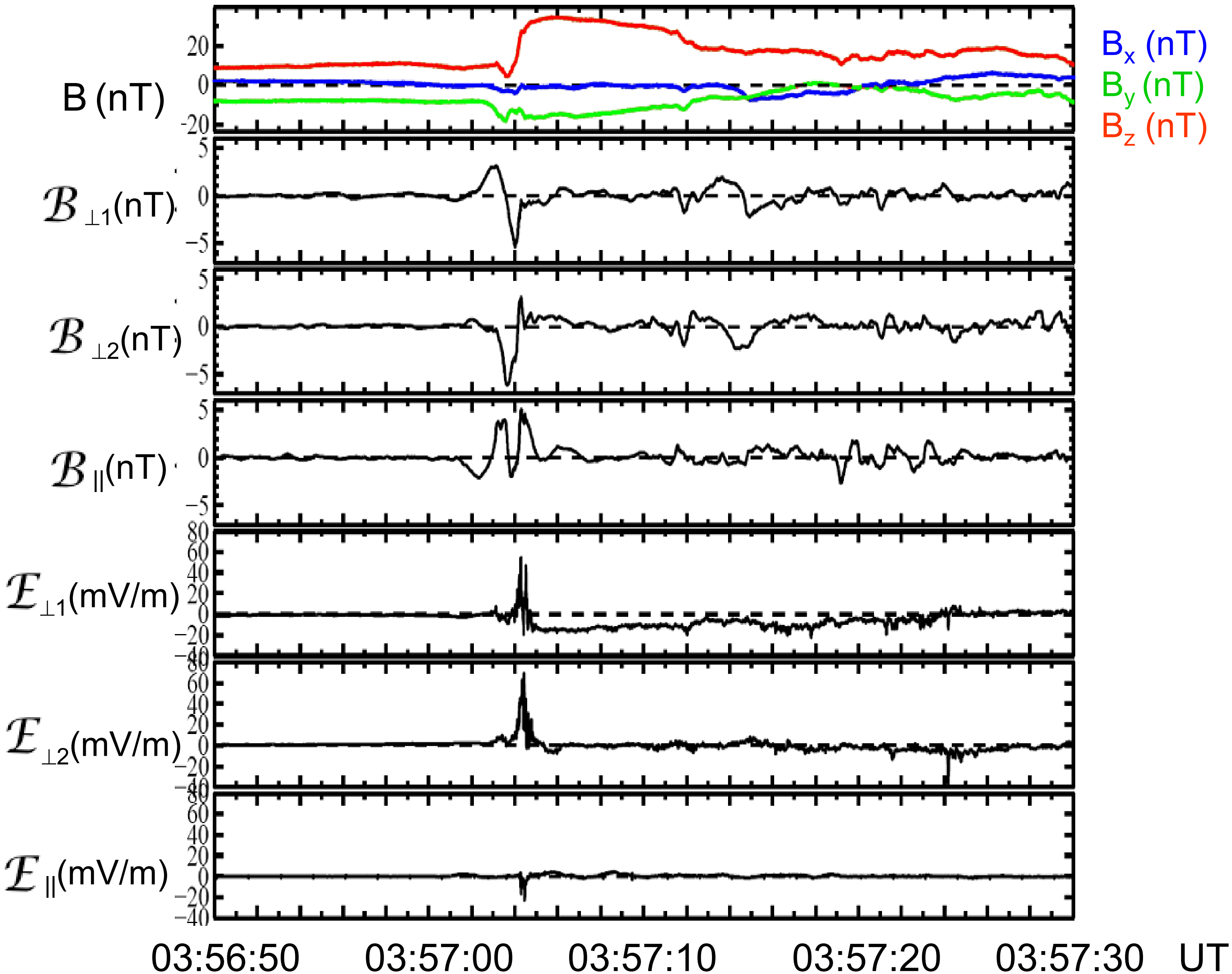
0350:00 UT
(L=47.0 R_E)



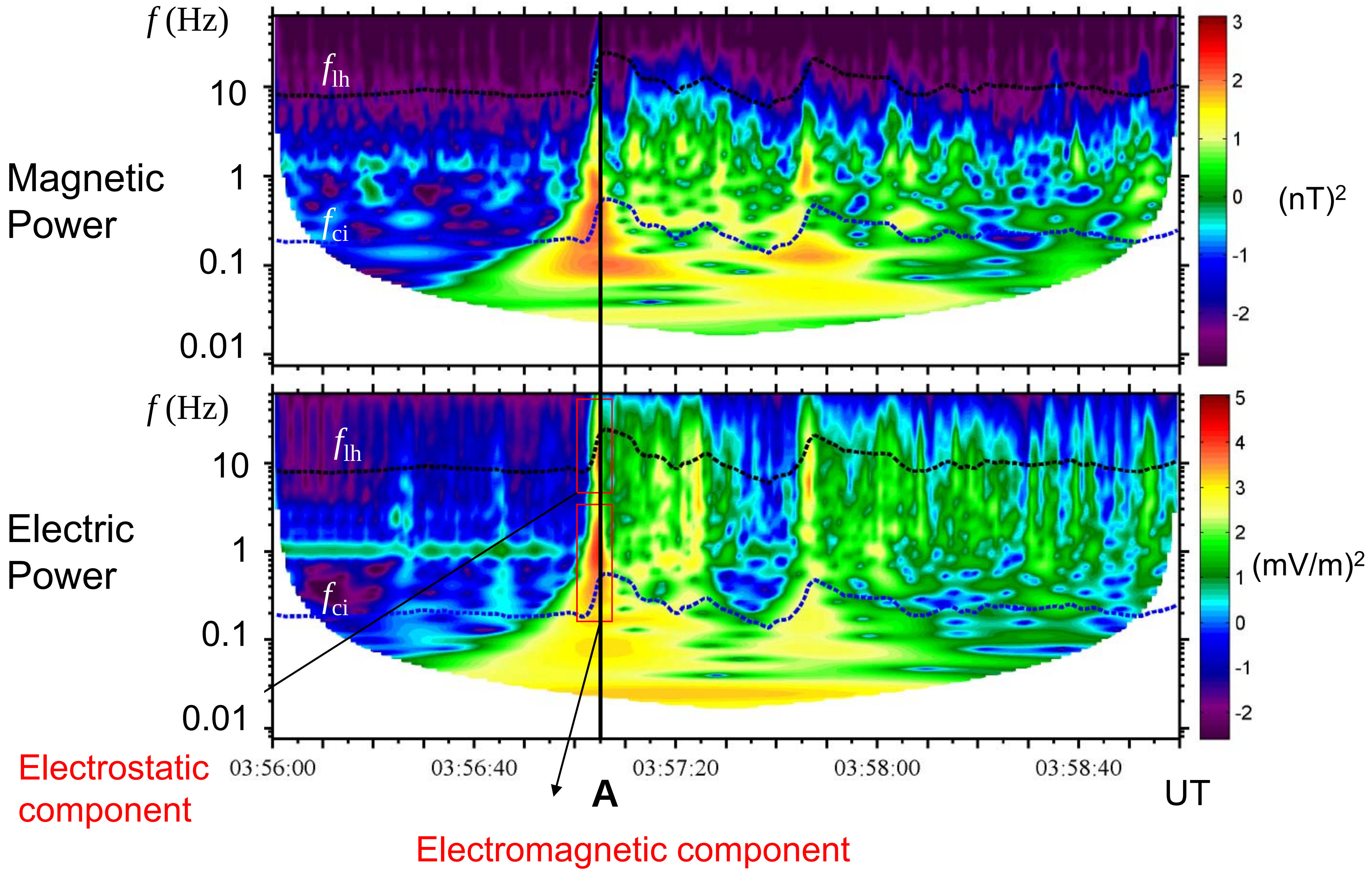
THEMIS E Data on February 15, 2008



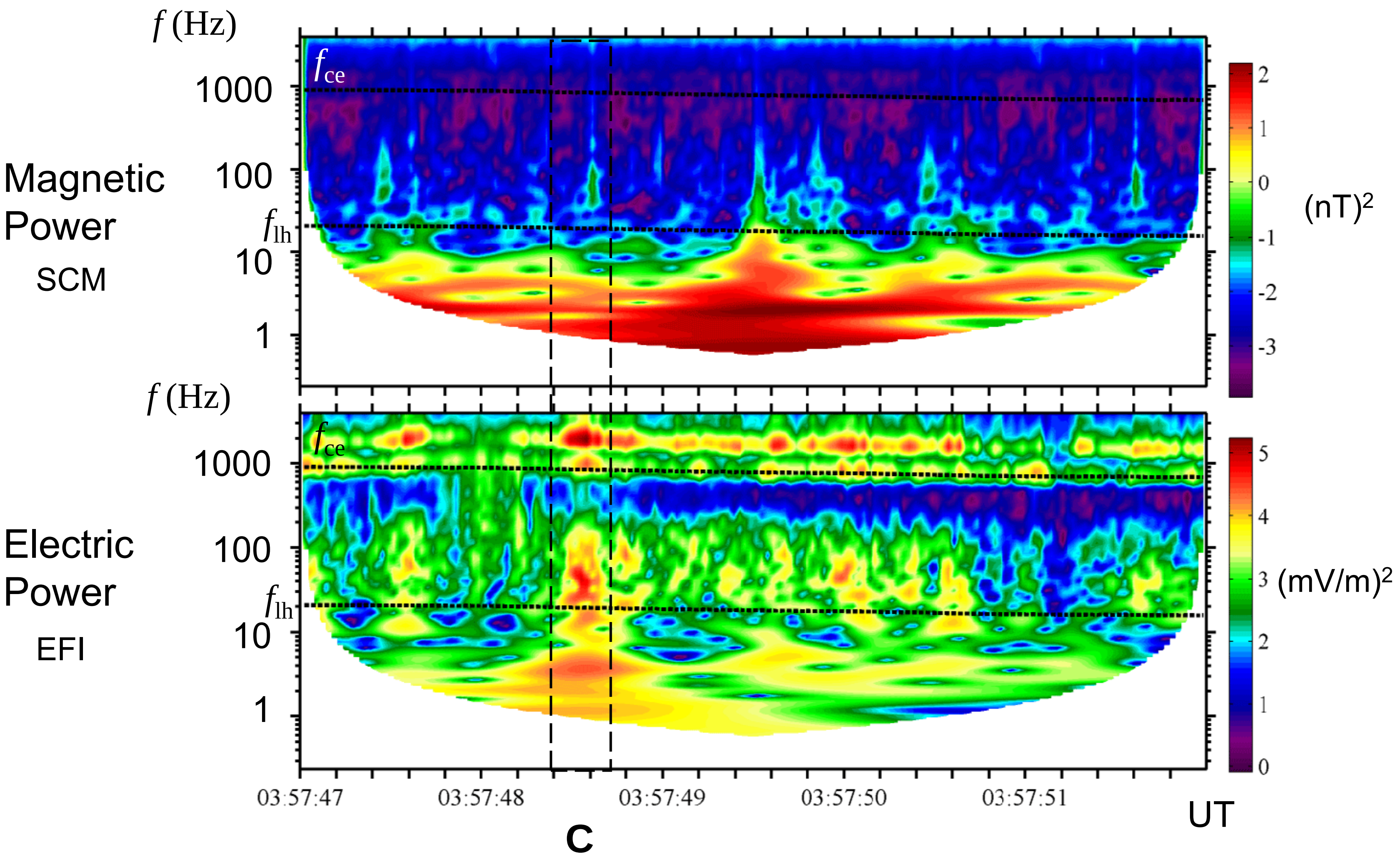
Wave Form THEMIS E



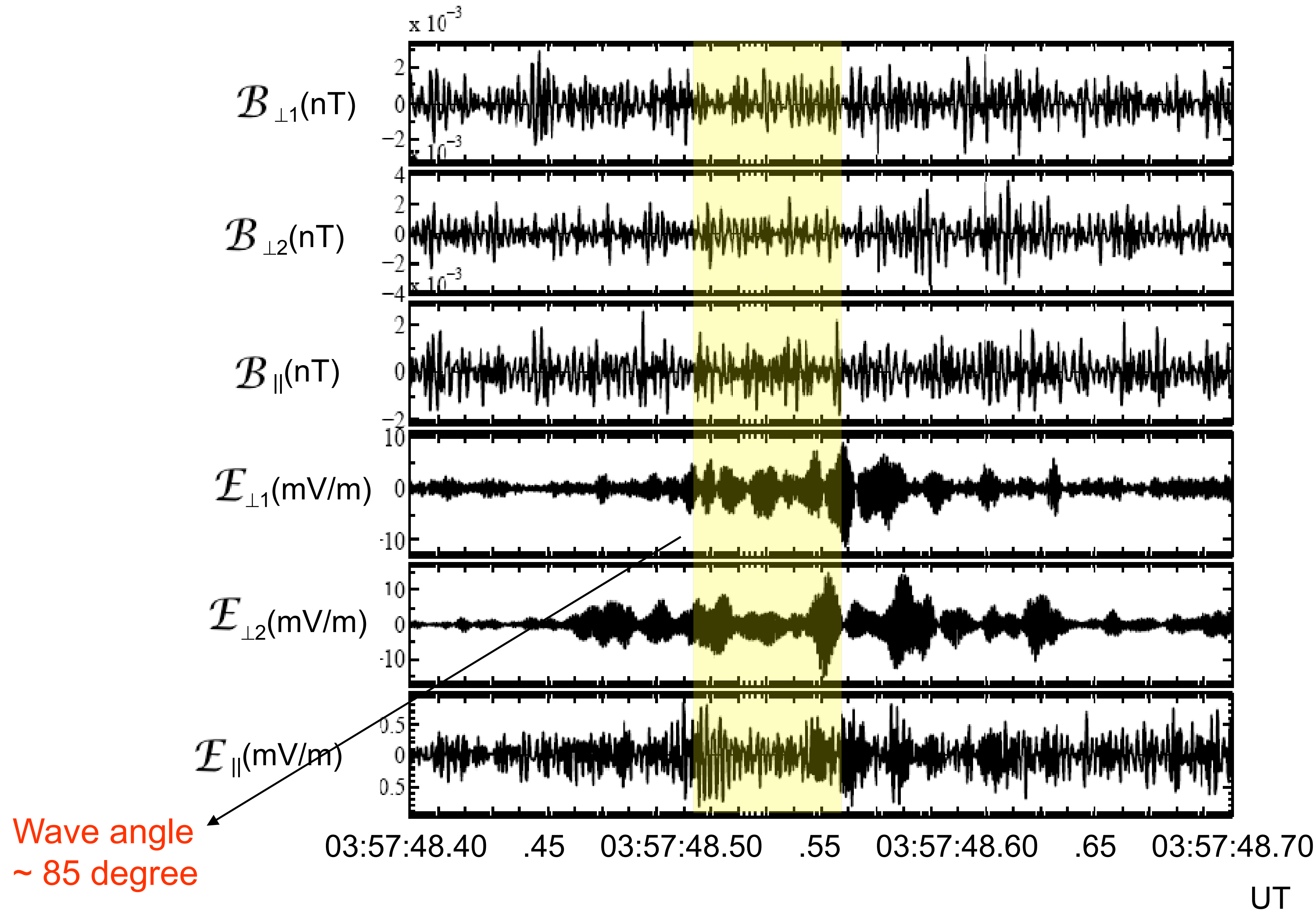
Power Spectrum THEMIS E



Power Spectrum THEMIS E (wave burst data)



Wave Form THEMIS E (between 1200 and 3000 Hz)



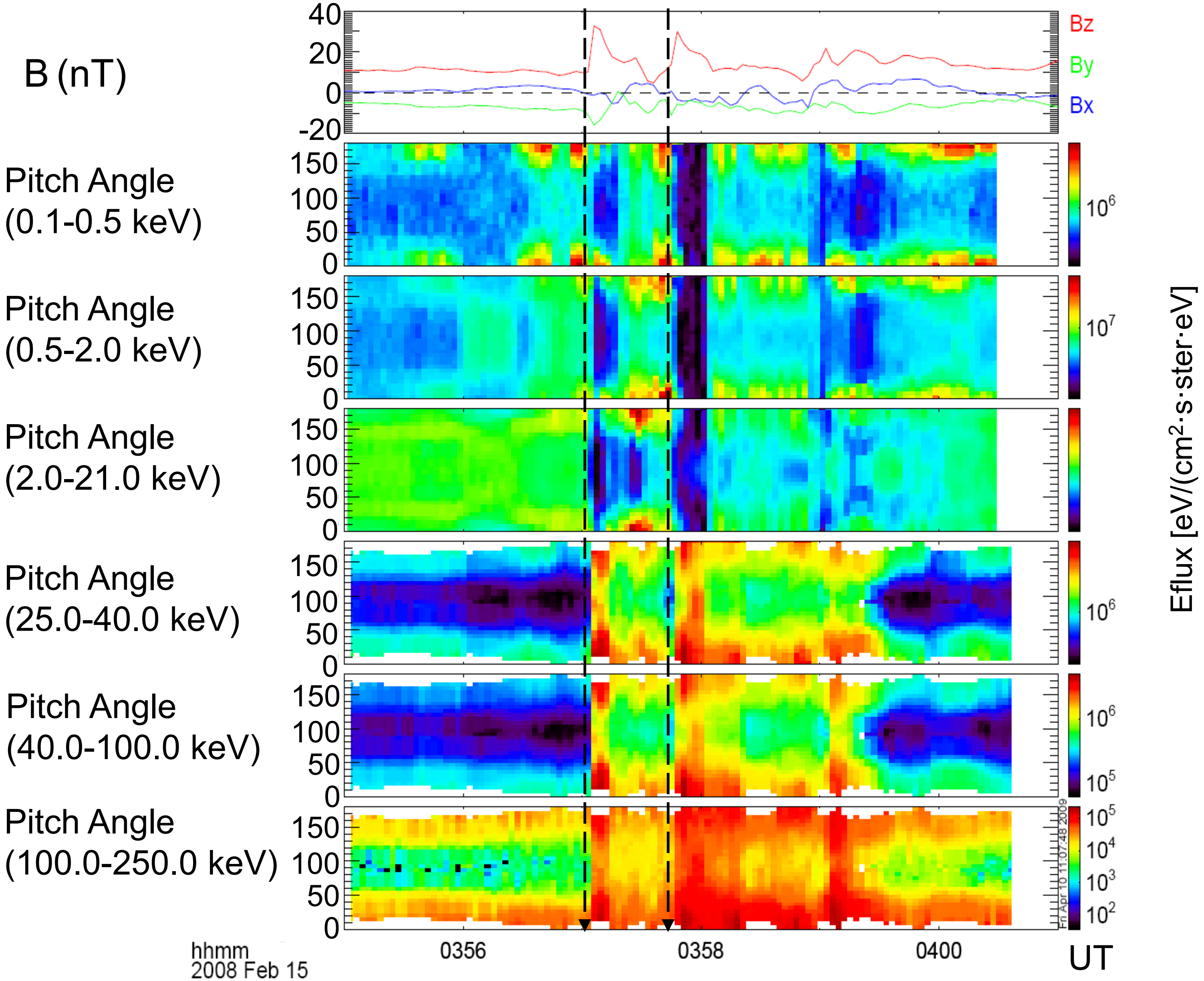
Observed Waves

- Ion cyclotron – electromagnetic, oblique
- Lower hybrid – electrostatic, oblique
- Upper hybrid – electrostatic, oblique
- Langmuir waves? – electrostatic, parallel, *but above instrument cutoff*

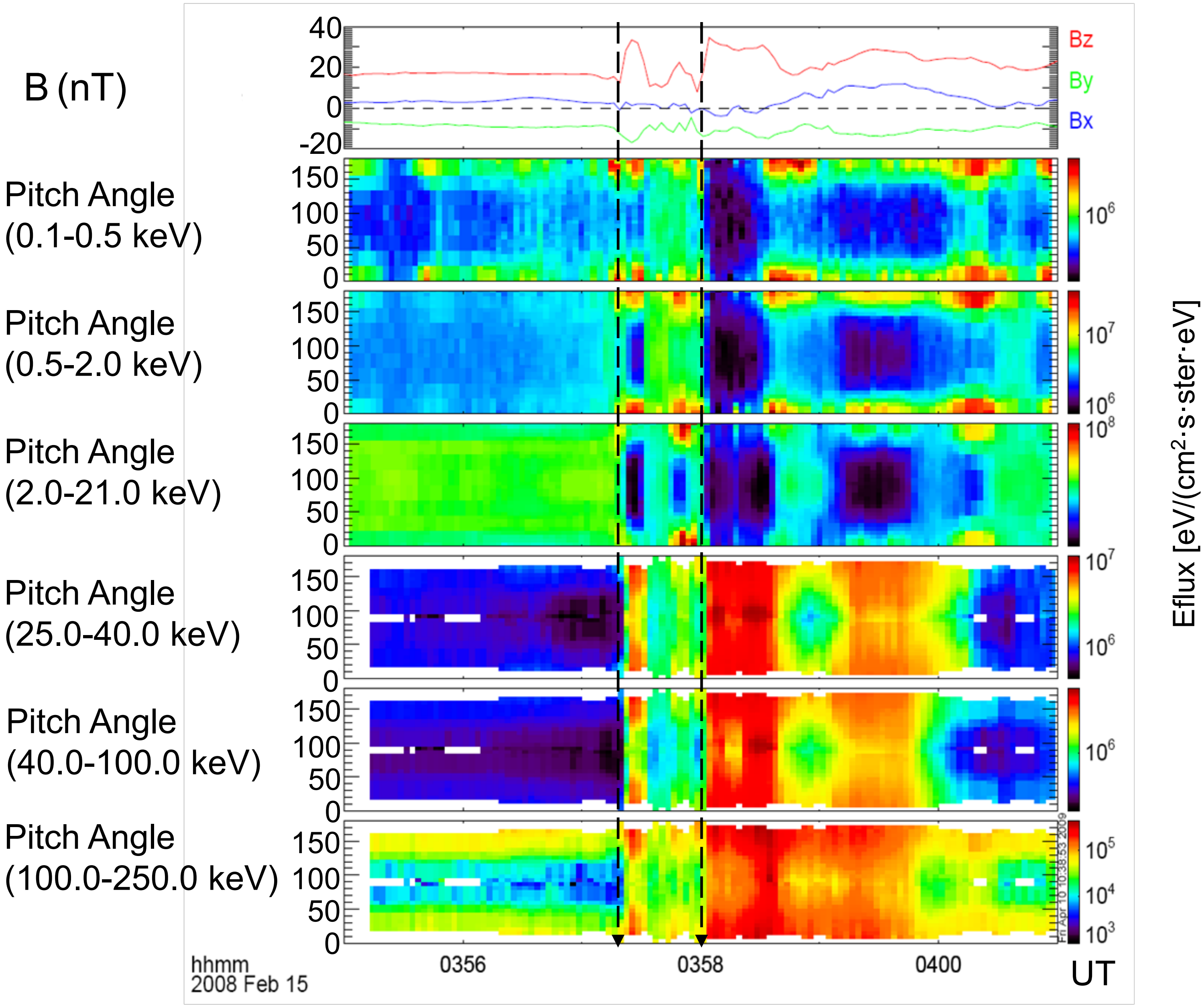
Possible Free Energy Sources

- Ion cyclotron – ion beam
- Lower hybrid – transverse current
- Upper hybrid – $df/dv_{\perp} > 0$
- Langmuir waves? – electron beam

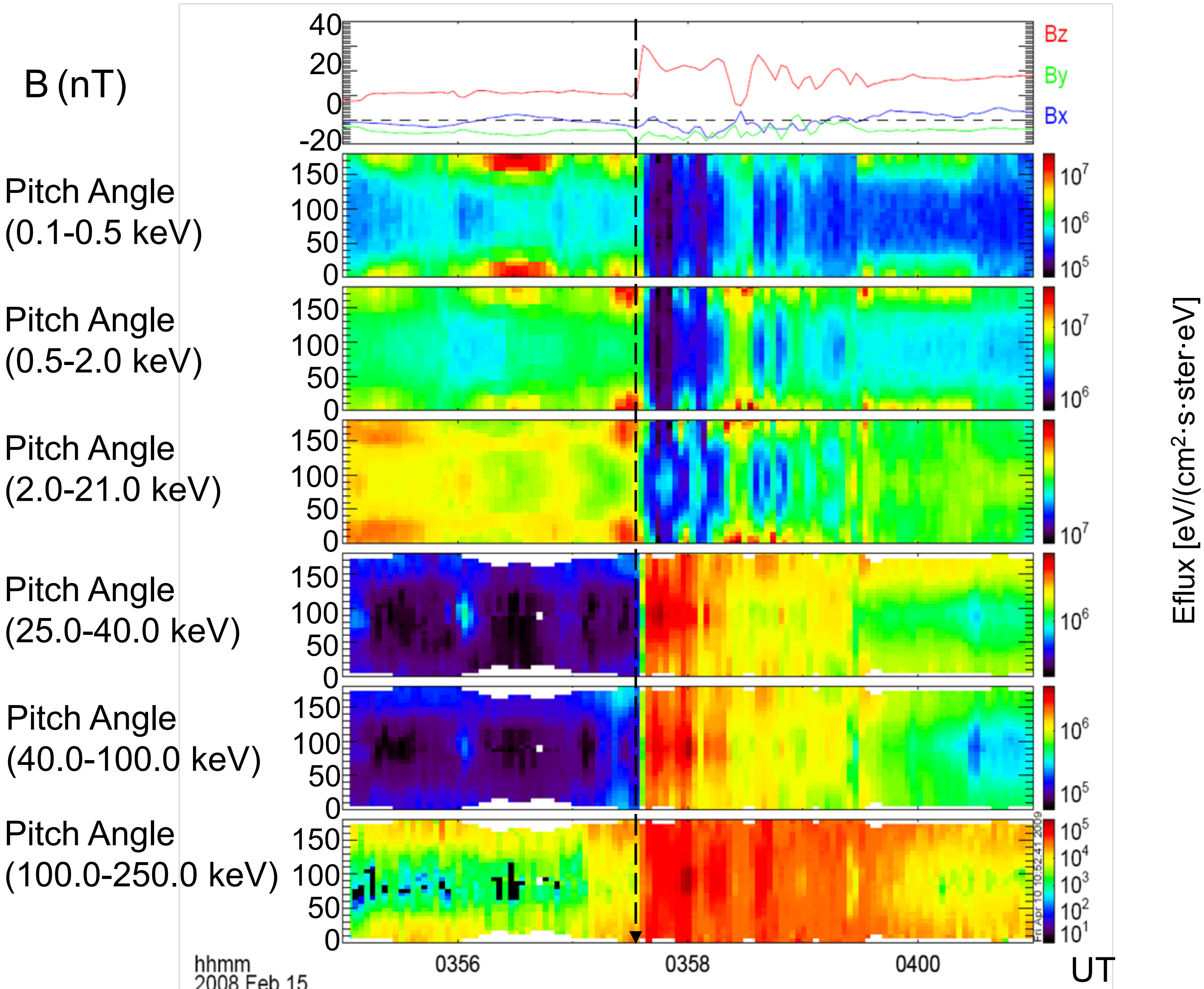
Pitch Angle Distribution THEMIS E



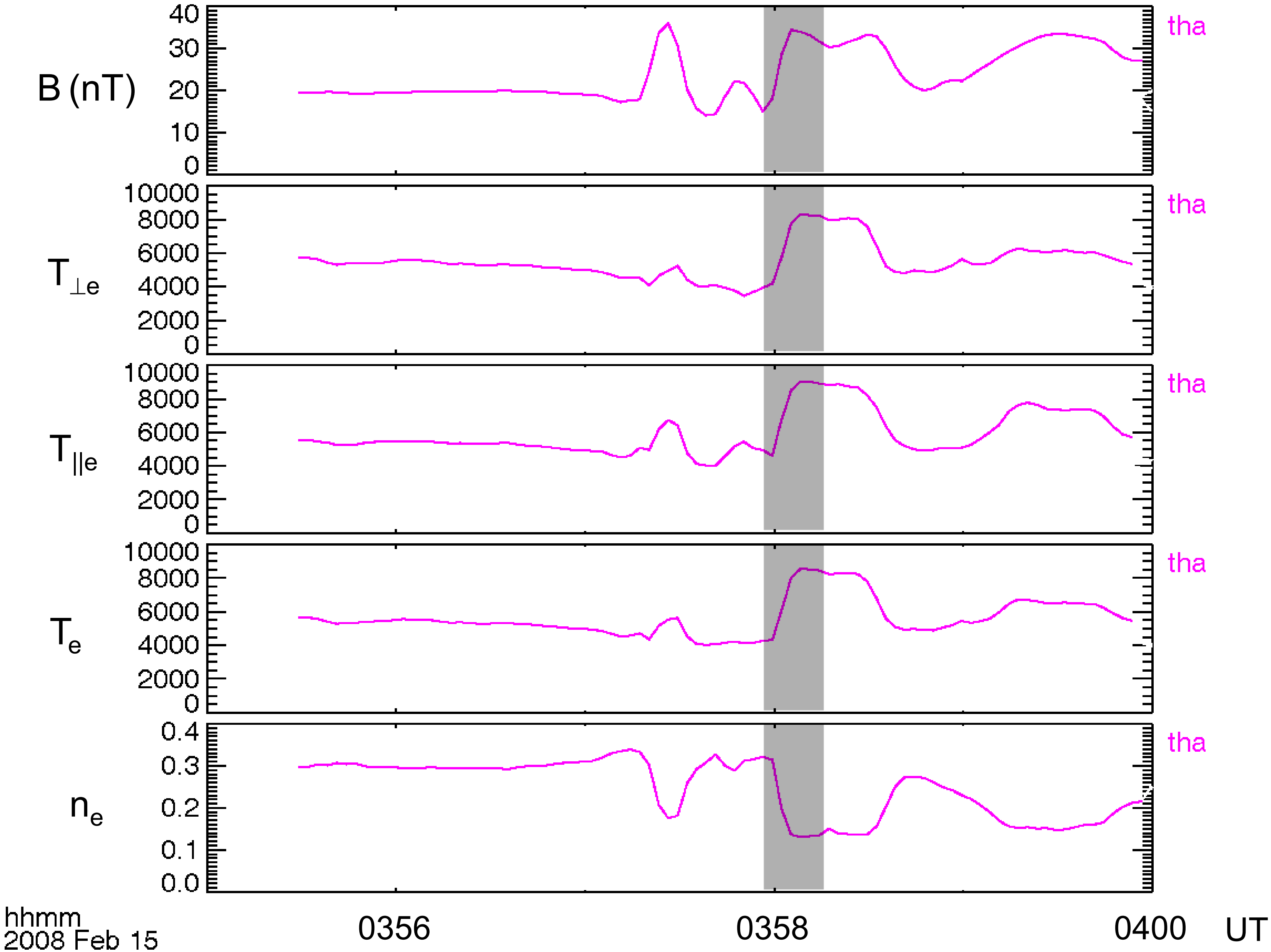
Pitch Angle Distribution THEMIS A



Pitch Angle Distribution THEMIS D



Magnetic Field, Electron Temperature and Density



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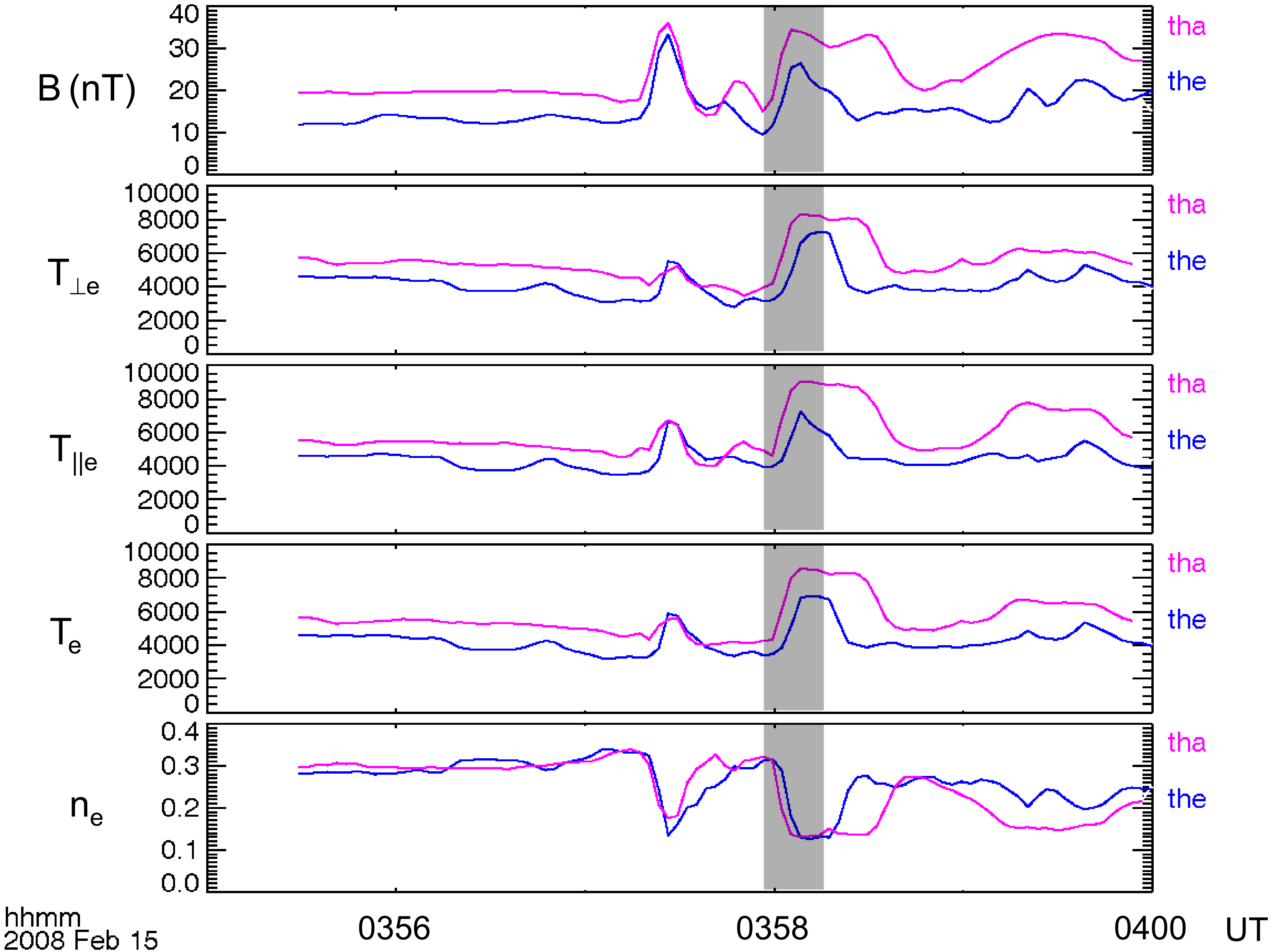
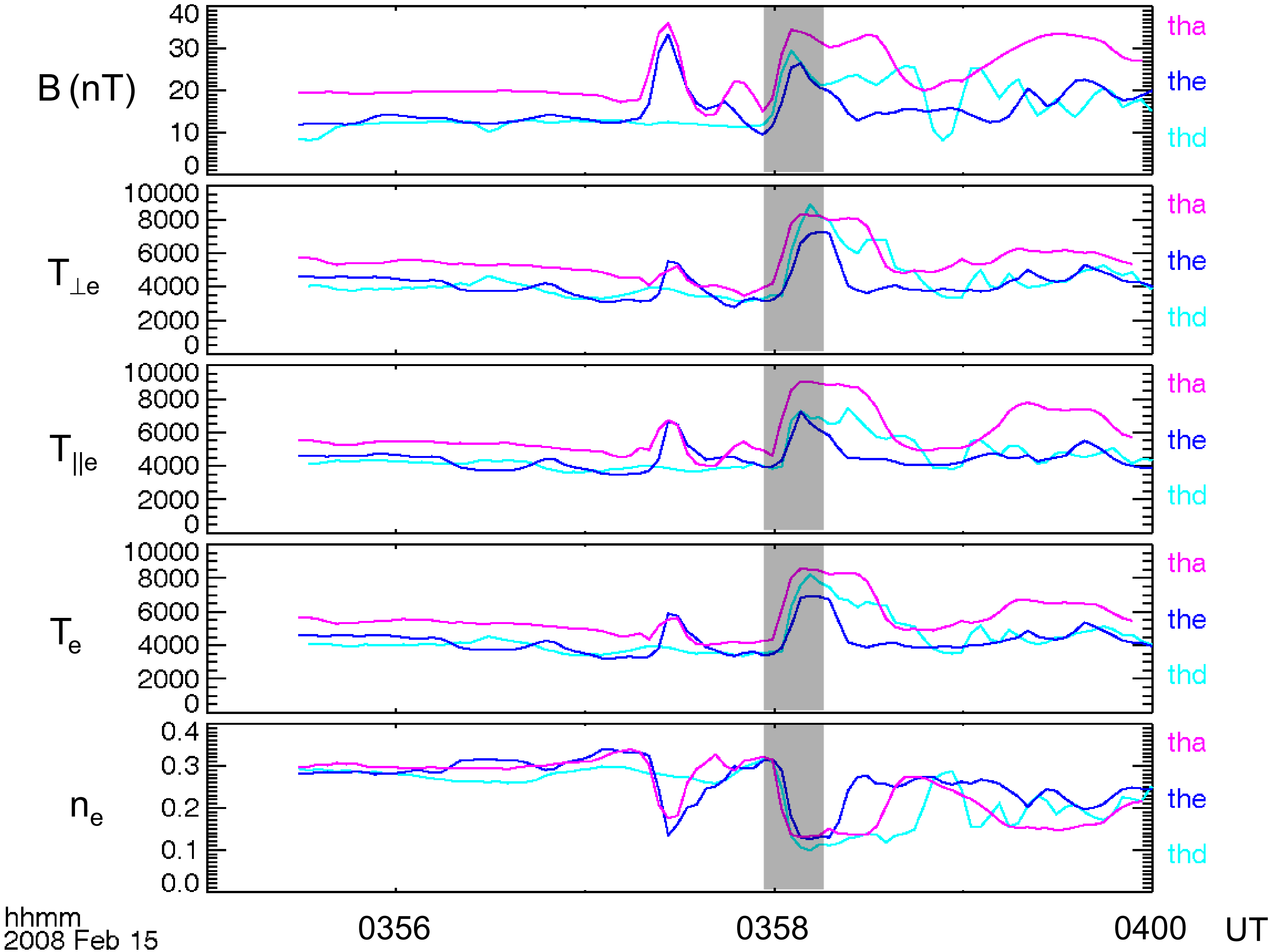


Magnetic Field, Electron Temperature and Density



Summary

- The THEMIS spacecraft observed a series of earthward moving dipolarizations. In our MHD simulation, the dipolarizations occurred when narrow bands of earthward flow from tail reconnection were directed at the spacecraft.

- The dipolarizations were accompanied by intense electromagnetic and electrostatic waves and electron acceleration. Very large (~60mV/m) electric field pulses are found in a thin region at the edge of the dipolarization front.

- A number of wave modes were observed including ion cyclotron, lower hybrid, and upper hybrid waves. Possible free energy sources including ion beams, transverse currents, and

  $$df / dv_{\perp} > 0$$

- Adiabatic processes (Betatron and Fermi) cannot account for the observed heating. Waves also are needed.

Dennis Papadopoulos

- Renaissance Scholar – Dennis has worked on a wide range of topics including laser plasmas, type III solar radio bursts, using high frequency heaters to generate ELF/VLF waves, anomalous transport, hybrid simulations of shocks, global MHD models and many more problems.

- Keen competitor – Dennis and I headed competing theory teams on ISTP and competed on the SPTP. He is a tough competitor who keeps you on your toes.

- Helpful colleague – When ISTP was cancelled we joined forces.

- Friend – He and his group hosted me when I was in Washington after September 11. They were very gracious.

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Betatron and Fermi Acceleration

- We compared peak B, $T_\perp$ and $T_{||}$ values from the first and second structures encountered by the THEMIS spacecraft.
- If the plasma and magnetic field were convected directly from one spacecraft another spacecraft, conservation of μ between implies that $T_\perp/B$ should be constant (betatron acceleration.) This was true for structure 2 encountering THEMIS A and then THEMIS E.
- The peak magnetic field at E was 26 nT and the temperature was 7000 keV while at A the corresponding numbers were 34 nT and 8500 keV. This gives $T_\perp/B$ = 250 nT/eV at E and 269 nT/eV consistent with conservation of μ between the two observed peaks.

Betatron and Fermi Acceleration

- We then computed the quantity $T_{||}S^2$ for the two peaks, which should be approximately constant if the J is conserved (Fermi acceleration.)

- We used the MHD magnetic field to compute the field line lengths of a field line that convected from A to E.

- While the field line increased in length from 36.0 to 36.7 R_E the parallel temperature increased from 7000 the 9000 eV which is not consistent with Fermi acceleration.

- This result suggests that wave particle interactions are heating the particles in the parallel direction or isotropizing the distribution.

Summary of MHD Results

- Reconnection in the tail created a series of narrow earthward flow channels.

- During this event the flow channels were directed at the three THEMIS satellites.

- As the earthward convecting flux tubes reached the THEMIS location they became dipole-like.

- A series of dipolarizations resulted – THEMIS E and A observed both but THEMIS D only observed the second.