University of Iowa

NONLINEAR ELECTROSTATIC SOLITARY WAVES OSBERVED IN CONNECTION WITH EXTREME SPACE WEATHER CONDITIONS

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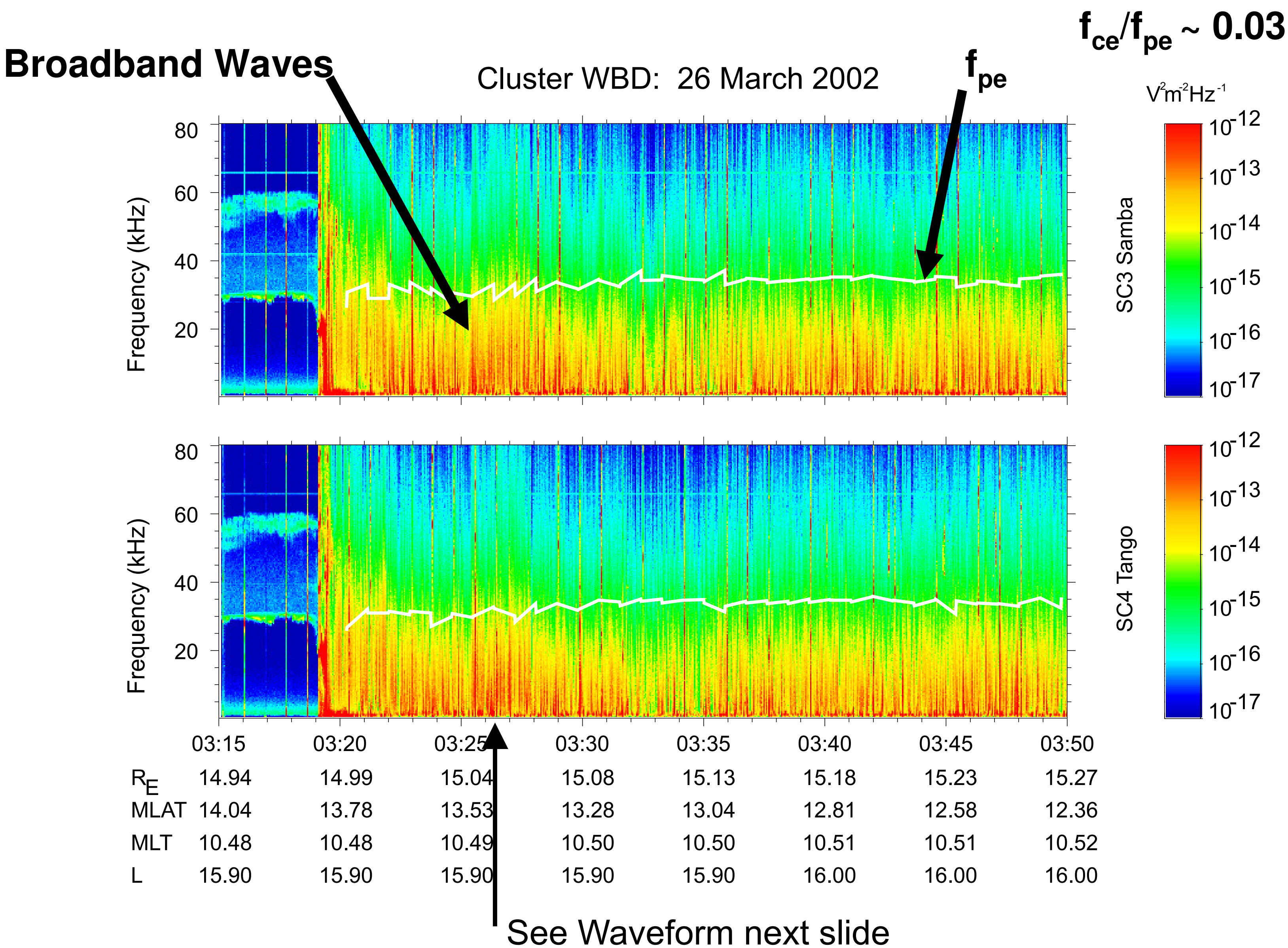
OUTLINE

- Description of Electrostatic Solitary Waves (ESWs), examples of ESWs observed in the magnetosheath, and where ESWs are observed in Earth space by Cluster
- Details of the super-substorm
- Cluster WBD overview of wave data obtained during the super-substorm of 24 August 2005
- Example of some of the ESWs that were detected around the time of the substorm onset
- Characteristics of the ESWs observed during the super-substorm
- Examination of ESW data in light of magnetic field and particle data
- Discussion of Kelvin-Helmholtz instability
- Summary

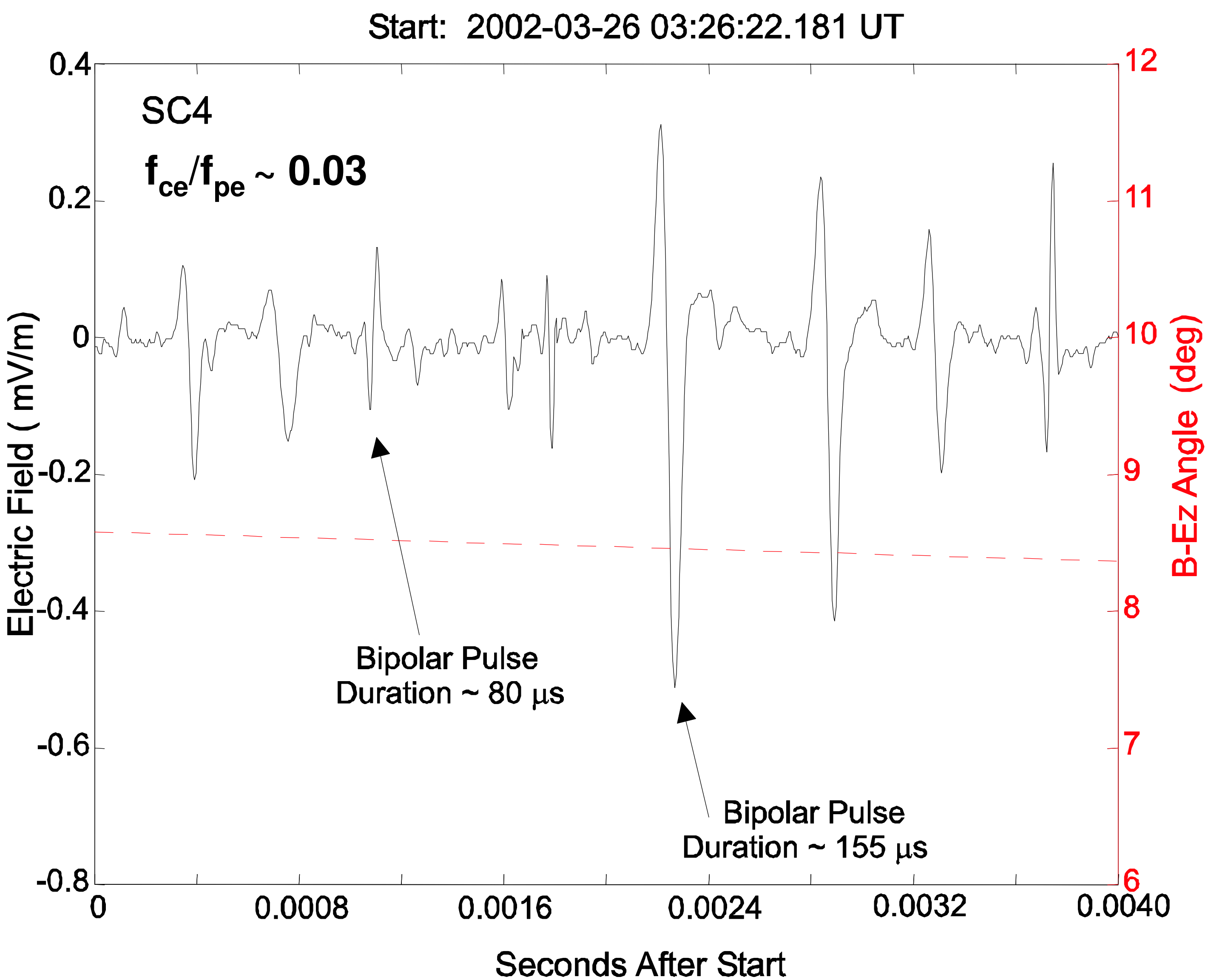
WHAT ARE ELECTROSTATIC SOLITARY WAVES?

- ESWs are isolated pulses, representing potential or density structures, observed in high time resolution ac electric field waveform data; first seen on S3-3 spacecraft [Temerin et al., *Phys. Rev. Lett.*, 1982].
- ESW types:
  - Bipolar: half sinusoid-like cycle followed immediately by a similar half cycle of opposite sign (phase space holes or density structures)
  - Tripolar: two half sinusoids of one polarity with an intervening half sinusoid of opposite polarity and generally larger amplitude (double layer)
  - Monopolar: half sinusoid of one polarity (double layer)
  - Offset Bipolar: same as Bipolar except with a null field between the two half sinusoids (phase space holes).
- Generation in space most likely through the following nonlinear processes
  - Beam instability (e.g., two-stream) → BGK Mode
  - Acoustic Instability → Electron and Ion Mode
  - Spontaneously out of turbulence

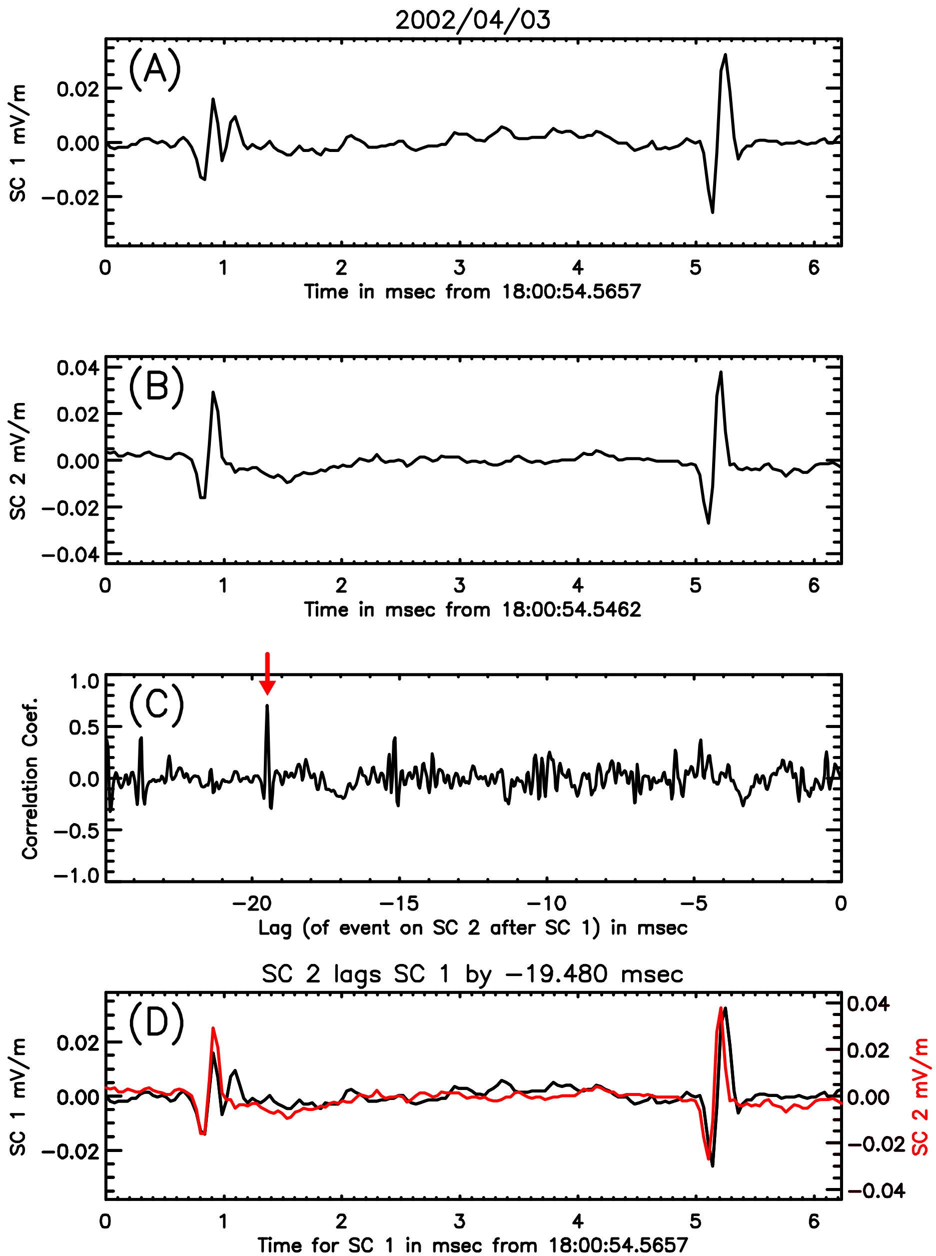
QUASI-PERPENDICULAR BOW SHOCK CROSSING AND MAGNETOSHEATH



MAGNETOSHEATH SOLITARY WAVES



EXAMPLE OF ESW PROPAGATION IN THE MAGNETOSHEATH



- Two bipolar pulses of ~0.3 ms time duration observed on SC1 and SC2 (panels A and B)
- Correlation coefficient of 0.70 at about 19.5 ms lag of SC1 from SC2 (panel C)
- Plotting SC1 and SC2 6 ms waveforms on top of each other using 19.5 ms lag gives good fit of both bipolars (Panel D)
- Based on 38 km separation along B and 95 km across B: v = 1,947 km/s toward Earth, parallel size of 0.6 km and perpendicular size of at least 95 km (i.e., flat or pancake shaped).

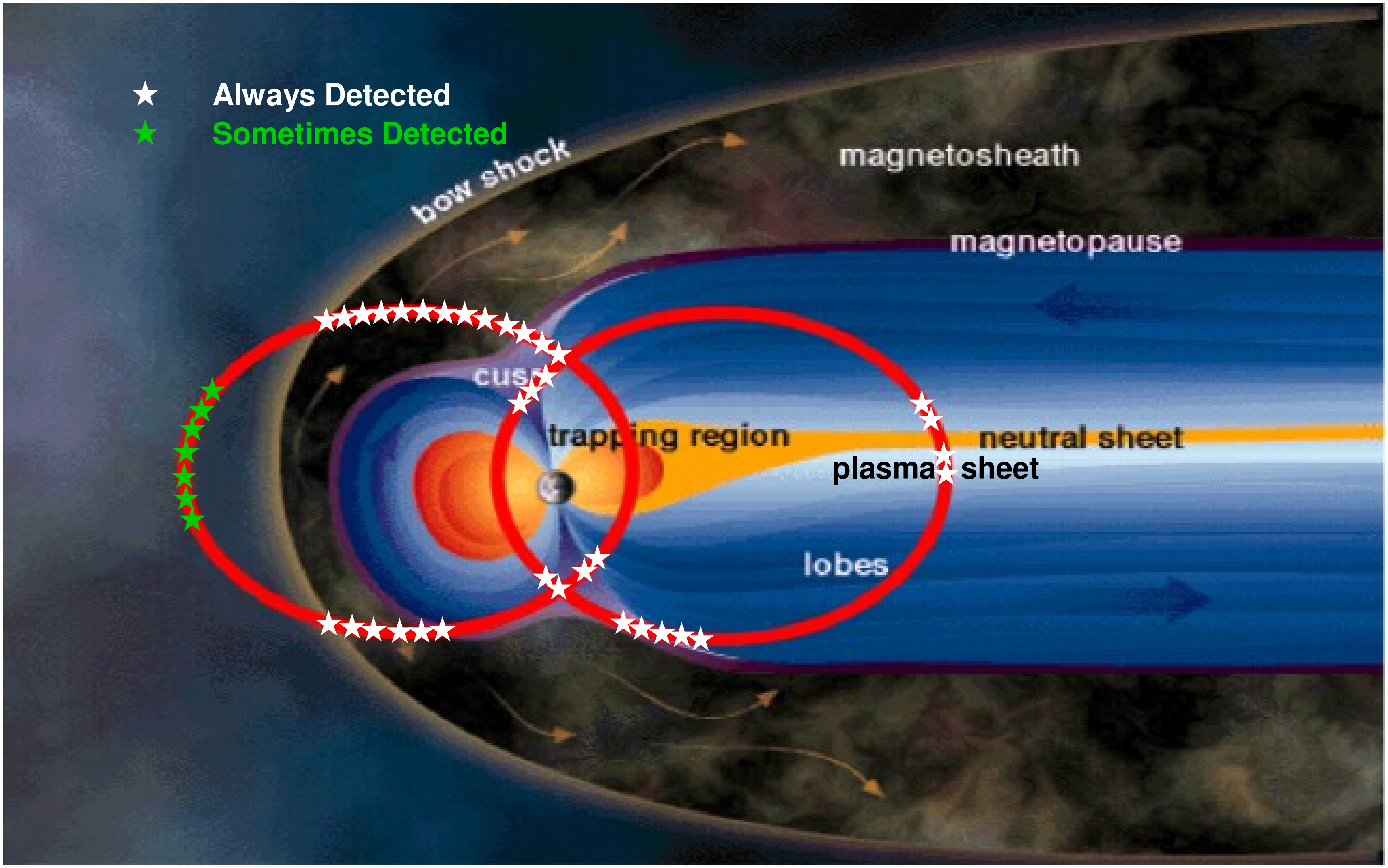
SURVEY OF ESW PROPAGATION IN THE MAGNETOSHEATH CLOSE TO THE MAGNETOPAUSE

Date	Time (UT)	Cluster space-craft	Lag (ms)	Pulse Duration (ms)	$D_{B//}$ (km)	$D_{B\perp}$ (km)	Velocity (km/s)	Direction (referenced to Earth)	$L_{B//}$ (km)	$L_{B\perp}$ (km)
2002/02/19	22:20:27.90	4,3	22.5	0.60	30	40	1,334	Away	0.8	≥40
2002/04/03	18:00:54.54	2,1	19.5	0.30	38	95	1,947	Toward	0.6	≥95
2002/05/04	14:02:57.11	4,1	37.8	0.25	71	79	1,870	Toward	0.5	≥79
2002/05/04	14:08:06.19	3,1	21.4	0.37	37	97	1,724	Toward	0.6	≥97
2002/05/04	14:08:06.20	3,1	15.6	0.30	37	97	2,365	Toward	0.7	≥97
2002/05/04	14:08:00.23	3,1	17.0	0.45	37	97	2,167	Toward	1.0	≥97

Note: $D_{B//}$ and $D_{B\perp}$ are the distance between the two spacecraft along the magnetic field and perpendicular to the field, respectively; $L_{B//}$ and $L_{B\perp}$ are the structure's size along and perpendicular to the field.

[From Pickett et al., IUGG-2007 presentation in Perugia, Italy]

ELECTROSTATIC SOLITARY WAVES ARE DETECTED IN CLUSTER'S ORBIT IN REGIONS OF TURBULENCE AND MIXING OF PLASMAS



[See Pickett et al., *Annal. Geophys.*, 2004]

INTRODUCTION TO SUPER-SUBSTORMS

- The first Sun-Earth Virtual Conference was held 13-16 November 2006, hosted by Johns Hopkins Applied Physics Laboratory and titled "The State of the Sun-Earth System During Extreme Space Weather: Return to the Auroral Oval for the Anniversary of the IGY" (see website http://workshops.jhuapl.edu/). Many citations in the following presentation are to presentations from that virtual conference and will be cited as VC2006.

- This Virtual Conference was devoted to the study of so-called super-substorms occurring on 15 May 2005 and 24 August 2005.

- One interesting question that came to light from the results of that Virtual Conference is whether the Electrostatic Solitary Waves (ESWs) observed by the Cluster Wideband (WBD) plasma wave receiver at main phase onset of the super-substorm on 24 August 2005 are a signature of the mixing of boundary layer plasma into the magnetosphere by Kelvin-Helmholtz (K-H) vortices.

- In the following we briefly explore this possibility as well as other possibilities for the presence of ESWs in connection with the super-substorm.

DETAILS OF THE 24 AUGUST 2005 "SUPER SUBSTORM"

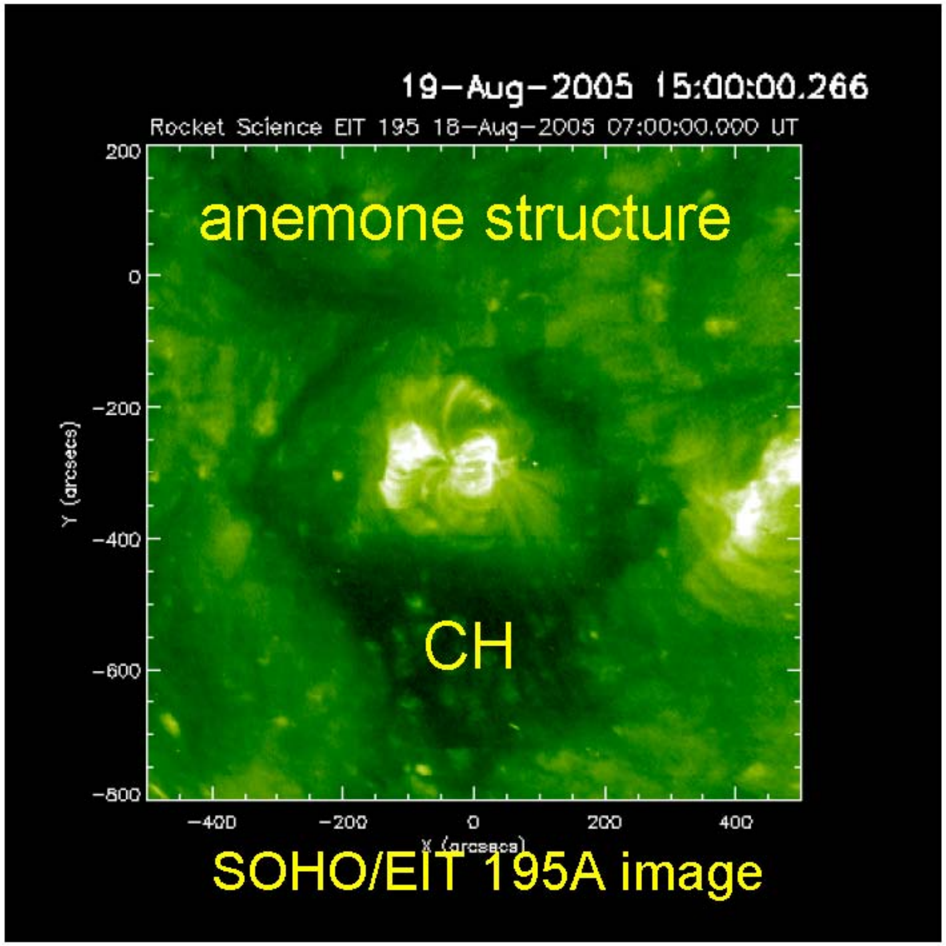
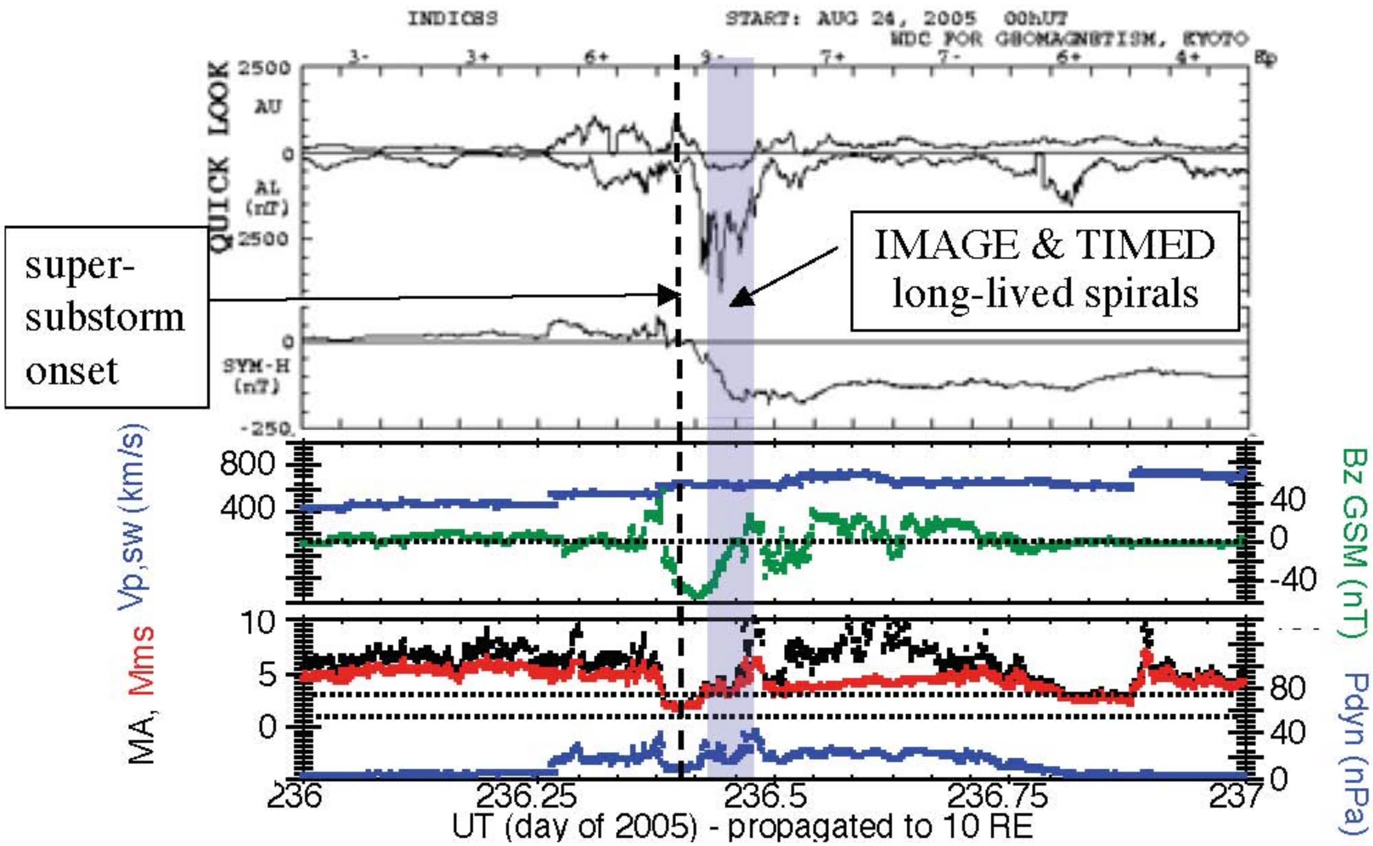


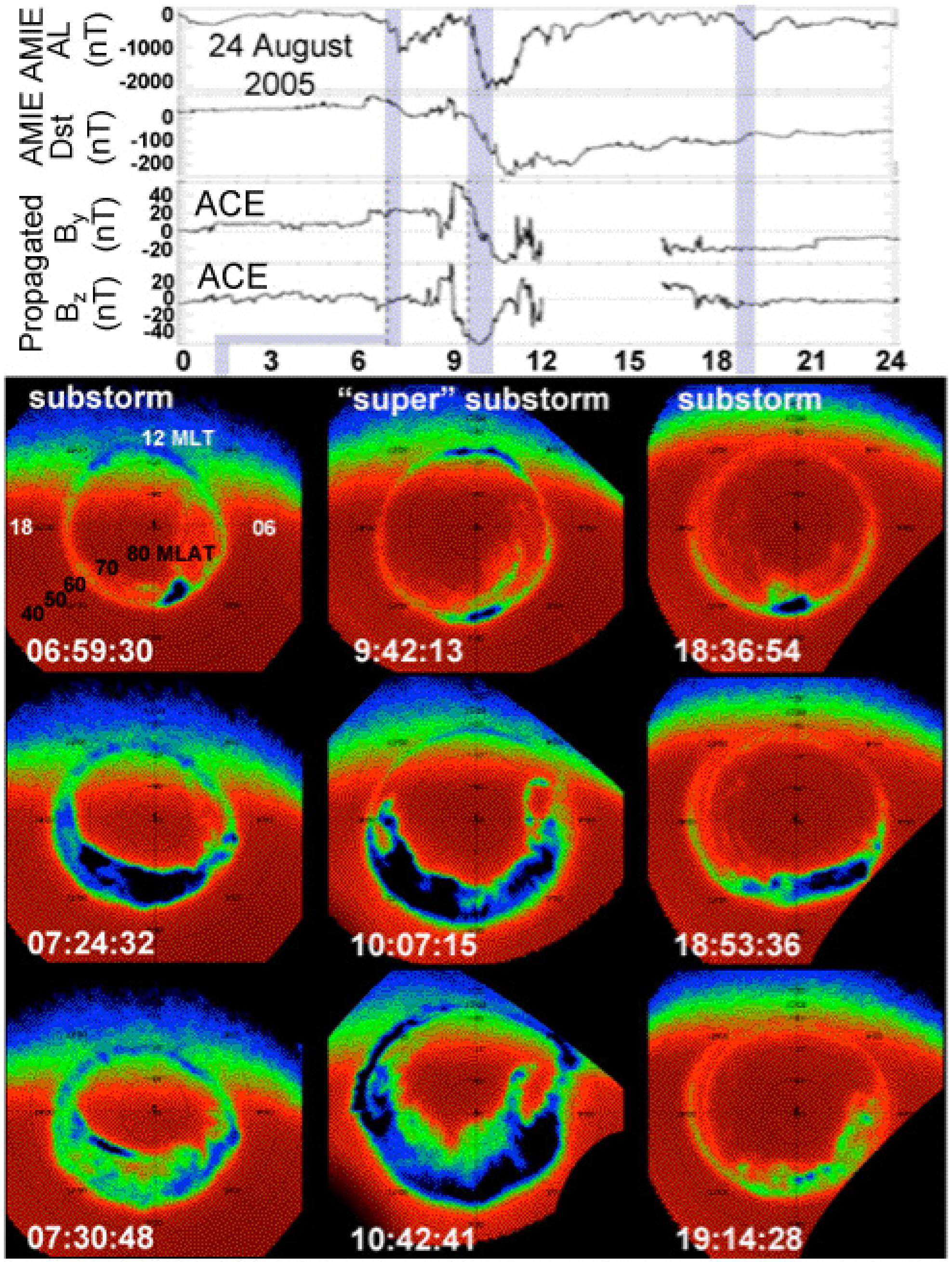
Image of Active Region (AR) 10798 from SOHO EIT clearly showing its unusual "anemone" structure (AR surrounded by a coronal hole) several days before the eruption that produced the 24 August 2005 super substorm. [From Asai et al., VC2006]

- Eruptions of AR10798 were accompanied by M2.6 and M5.6 x-ray flares at ~01 UT and ~17 UT, respectively on 22 August.
- Even though the AR was near the southwest limb of the Sun at the time, these eruptions produced Earthward-directed CMEs.
- A shock, presumably from the first eruption, reached SOHO at 05:33 UTC on 24 August.
- The first CME was released near 01 UT and had a velocity of 1200 km/s and the second was released near 1700 UT with a velocity of 2400 km/s. The second caught up to the first and they arrived at Earth as one complicated disturbance.

DETAILS OF THE 24 AUGUST 2005 “SUPER SUBSTORM” (Continued)



Characteristics of this super substorm: 1) unusually low magnetosonic and Alfven mach numbers of about 1-3 during main phase (second panel from bottom), 2) low DST (below -250 nT, top panel), very low AL (as low as -2400 nT, second panel) 3) Bz turning southward between ~09:00 and 11:00 UT reaching values as lows as ~-60 nT, 4) Intense substorm was triggered during the main phase, 5) Hemispheric power from NOAA peaked at 1286 GW demonstrating the geoeffectiveness of the ICME that was produced. [From VC2006 Timeline]

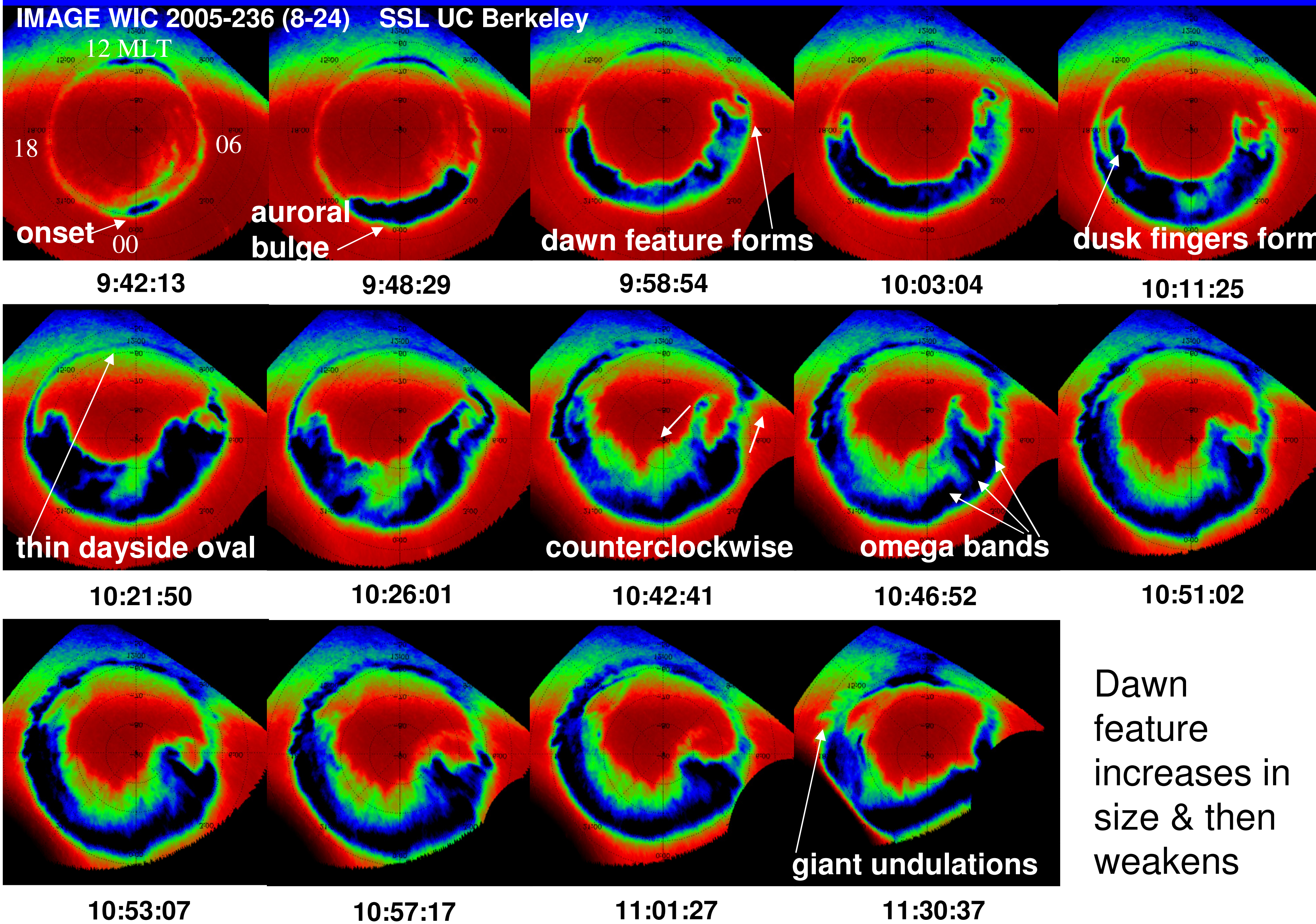


Kozyra, J. U., M.W. Liemohn, X. Cai, L. J. Paxton, S. B. Mende, R. A. Heelis, M. R. Hairston, W. R. Coley, C. R. Clauer, A. Ridley, M. G. Henderson, M. F. Thomsen, A. DeJong, M. Kuznetsova, An unusual configuration of the auroral oval associated with severe space storms, manuscript in preparation, 2006

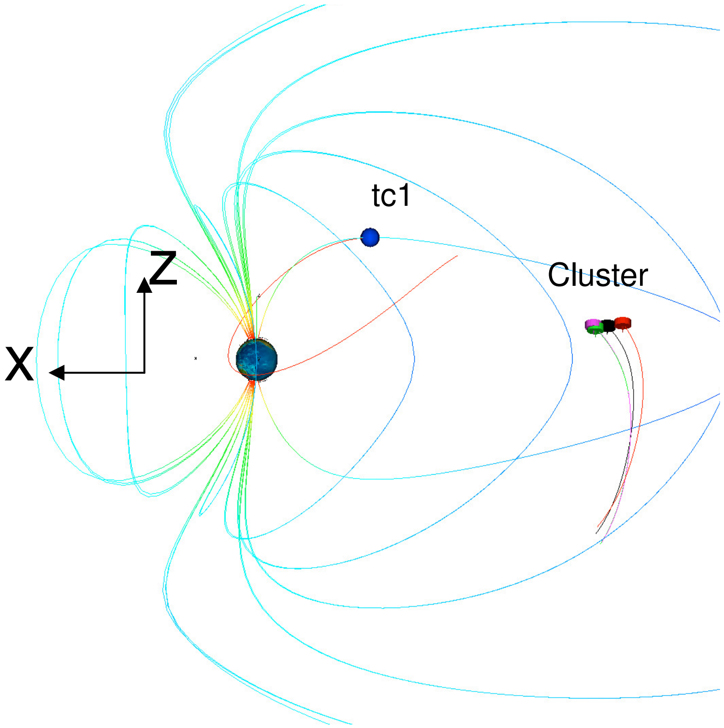
Substorm vs “Super” Substorm on 24 Aug 2005 [from Kozyra et al., VC2006]

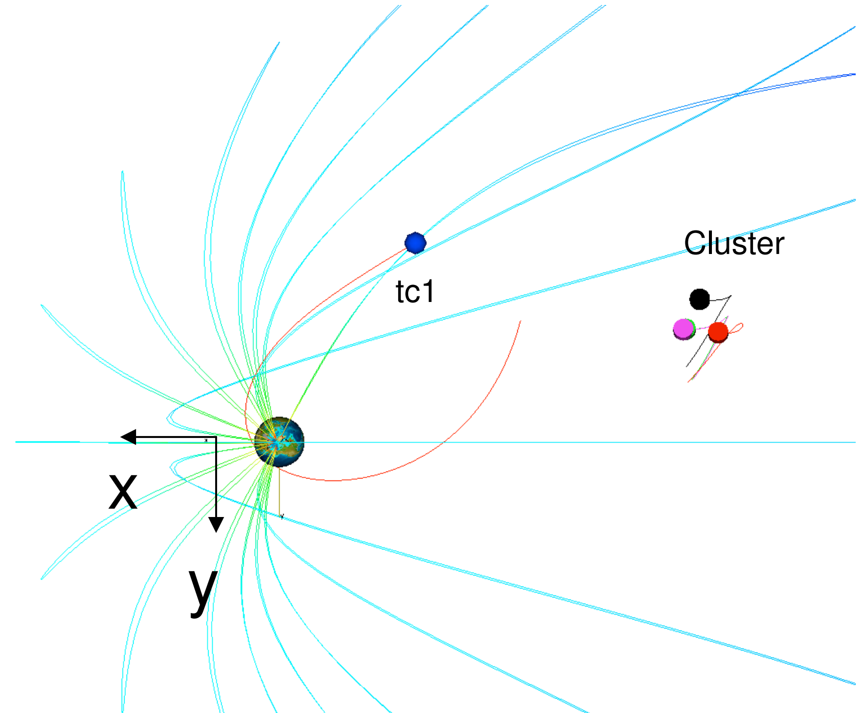
- No significant dawn or dusk activity in “more typical” substorms at 0700 UT and 1830 UT.
- However, large-scale dawn spiral and dusk finger form in the strong substorm during the superstorm main phase at 09:40 - 1130 UT during maximum IMF Bs.
- Omega bands (torches) appear to participate in formation of the dawnside spiral

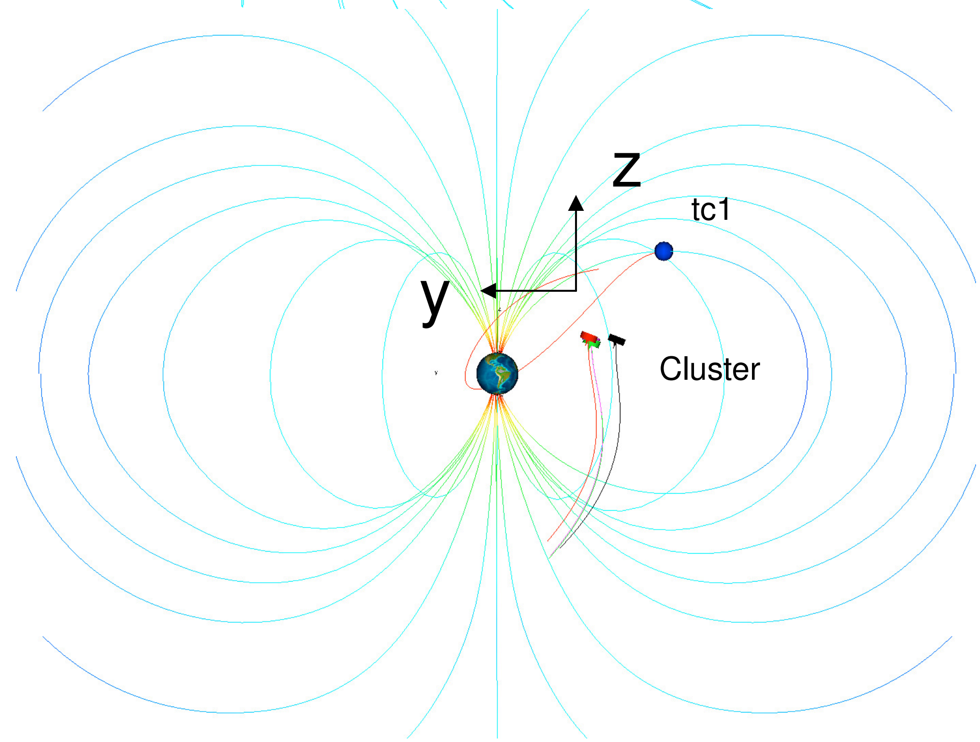
Development of “Super” Substorm on 24 August 2005 [from Kozyra et al., VC2006]



Dawn feature increases in size & then weakens

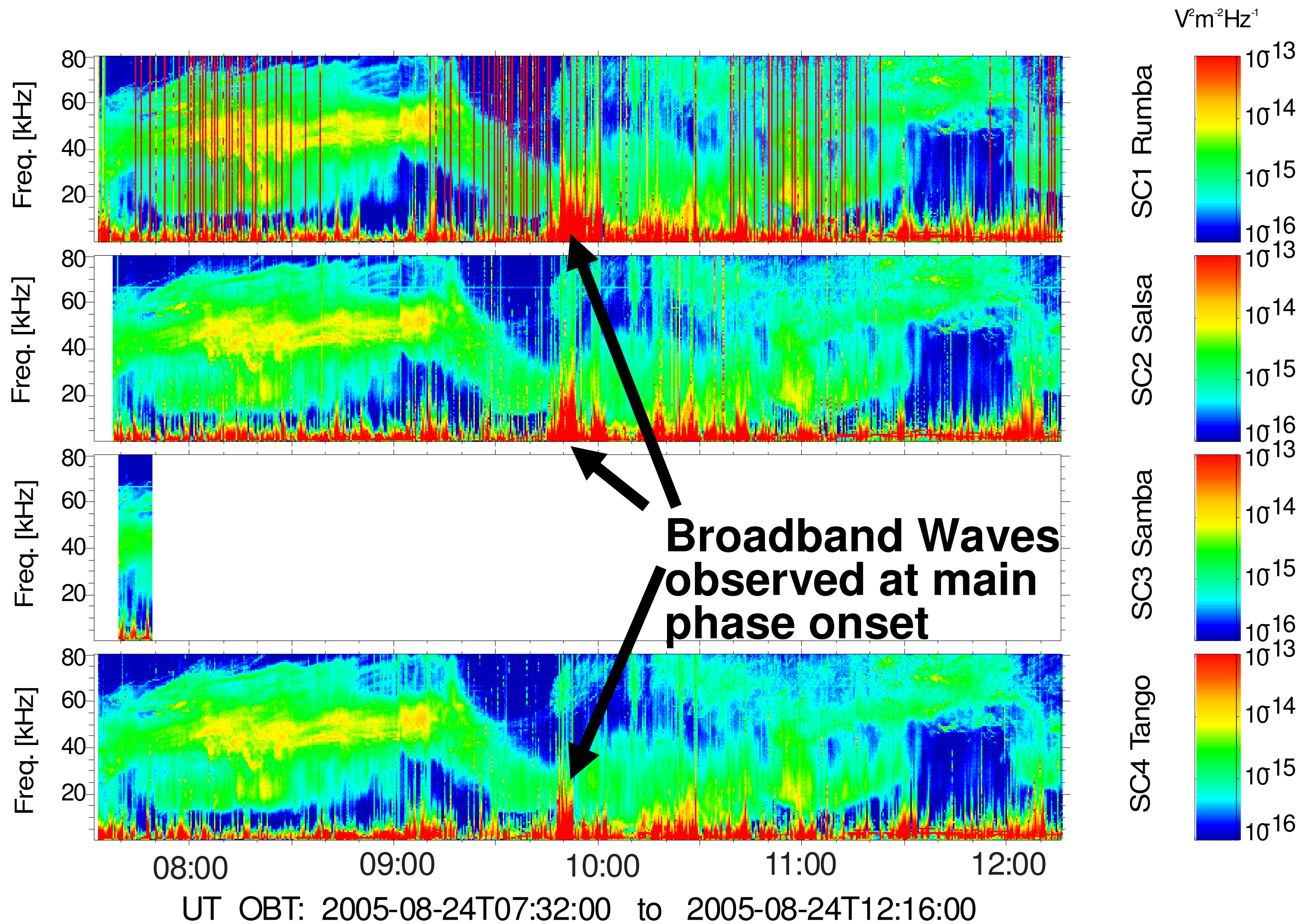






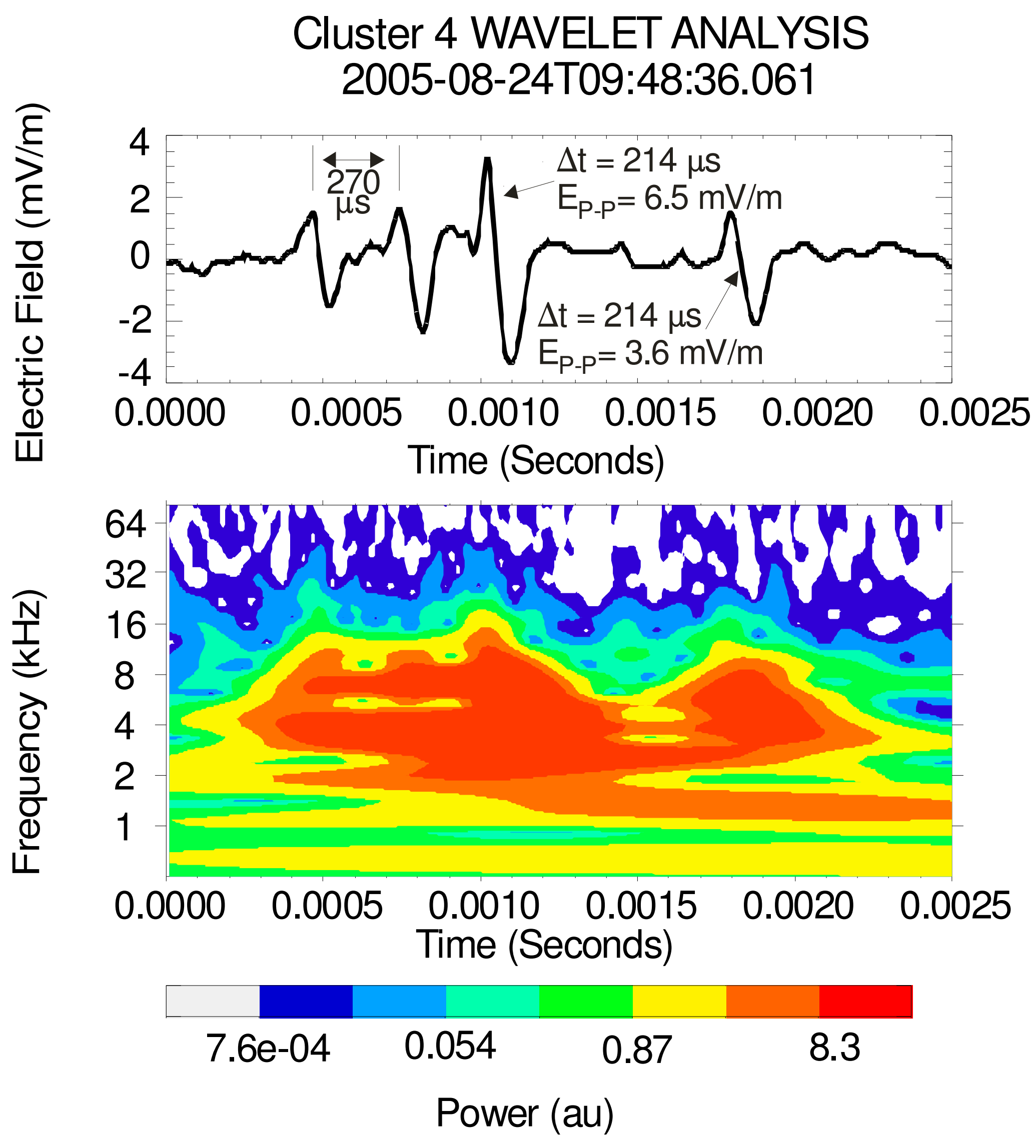
Location of the Cluster spacecraft on August 24, 2005 during the super-substorm

CLUSTER PLASMASHEET CROSSING AT ~18 R_E, 01:00 MLT, ~0°-25° λ_M



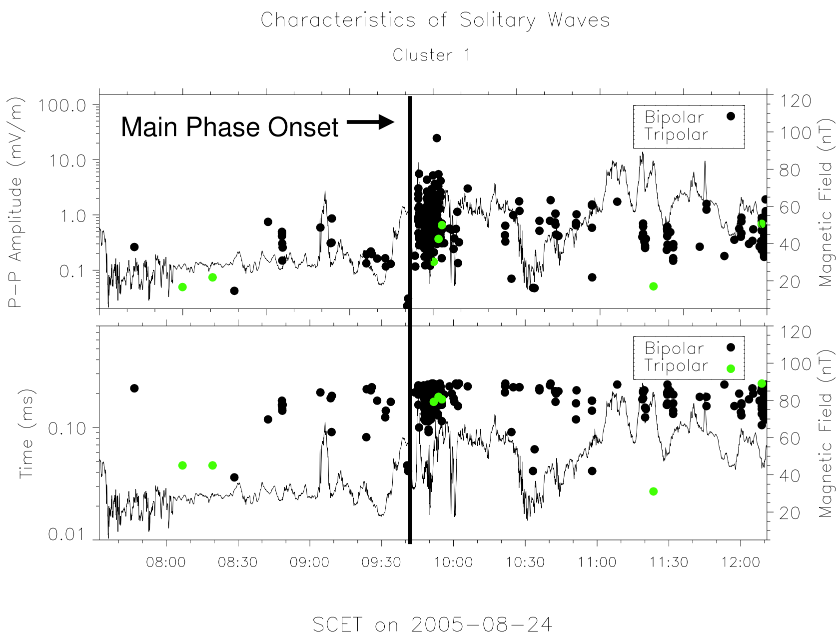
Cluster WBD data on 24 August 2005 show intense broadband waves at time of super-substorm main phase onset at about 09:45 UT on all spacecraft, with Cluster 1 observing them for a longer period of time and with larger amplitudes (note the vertical red lines in the top panel indicate times of Whisper radar soundings)

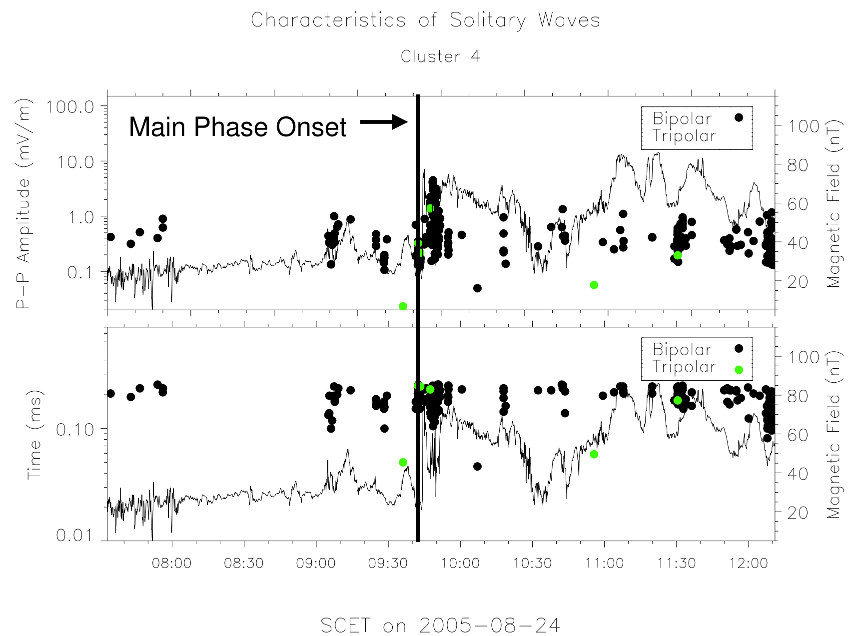
SAMPLE WAVEFORM AT 09:45 UT AND WAVELET ANALYSIS

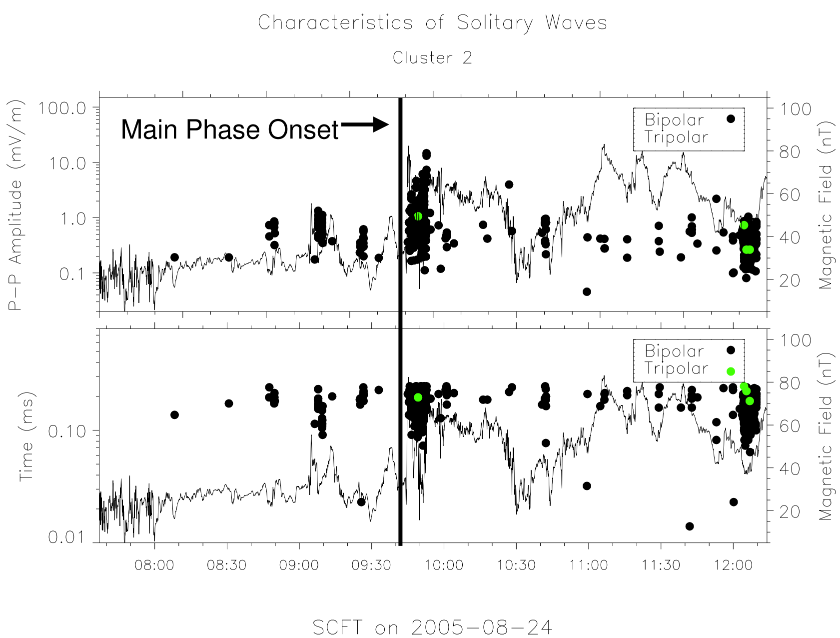


- Analysis of the waveforms (top panel) that comprise the broadband waves shows that these waves are actually Electrostatic Solitary Waves (ESWs), which are coherent, isolated pulses indicating the passage of potential or density structures by the spacecraft
- Noted are the time durations and the peak-to-peak electric fields of two of the pulses. Note that all 4 major pulses in this 2.5 ms interval have time durations of 214 µs.
- Wavelet transform in the bottom panel shows these structures are localized in time and frequency, with characteristic frequencies of about 4 kHz (inverse time duration).

DETECTION OF ESWS DURING SUPER-SUBSTORM

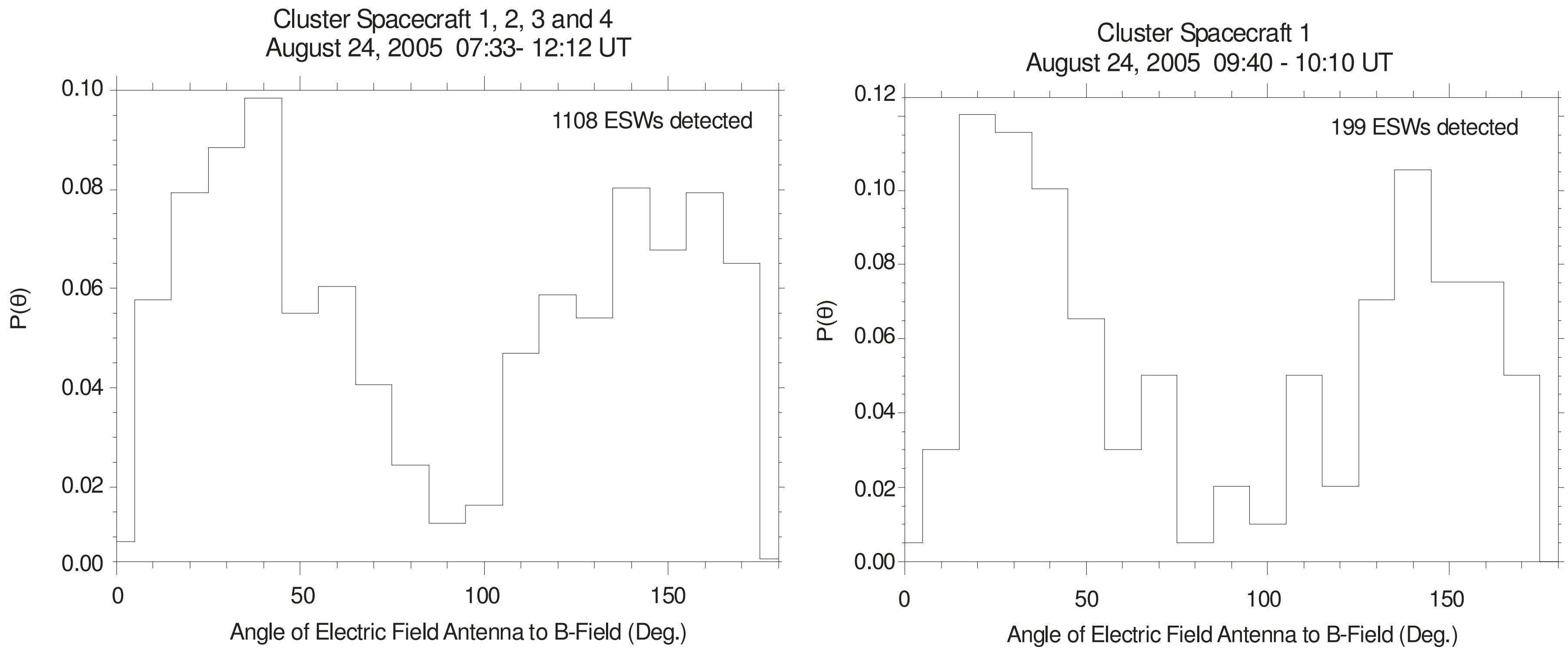






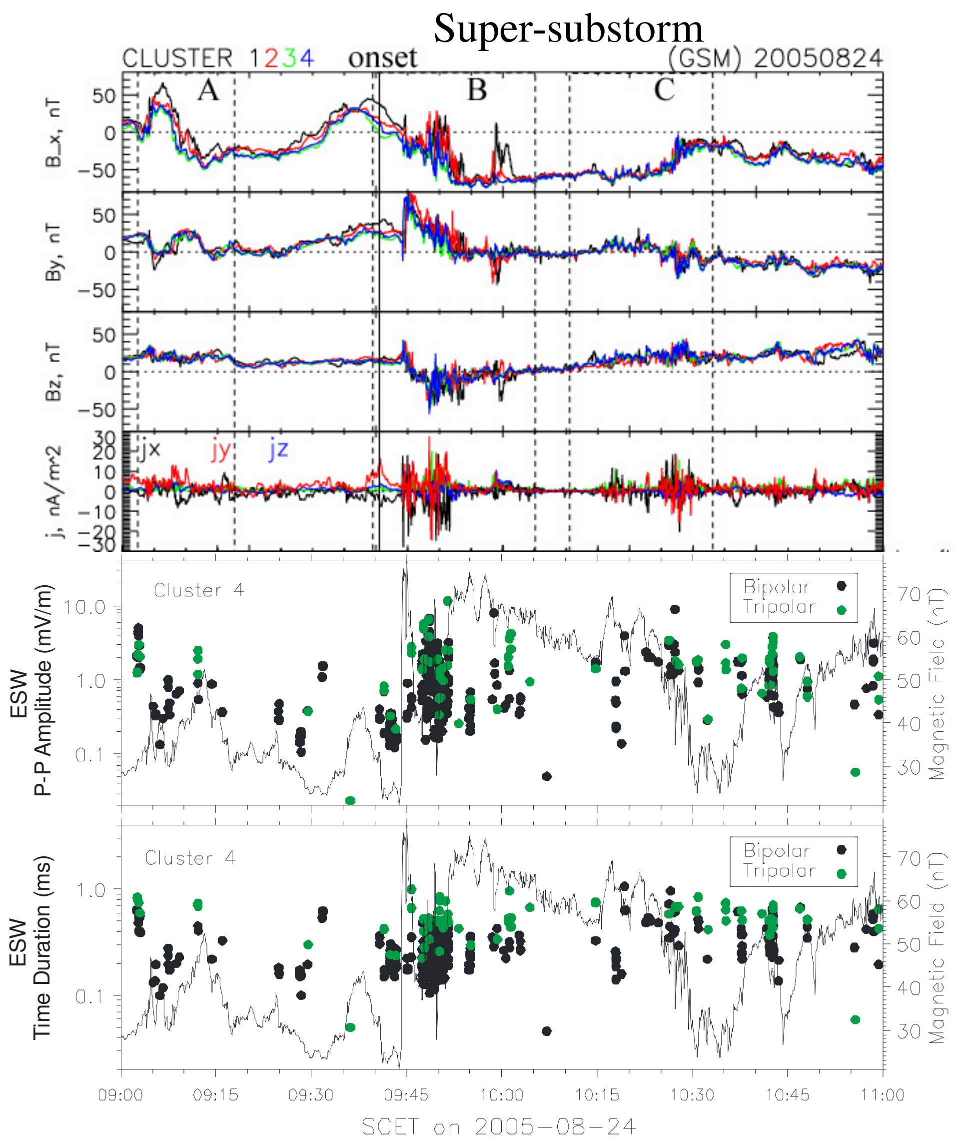
- Bipolar ESWs (black dots) and tripolar ESWs (green dots) are detected on all 3 spacecraft most plentifully just after main phase onset with time durations ranging from 80-250 μs (bottom panels) and amplitudes from 0.1-24 mV/m (top panels).
- Measured magnetic field is plotted as a solid line with scale on right vertical axis.

SOLITARY WAVE OCCURRENCE VS. ANGLE OF ANTENNA TO B



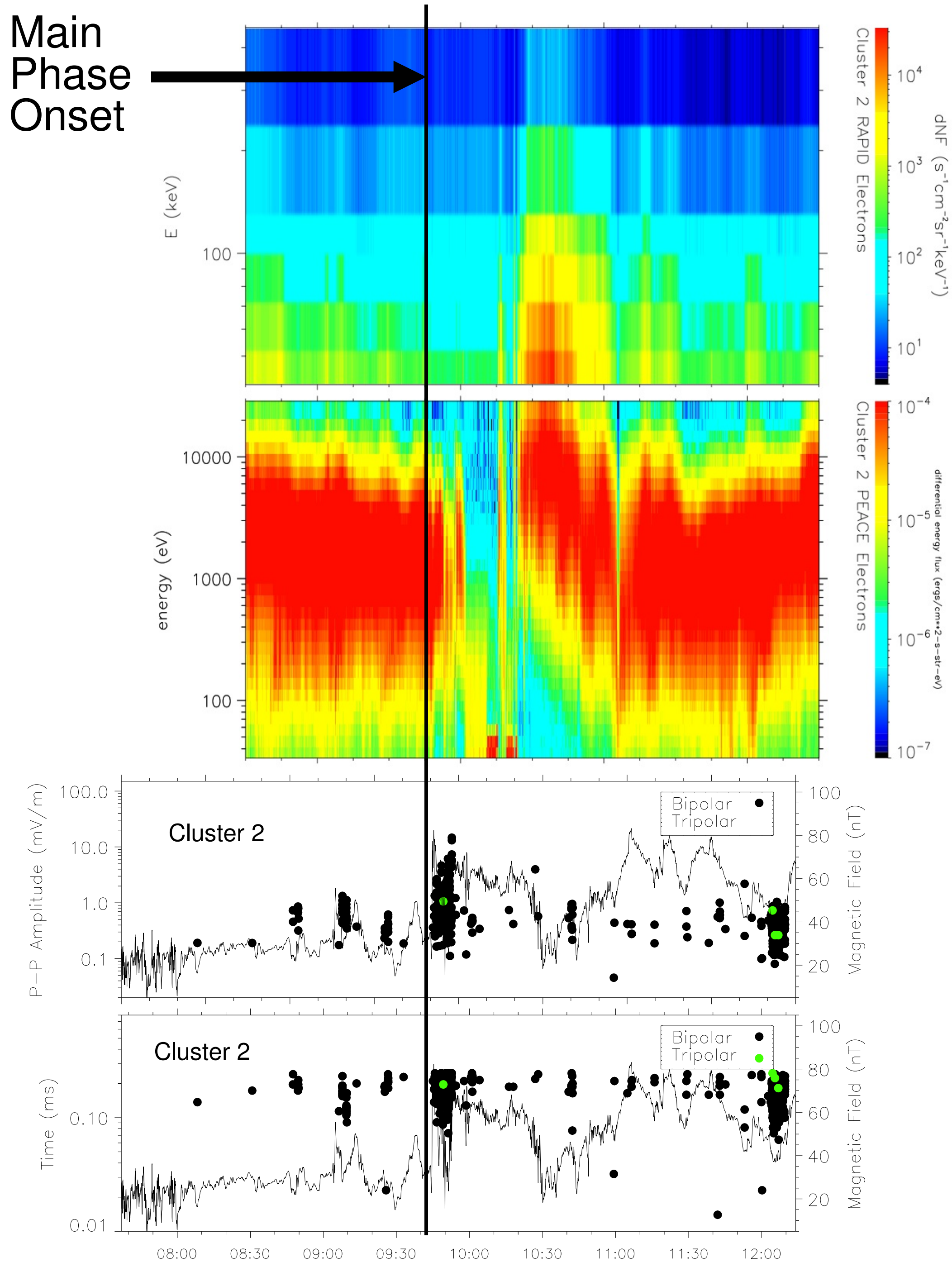
- Left panel shows ESW occurrence probability vs. the angle of the electric field antenna to the magnetic field for the entire WBD interval (07:33-12:12 UT) on all spacecraft; right panel shows this probability centered on the interval on SC1 around super-substorm onset (09:40-10:10 UT)
- Clearly there is a preference for angles closer to parallel and anti-parallel to the magnetic field direction, as opposed to perpendicular, in both plots
- There is some indication in both plots that the ESWs may be propagating at oblique angles to B and/or be generated out of processes that are not strictly field aligned

COMPARISON OF MAGNETIC FIELD DATA TO ESW DETECTION ON CLUSTER 4



- Panels 1,2,3 are the Bx,By,Bz components of the magnetic field for all 4 Cluster spacecraft.
- Panel 4 is the current density
- Bottom 2 panels: Amplitude and time duration of detected ESWs
- Most ESWs are detected just after main phase onset when B-field fluctuations are greatest and currents are present.

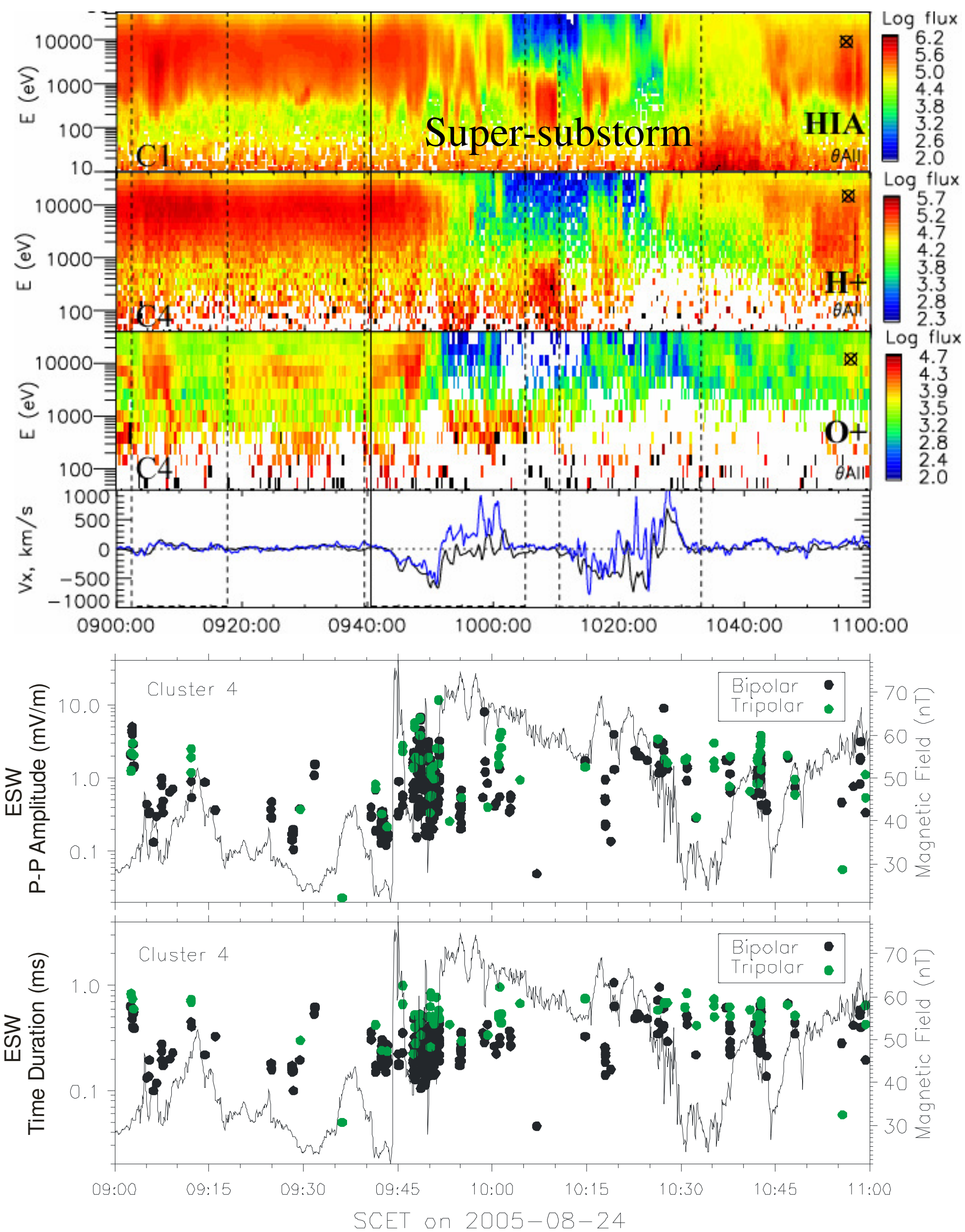
[Top plot from Runov et al., VC2006]



COMPARISON OF ELECTRON DATA TO ESW DETECTION ON CLUSTER 2

- Panel 1: RAPID electron data over range ~40-400 keV
- Panel 2: PEACE electron data over range ~30 eV to 25 keV
- Panel 3: Amplitude of detected ESWs
- Panel 4: Time Duration of detected ESWs
- Most of the ESWs are detected soon after main phase onset during time when electron flux is reduced and covering a smaller energy range centered around 1keV

[Electron data from Taylor et al., VC2006)



COMPARISON OF CIS ION DATA TO ESW DETECTION ON CLUSTER 4

- Top plot: Panel 1: CIS ion data over range ~10-40,000 eV for Cluster 1; Panels 2 and 3: CIS H+ and O+ data over range ~40-40,000 eV for Cluster 4; Panel 4: plasma flow velocity for Cluster 1 (black) and 4 (blue)
- Bottom plot: Amplitude and time duration of detected ESWs
- There are no clear correlations, although there is a slight tendency for ESW detection during periods of high energy O+ tailward flow and reduced flux of H+, and overall plasma flow velocity highly negative (as much as -600 km/s)

[Ion data from Runov et al., VC2006]

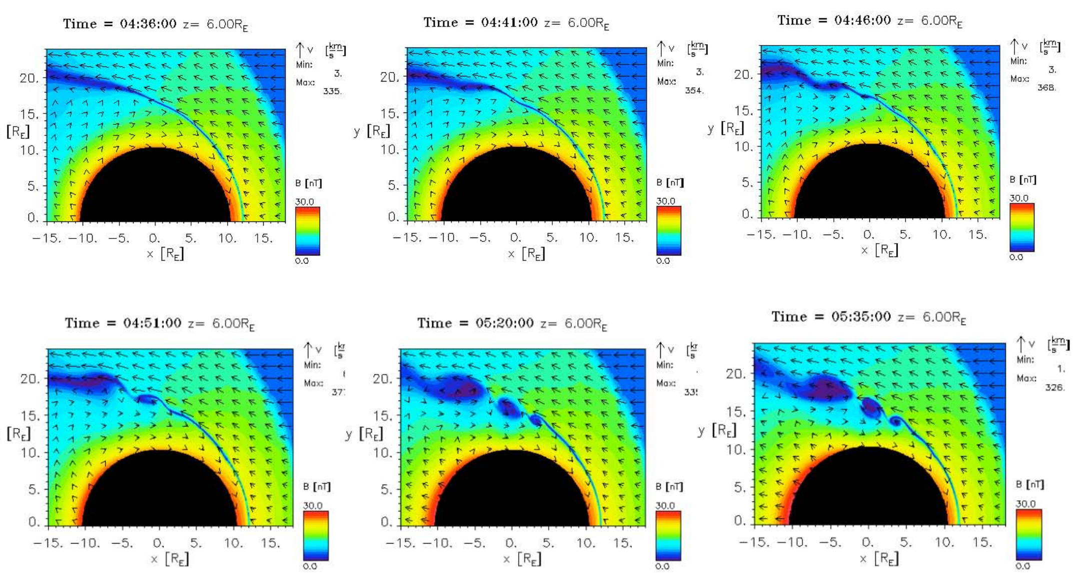
DISCUSSION OF KELVIN HELMOLTZ INSTABILITY
(From Kuznetsova et al., VC2006]

- Alfven Mach Number ~ 1-2 is the threshold for the onset of strong Kelvin-Helmholtz instabilities at the magnetopause under conditions of anti-parallel magnetic fields and strong velocity shears using the BATS-R-US global MHD model.
- Conditions for large shears at the flanks (and thus strong K-H instabilities) are a likely consequence when strong, large-scale earthward plasma flows from intense substorms, superposed on enhanced superstorm convection, divert around the dipole to the flanks and interact with enhanced anti-sunward flows in the LLBL.
- Under these conditions the growth rate and saturation level of the K-H instability with anti-parallel magnetic fields are 2-3 times larger than with parallel magnetic fields.
- Growth rate in a thin magnetic field reversal is ~5 minutes with wavelength 3-12 Re

DISCUSSION OF KELVIN HELMOLTZ INSTABILITY (Continued)
(From Kuznetsova et al., VC2006]

- Kelvin-Helmholtz vortices develop in two intervals during the superstorm, which include
  – During the first 2 hours after southward turning of the IMF (see below)
  – Middle stage of the next loading cycle as fast flows from the retreating reconnection line divert around the dipole and interact with solar wind flows near the magnetopause.

Vortices Generation at the Flanks Near Regions of
Anti-Parallel Magnetic Fields



DISCUSSION OF KELVIN HELMOLTZ INSTABILITY (Continued) (From Kuznetsova et al., VC2006]

- Such waves should mix boundary layer plasma (which is cooler and denser than typical plasma sheet material) into the magnetosphere.
- If large K-H vortices exist, they will result in mixing of LLBL plasma into the plasmasheet, providing a cooler source of plasma for ring current formation and subtly altering the various interactions that produce ring current decay and couple its energy into the underlying ionosphere/atmosphere. This alters the evolution of the magnetic storm itself
- Conclusion: There is no clear evidence that the ESWs observed at prime phase onset of the super-substorm are related to mixing of boundary layer plasma into the plasmasheet via K-H vortices, but
  - More detailed work needs to be done with the particle data to help make a final determination
  - Various theoretical models for generation of ESWs need to be tested using the measurements as inputs
  - Possibility of non-local ESW generation needs to be investigated since ESWs have been shown to be stable enough to propagate over distances as great as tens of km.

USING MODELING TO DETERMINE MODE OF ESWS

- Electrostatic solitary waves are observed in different regions of the magnetosphere, including the plasma sheet boundary layer, auroral acceleration region, cusp, magnetosheath and bow shock.

- To date most electrostatic solitary waves have been interpreted as ion and electron phase space holes (BGK mode solutions) [e.g., *Omura et al., 1994* using Geotail data showing ESWs present in the magnetotail].

- However, the presence of energetic ions ($T_i > T_e$) in many of these regions also suggests a possible excitation of the electron acoustic mode [*Berthomier et al. (2000)*].

- Recent investigations of electron acoustic solitary waves through a model that depends on multiple ion species have shown good agreement with satellite observations for some selected parameter regions, most notably the magnetosheath and cusp. This strengthens the applicability of the electron acoustic mode in space observations.

- Analysis of both types of instabilities (beam and electron acoustic) will be carried out in the future using measurements of the various input parameters to determine if one or both of these are active during any part of this super substorm event.

SUMMARY

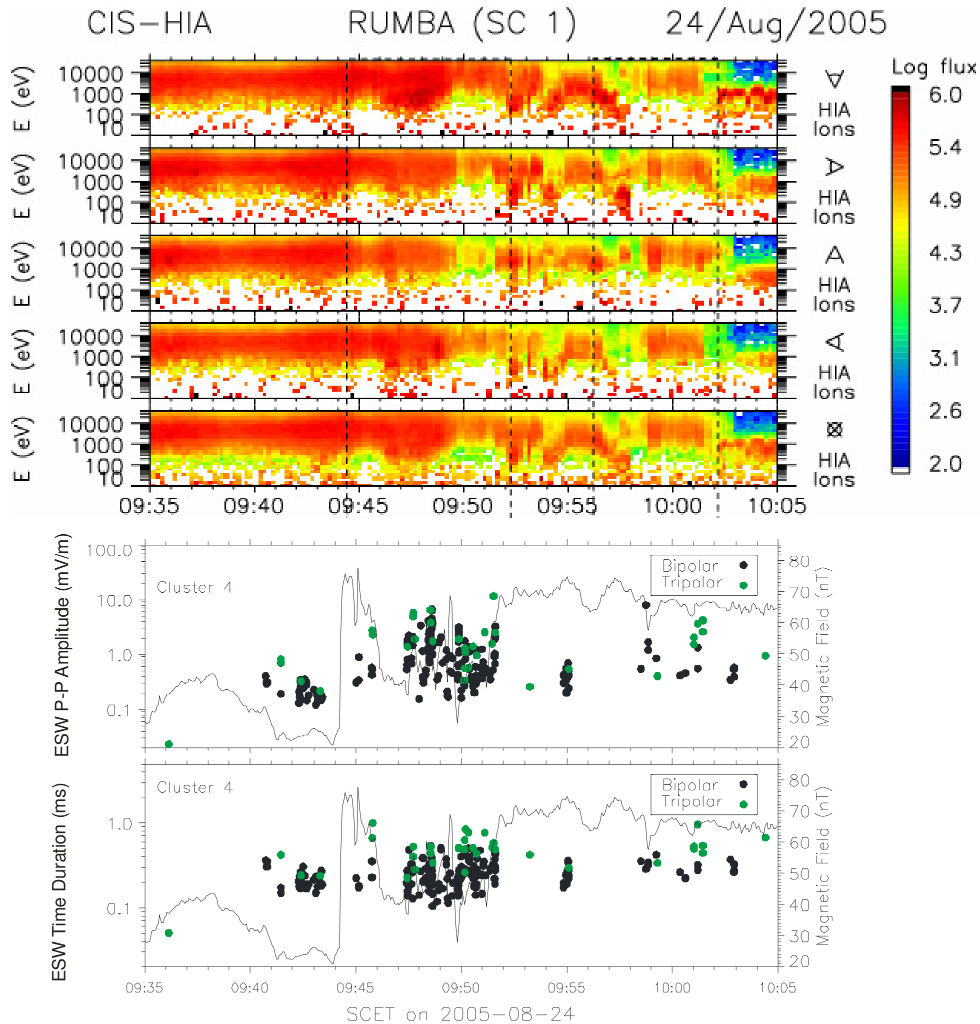
- Electrostatic solitary waves/pulses are nonlinear, coherent structures that are observed at most boundaries in space, are of short time duration and relatively small electric field amplitude, and are stable enough to propagate over distances as great as tens of km.
- ESWs are observed in great numbers by Cluster WBD around the time of main phase onset of the super-substorm on August 24, 2005.
- The short time duration of these ESW pulses (80-250 microseconds) indicates that these structures are from the kinetic regime.
- The data would suggest that just after main phase onset Cluster is either in a local reconnection site (current sheet) or in a region of mixing plasmas perhaps via Kelvin-Helmholtz vortices which leads to a cooler denser plasmasheet.
- A closer examination of the particle and field data, together with modeling, should help us determine if the ESWs are being generated locally through reconnection or plasma mixing processes, or whether the ESWs are generated at some other location and have propagated to Cluster.
- We have begun a study entitled “Dynamics of electrostatic solitary waves and their effects on current layers” which combines space measurements, laboratory experiments and theory which should eventually help us to better understand the space observations.

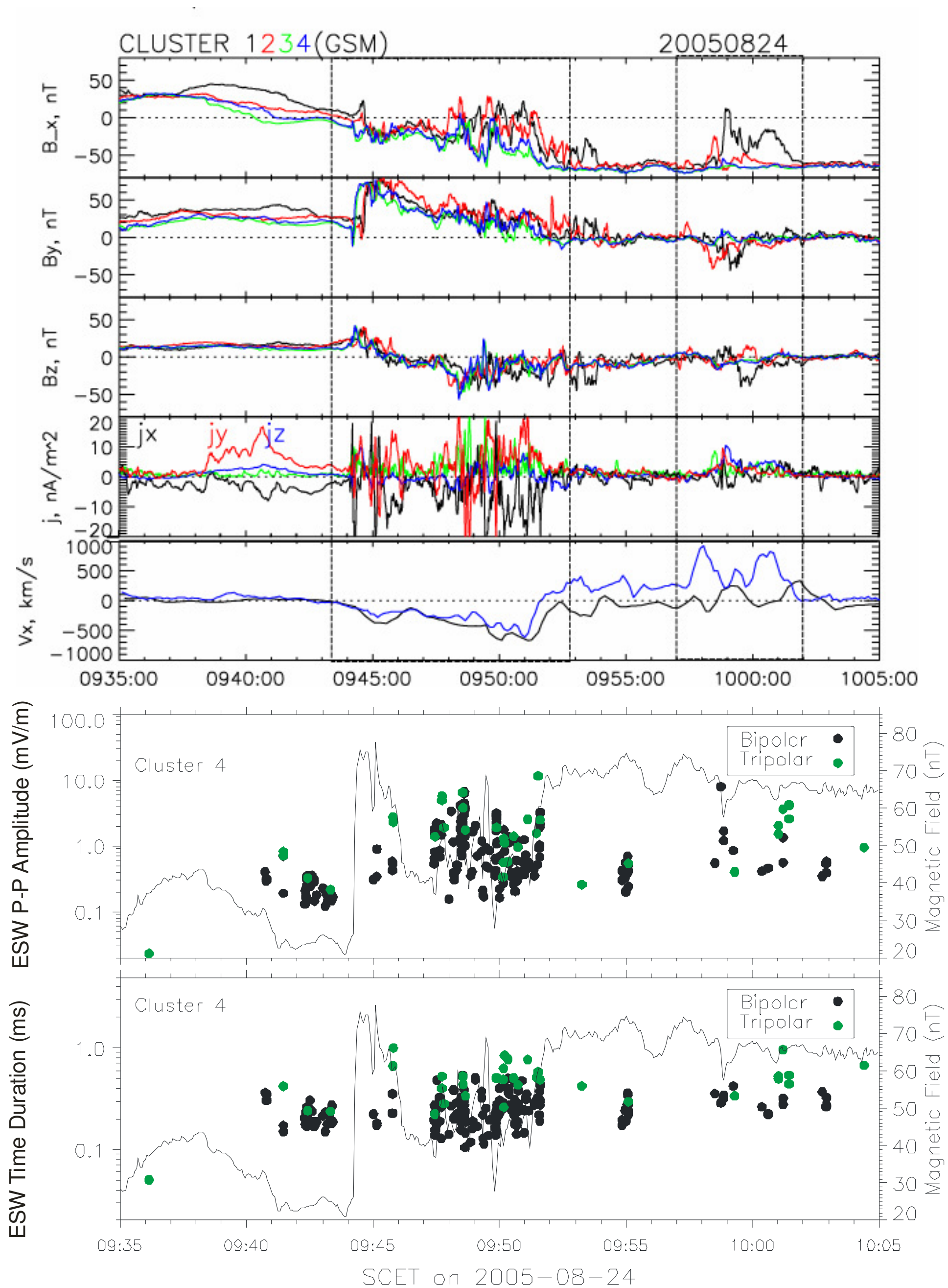
SUPPORTING DATA

Interval B:
Flow Reversal & Flux Rope

- Top plot: CIS H+ ion data over range ~10-30000 eV for several different look angles
- Bottom plot: Amplitude and time duration of detected ESWs
- There appears to be no correlation between the ion data and the ESW detections.

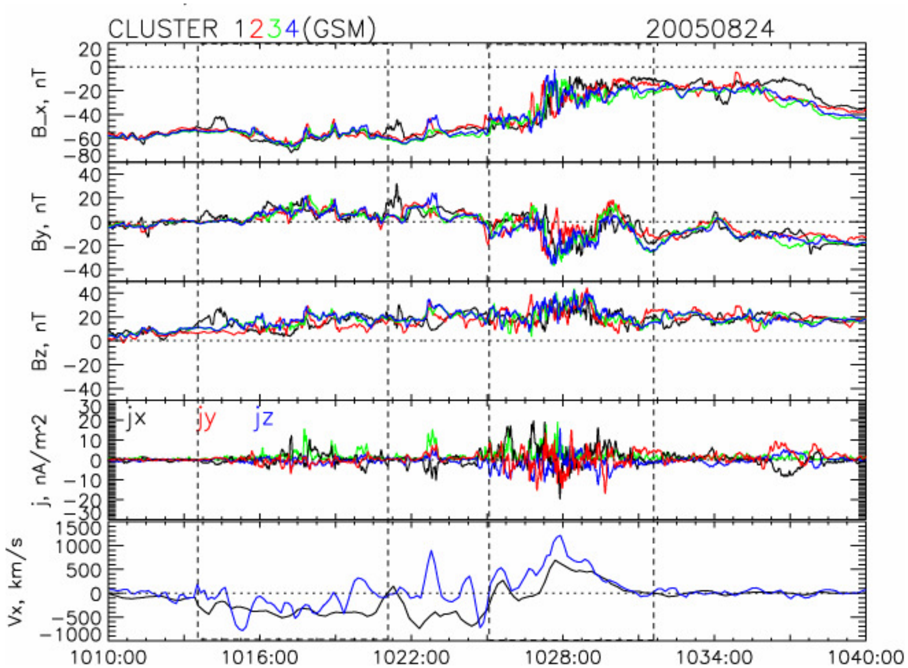
(Ion data from Runov et al., VC2006)

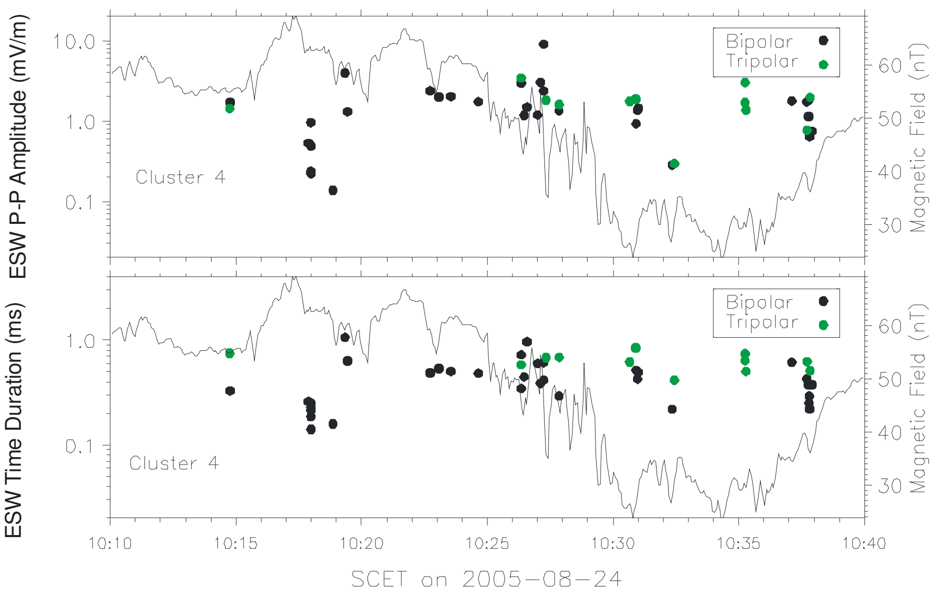




Interval B: Flow Reversal & Flux Rope

- Panels 1,2,3 are the Bx,By,Bz components of the magnetic field for all 4 Cluster spacecraft.
- Panel 4 is the current density
- Panel 5 is the flow velocity
- Bottom 2 panels: Amplitude and time duration of detected ESWs
- Most ESWs are detected just after main phase onset when B-field fluctuations are greatest and flow is highly negative
- Top plot from Runov et al., VC2006

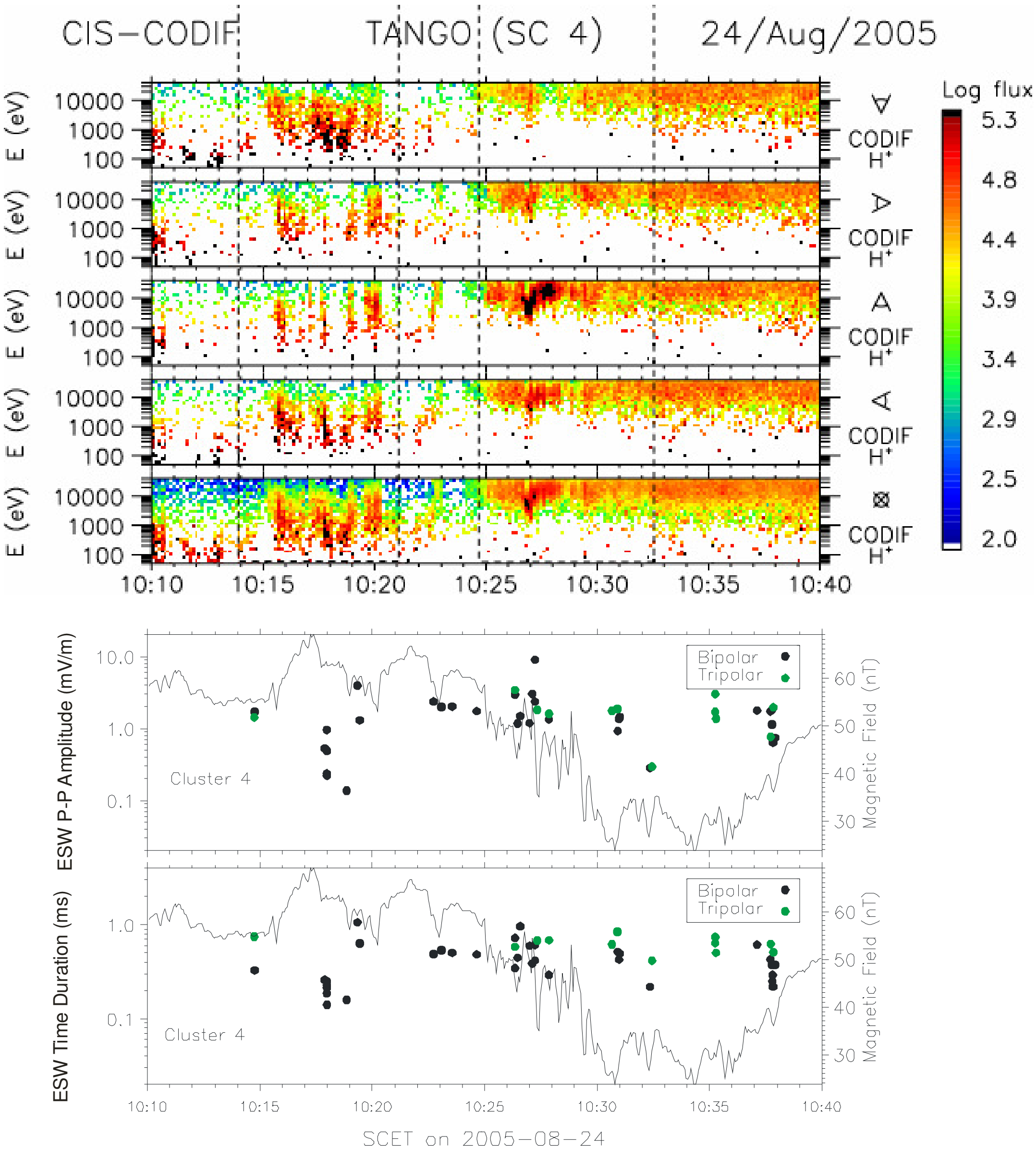




Interval C: Flow Reversal

- Panels 1,2,3 are the Bx,By,Bz components of the magnetic field for all 4 Cluster spacecraft.
- Panel 4 is the current density
- Panel 5 is the flow velocity
- Bottom 2 panels: Amplitude and time duration of detected ESWs
- Not many ESWs are detected during this second flow reversal ~25 minutes after main phase onset
- Top plot from Runov et al., VC2007

Interval C: Flow Reversal



- Top plot: CIS H+ ion data over range ~100-30000 eV for several different look angles
- Bottom plot: Amplitude and time duration of detected ESWs
- Most of the ESWs are detected about 25 minutes after main phase onset during time of flow reversal of the ions

(Ion data from Runov et al., VC2007)

Orbit
(2005 08/24)