



ELECTROSTATIC SOLITARY WAVES OBSERVED IN SPACE AND IN LABORATORY EXPERIMENTS

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OUTLINE

- What are Electrostatic Solitary Waves (ESWs)?
- Our Current Understanding of ESWs observed in space
- Examples: Cluster spacecraft observations of BEN and associated ESWs from two differing plasma regimes (highly vs. weakly magnetic).
- Differentiating between ESWs and wave signatures of dust impacts.
- ESWs observed at Shock Crossings
- Properties of ESWs Obtained from Measurements on One Spacecraft
- Propagation and Stability of ESWs Using Multi-Spacecraft Measurements
- LAPD/Laboratory Experiments and Comparison to Space Observations
- Modulation of ESWs at 1.5 Hz
- Generation Mechanisms
- Conclusions



WHAT ARE ELECTROSTATIC SOLITARY WAVES?

- ESWs are coherent, isolated pulses observed in high time resolution ac electric field waveform data; first seen on S3-3 spacecraft in the auroral acceleration region (Temerin et al., PRL, 1982).
- ESWs represent the high frequency part of Broadband Electrostatic Noise (BEN) when transformed by FFT to frequency domain (first inferred by Dubouloz et al., GRL, 1991 using Viking data and later demonstrated by Matsumoto et al., GRL, 1994 using Geotail data).
- ESWs, as a minimum, are characterized by their pulse duration and peak-to-peak amplitude, as well as their shape and orientation with respect to the magnetic field
- ESWs represent potential or density structures passing by the spacecraft and are generated out of nonlinear processes



OUR CURRENT UNDERSTANDING

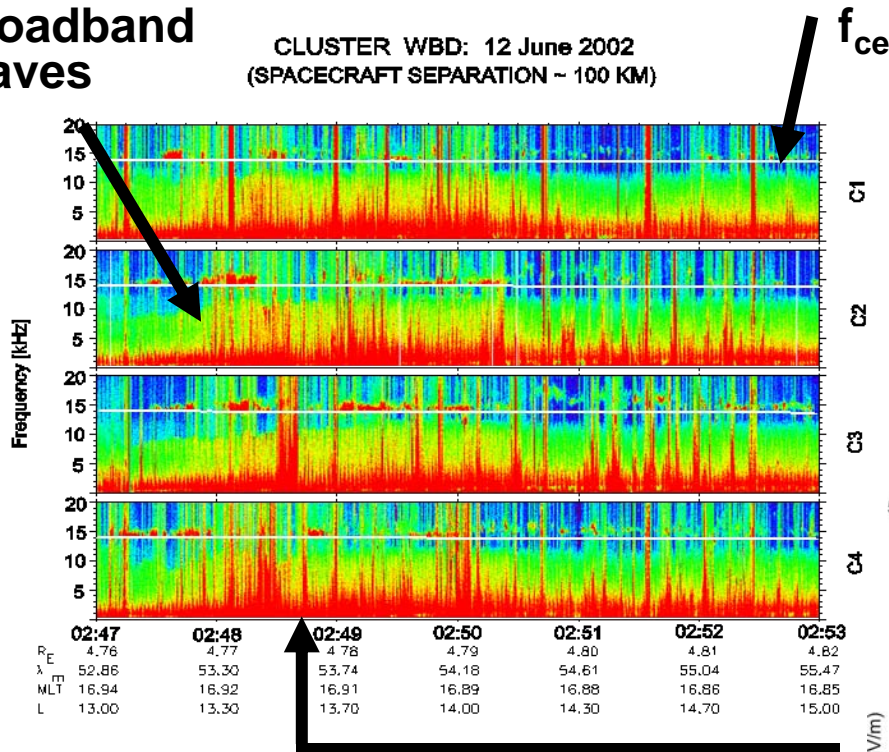
- ESWs in the form of phase space holes have been observed in:
 - Close vicinity of reconnection current layers at the magnetopause [*Drake et al., 2003; Matsumoto et al., 2003; Deng et al., 2005*] and in the Magnetotail [*Farrell et al., 2002; Cattell et al., 2005; Deng et al., 2005*]
 - Bow shock current layers at Earth [*Bale et al., 1998, 2002*] and Saturn [*Williams et al., 2006*]
 - Auroral current layers [*Ergun et al., 1998; Pickett et al., 2004*]
 - Interplanetary shock current layer [*Williams et al., 2005*]
- These phase-space holes are thought to be important in:
 - Scattering and energizing electrons, thus providing dissipation for collisionless reconnection [*Drake et al., 2003; Matsumoto et al., 2003; Deng et al., 2005*]
 - Heating electrons across collisionless shocks [*Bale et al., 2003*]
 - Perpendicular heating of ions in the auroral upward current region

AURORAL ZONE CROSSING AT $\sim 5 R_E$ AROUND DUSK

From Pickett et al., *Annales Geophys.*, 2004

Broadband Waves

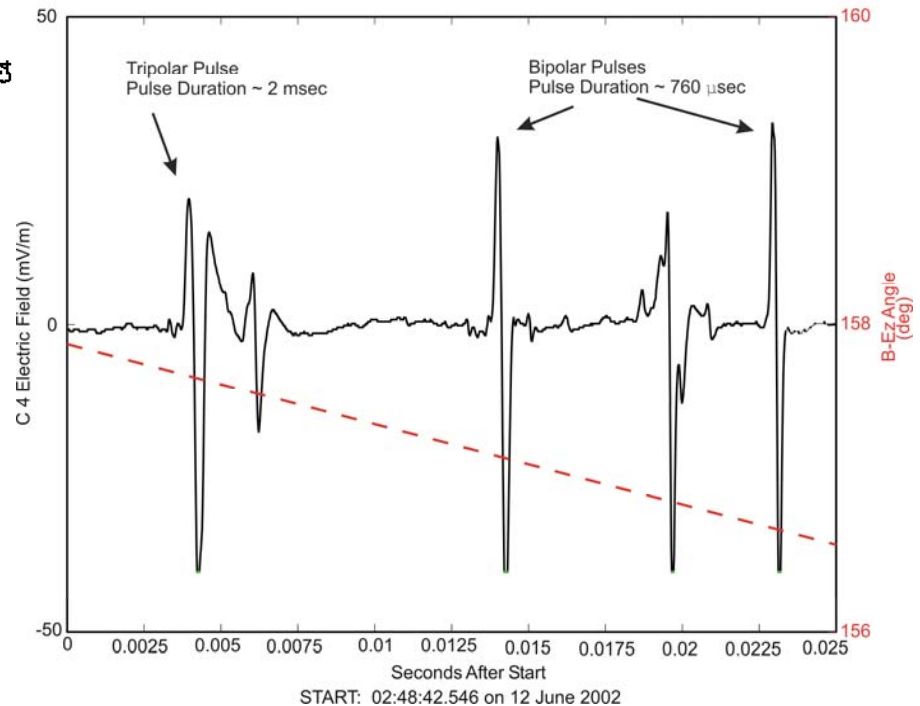
CLUSTER WBD: 12 June 2002
(SPACECRAFT SEPARATION ~ 100 KM)



$$f_{ce}/f_{pe} \sim 5.0$$

AURORAL ZONE ($4.8 R_E$ $53.5 \lambda_m$, 16.9 MLT, 13.5 L)

	02:47	02:48	02:49	02:50	02:51	02:52	02:53
R_E	4.76	4.77	4.78	4.79	4.80	4.81	4.82
λ_m	52.86	53.30	53.74	54.18	54.61	55.04	55.47
MLT	16.94	16.92	16.91	16.89	16.88	16.86	16.85
L	13.00	13.30	13.70	14.00	14.30	14.70	15.00

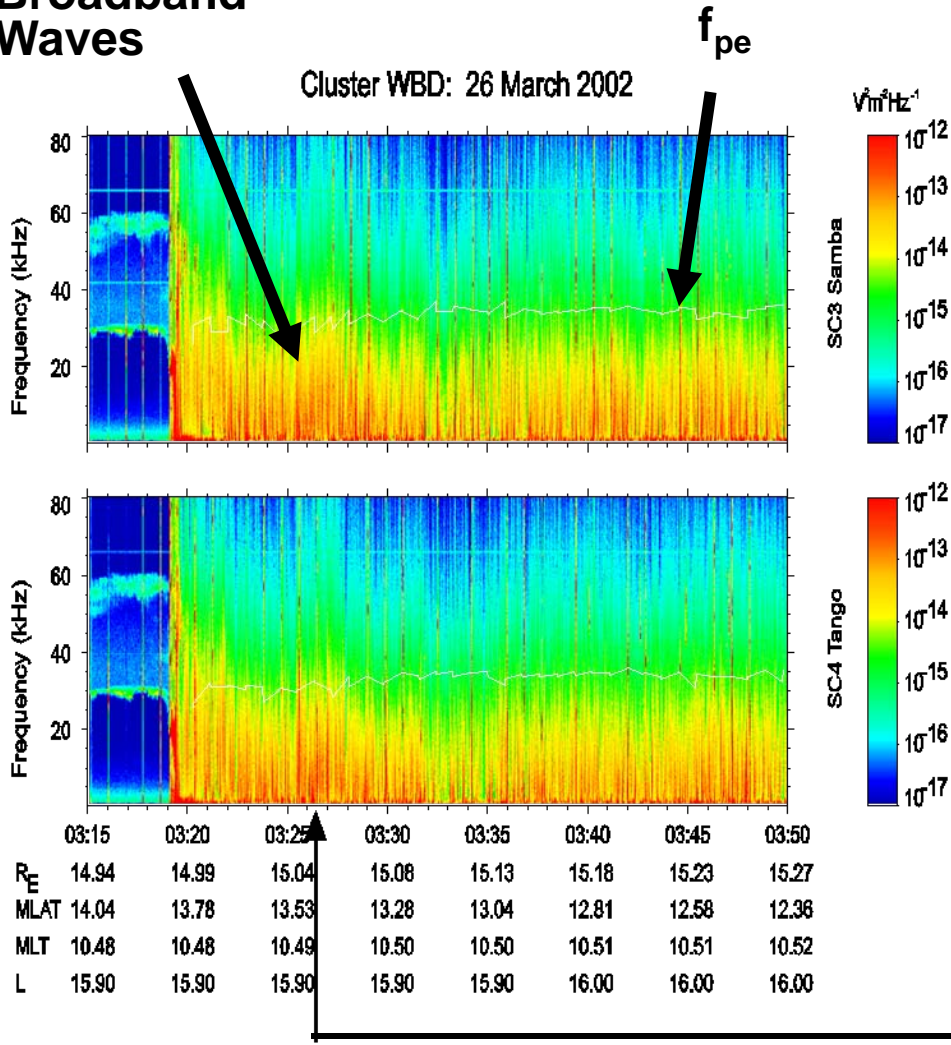


START: 02:48:42.546 on 12 June 2002

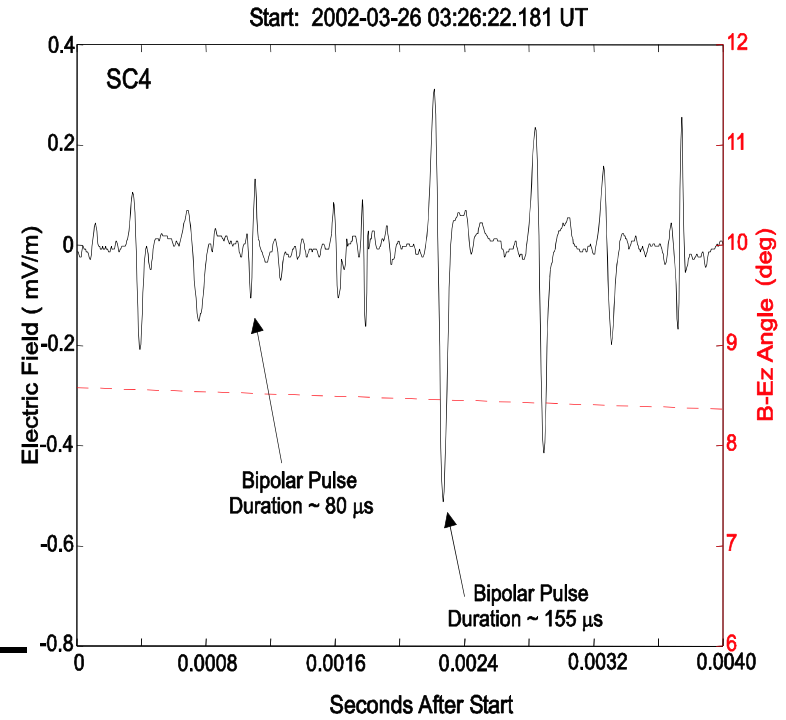
QUASI-PERPENDICULAR BOW SHOCK CROSSING AND MAGNETOSHEATH

From Pickett et al., *Nonlinear Proc. In Geophys.*, 2005

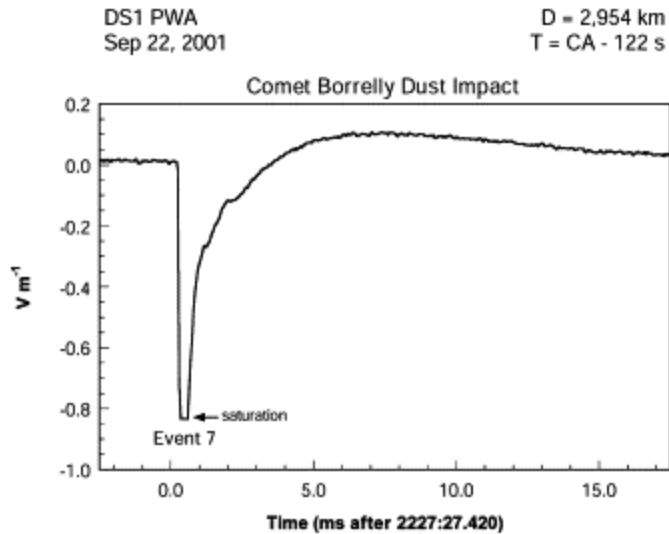
Broadband Waves



$$f_{ce}/f_{pe} \sim 0.03$$

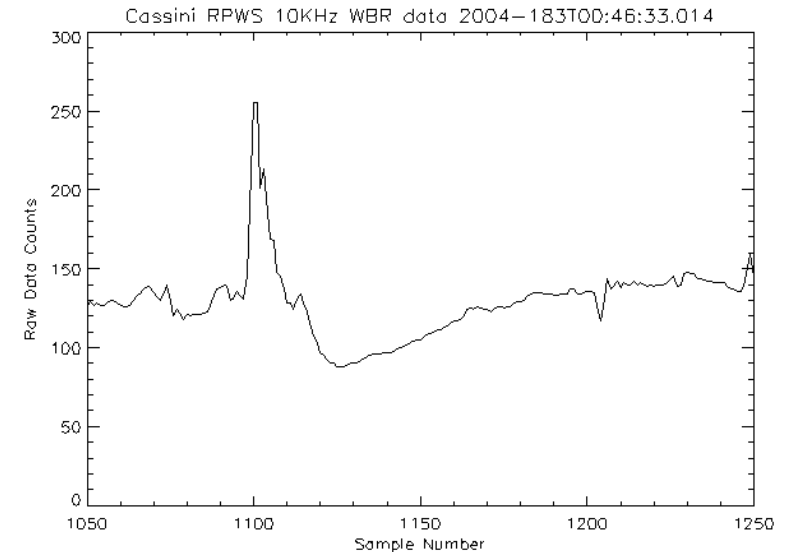


PULSES ASSOCIATED WITH DUST IMPACTS



DS1 AT COMET P/BORRELLY (from Tsurutani et al., *Icarus*, 2004)

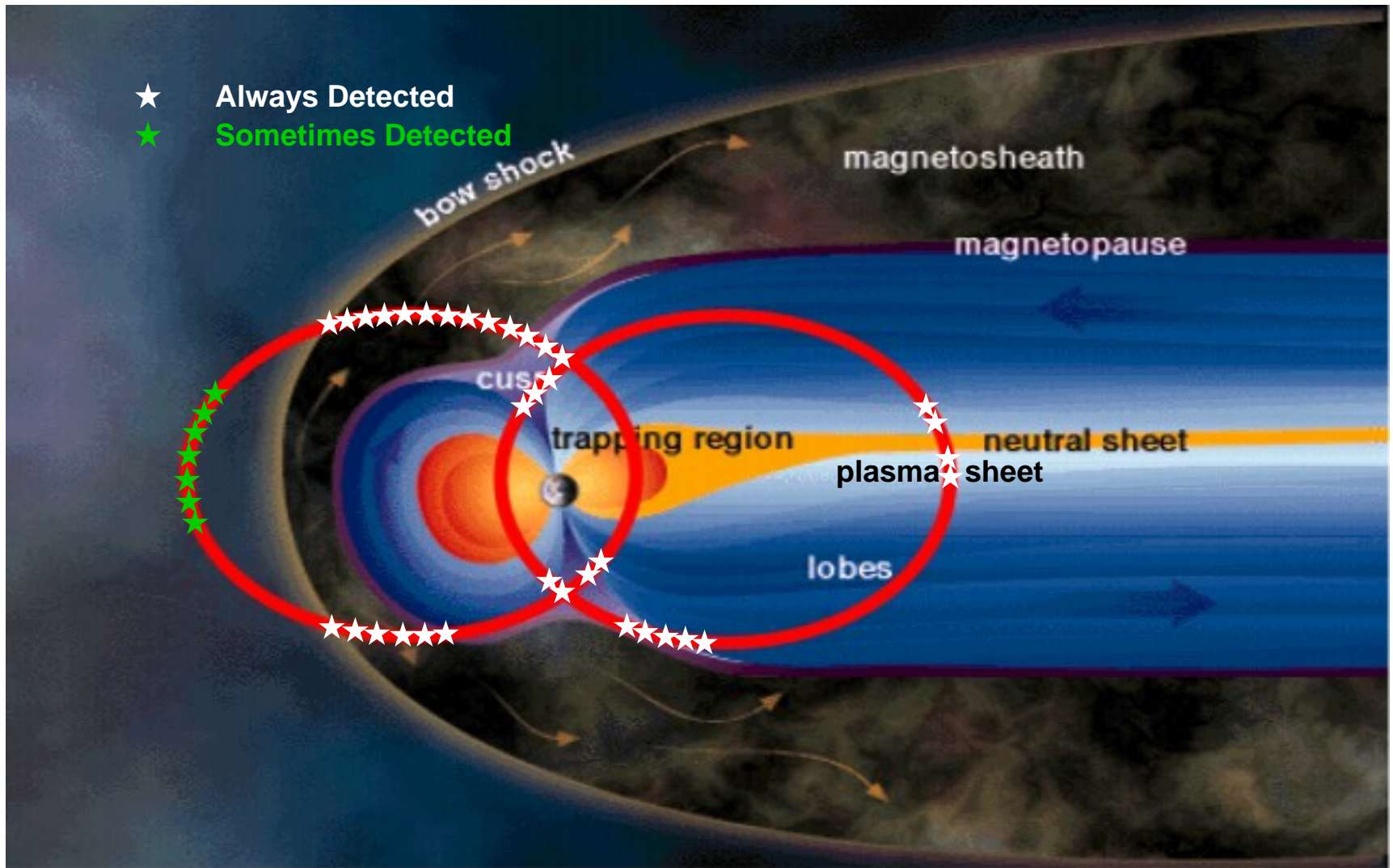
- Fast initial pulse ($<50 \mu\text{s}$) to almost 1 V/m , $1/e$ exponential decay over $650 \mu\text{s}$, exponentially shaped overshoot rise and decay over $\sim 10 \text{ ms}$.
- Dust particle impacts spacecraft, dipole antenna detects expanding plasma cloud—first electrons and then ions.



CASSINI AT SATURN (from Wang et al., *PSS*, 2006)

- Very rapid rise on a time scale of a few tens of a μs , followed by a complicated **recovery** waveform with total duration of initial pulse less than 1 ms
- Dust particle impacts spacecraft, produces a small plasma cloud that expands radially outward and is detected by a dipole antenna

LOCATION OF SOLITARY WAVE DETECTIONS IN CLUSTER'S ORBIT



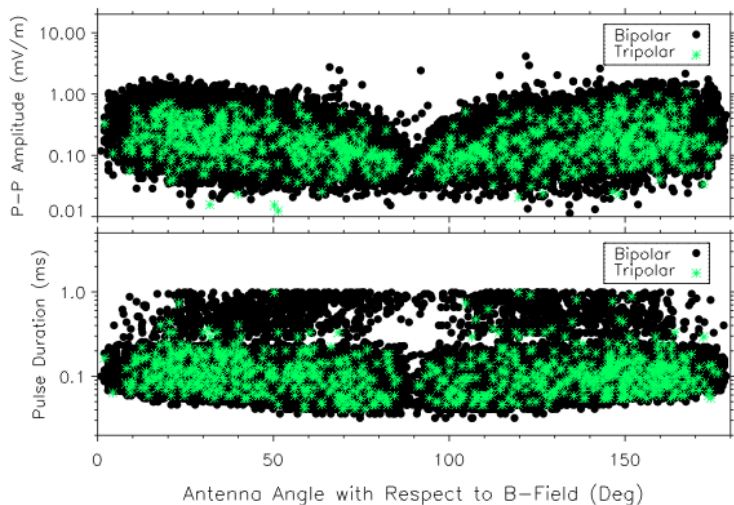
From Pickett et al.,
Annales Geophys., 2004



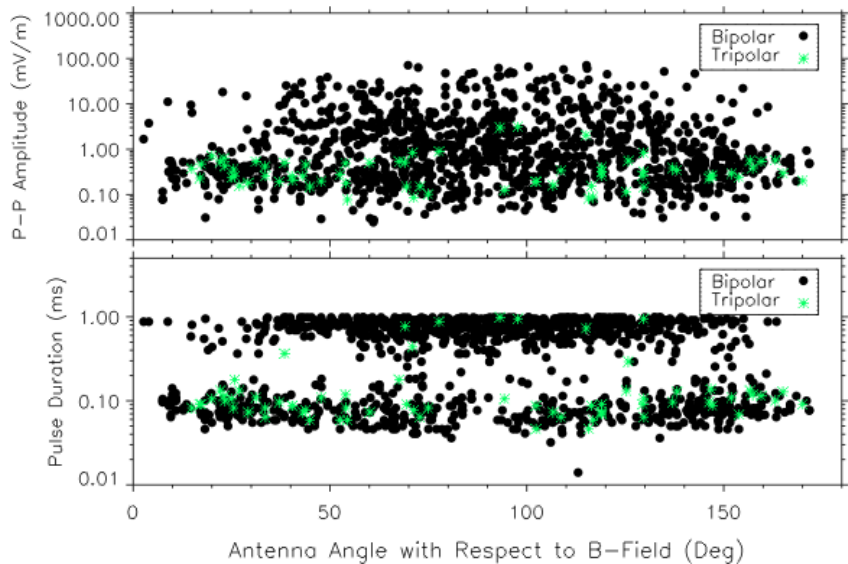
Shock Crossings

ESW CHARACTERISTICS VS. ANTENNA ANGLE TO B

EARTH MAGNETOSHEATH

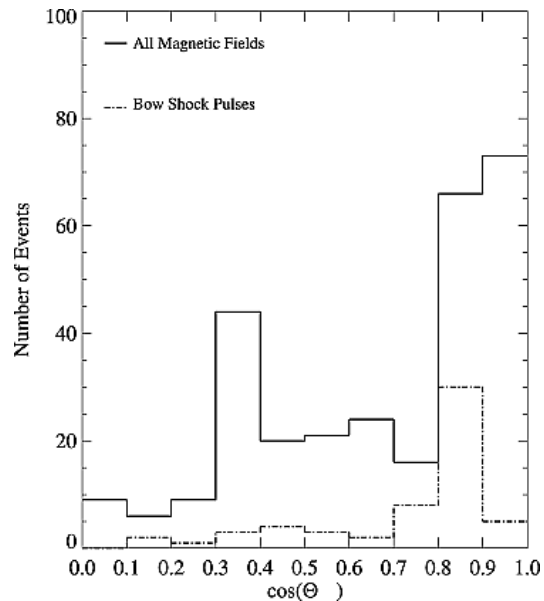
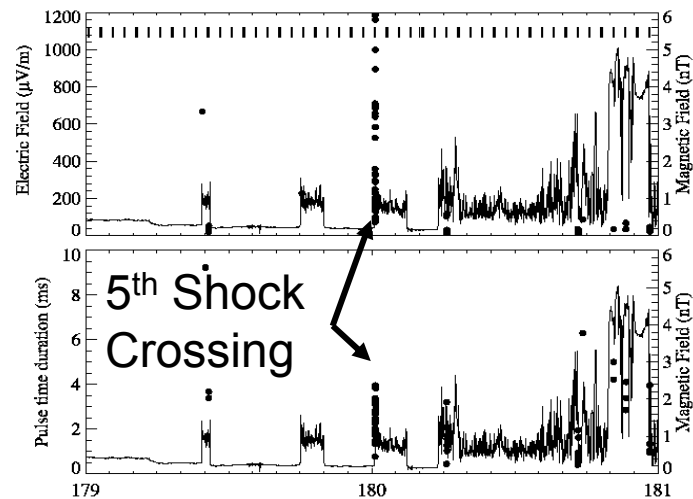


EARTH BOW SHOCK CROSSINGS



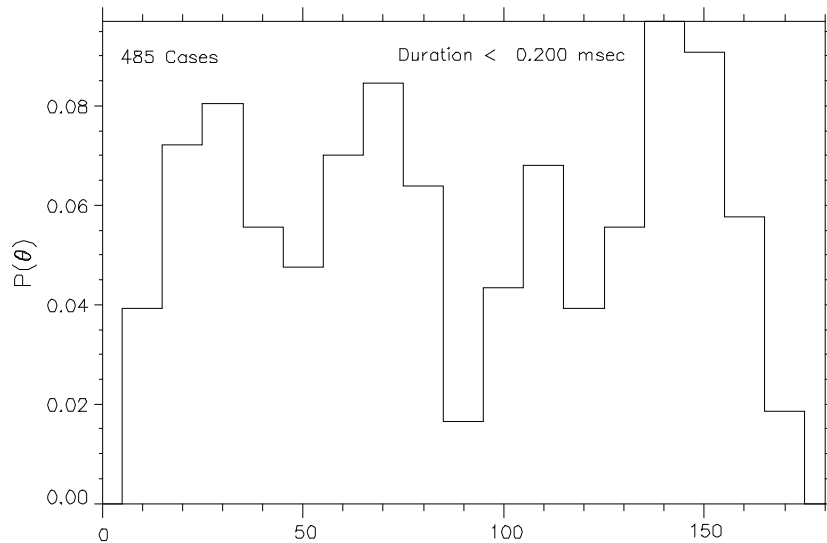
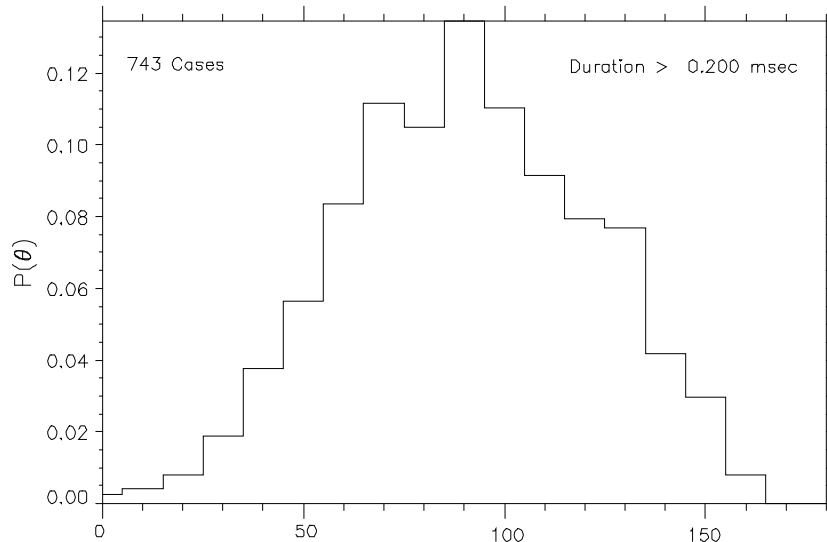
SATURN BOW SHOCK CROSSINGS

From Williams et al., *GRL*, 2006



CHARACTERISTICS OF ESWs DETECTED AT BOW SHOCK CROSSINGS

Occurrence of Solitary Waves as a Function of Antenna Angle
Bow Shock



Antenna Angle with Respect to B-Field (Deg)

Analysis:

ESWs with time durations > 0.2 ms:

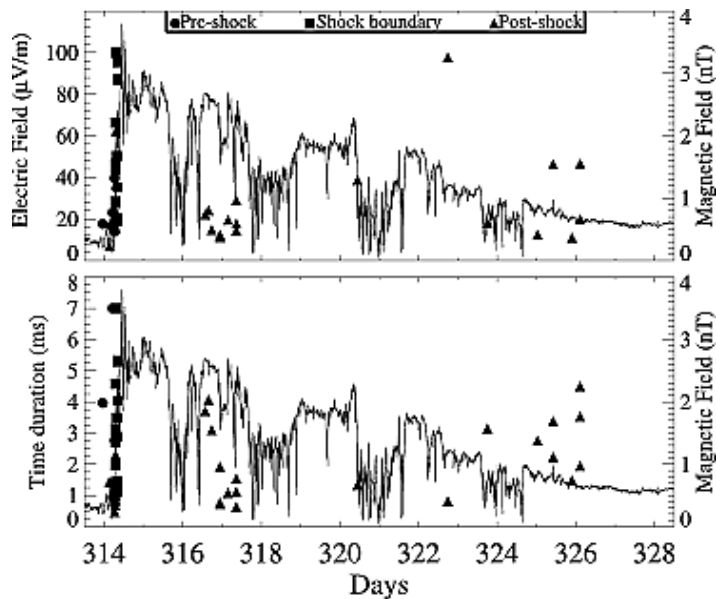
- Occurrence probability is greatest for antenna angles to **B** around 90°, corresponding to the same distribution of this angle, $\sin(\theta)$, regardless of the measurements
- Long duration and angle suggests a possible role of ion dynamics in ESW generation.

ESWs with time durations < 0.2 ms:

- Occurrence probability is nearly zero at 90° and greatest around 0° and 180°
- Since a plasma period ranges from ~ 15-30 μ s, suggests a strong link to electron dynamics for ESW generation



ESW CHARACTERISTICS AT AN INTERPLANETARY SHOCK CROSSING



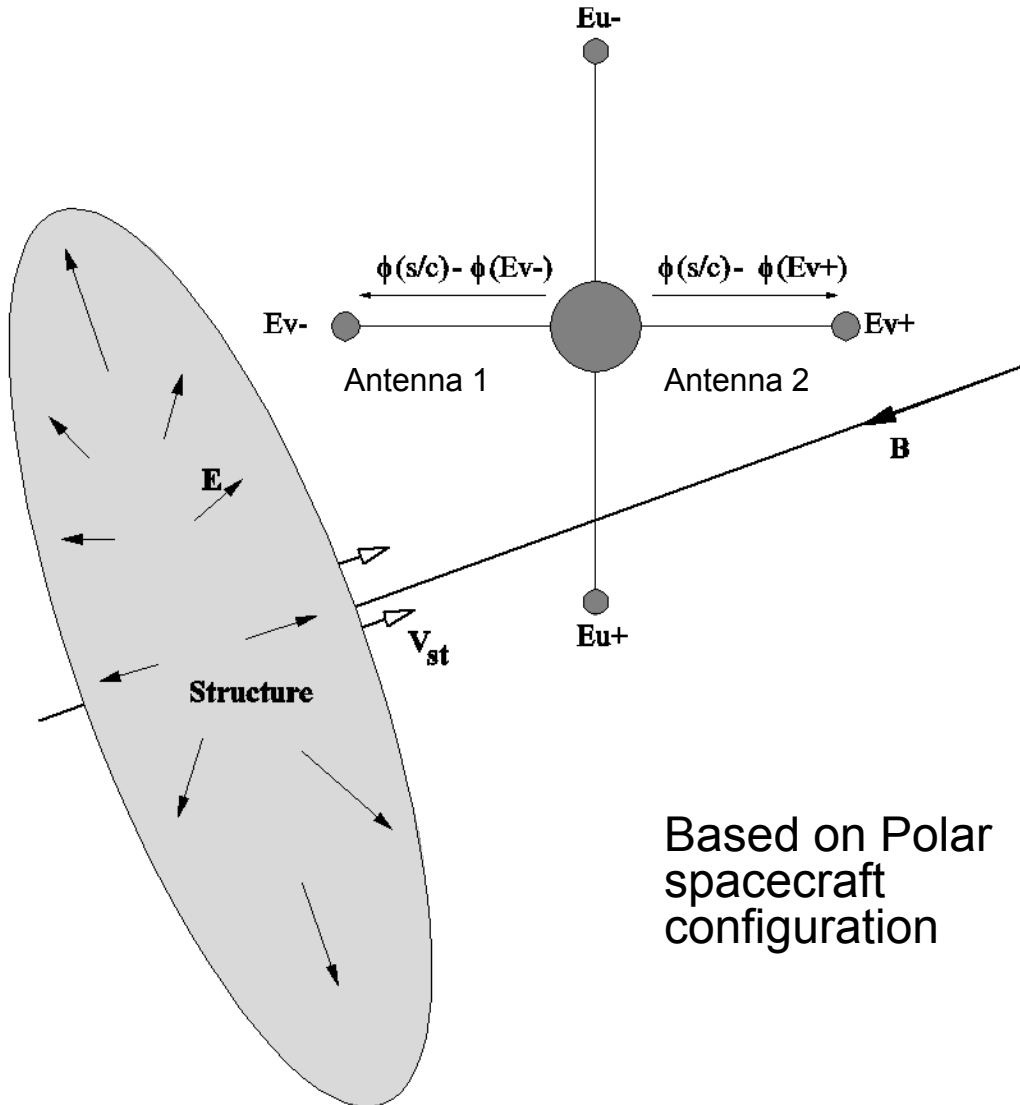
[From Williams et al., *GRL.*, 2005]

- Solitary structures observed as a result of the Oct./Nov. 2003 solar flare events
- 10 preshock events likely related to shock-accelerated particles running ahead of the shock
- Largest amplitude solitary structures associated with largest magnetic field change



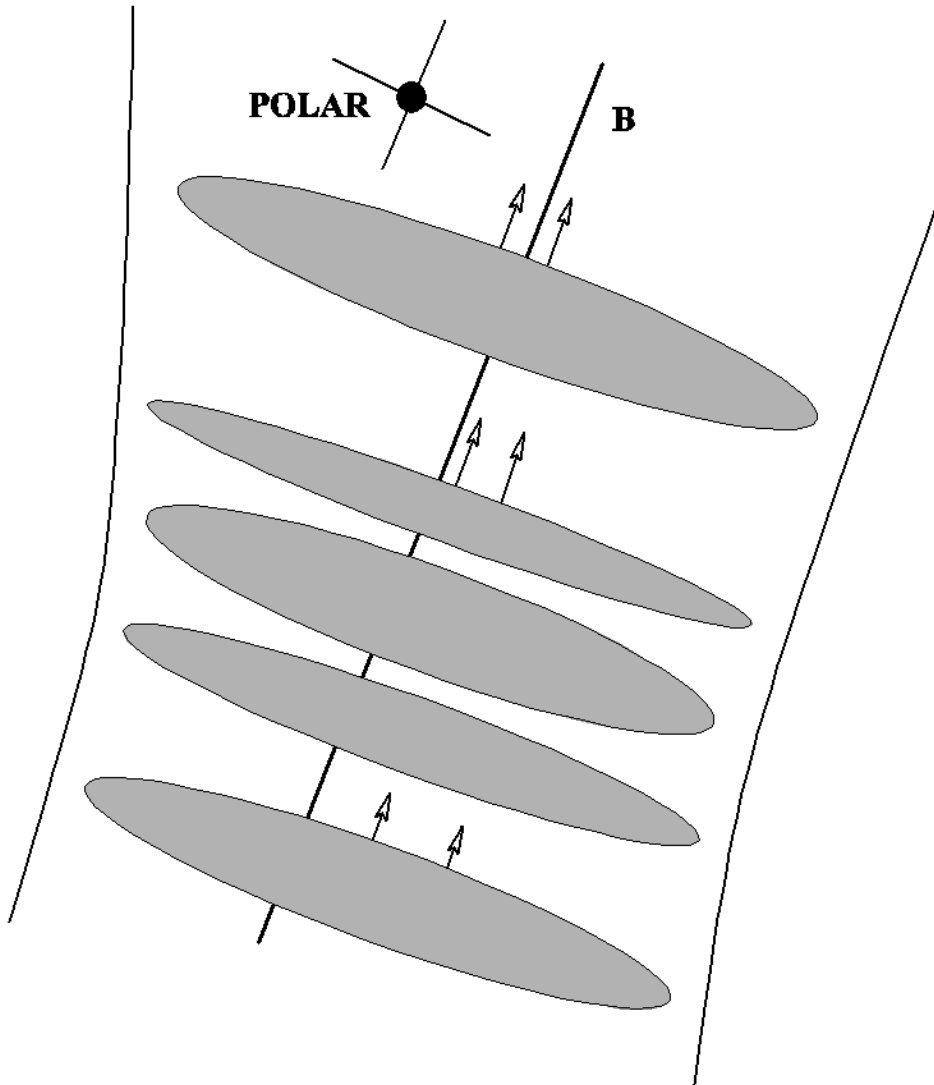
**Properties of ESWs Obtained
from Measurements on One Spacecraft**

PROPERTIES OF ESWs OBSERVED BY POLAR



- Configure two antennas using the spacecraft as a probe for each of them (see figure) or use two separate antennas
- Measure delay of ESW from antenna 1 to antenna 2
- Determine angle of antenna with respect to B
- **CONCLUSION:** Maximum travel distance is 100 m or less, which does not allow for adequate analysis of lifetime and stability. Multi-spacecraft are required.

PROPERTIES OF ESWs OBSERVED BY POLAR

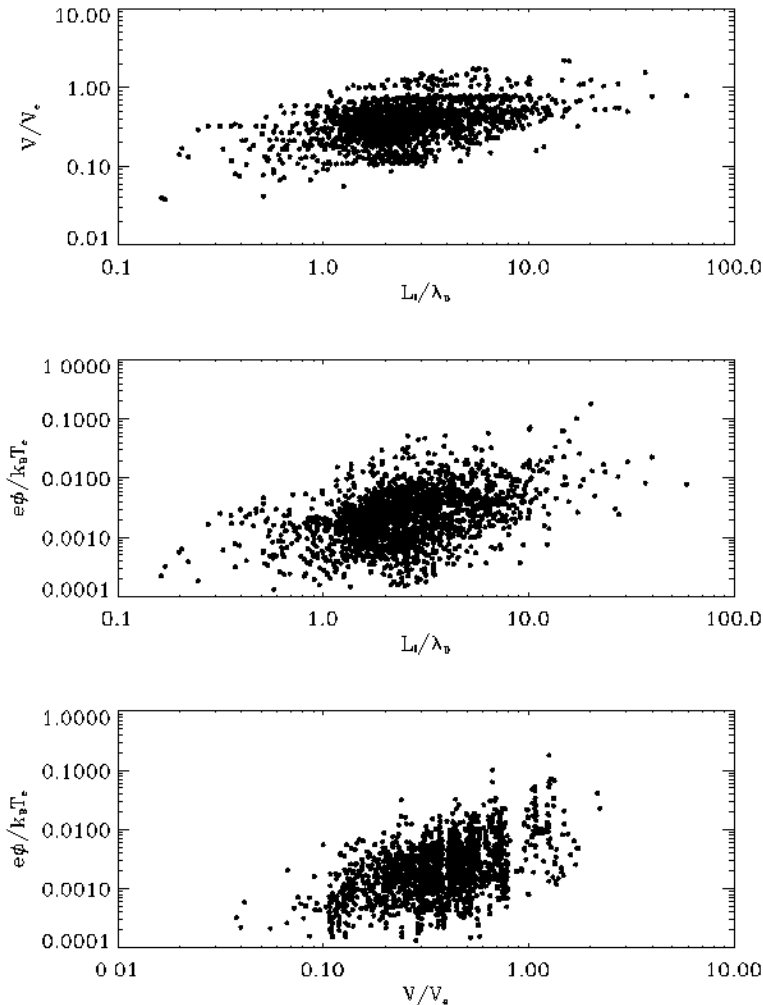


- ESWs in the cusp and plasmasheet are often observed to have the same polarity in the direction perpendicular to **B**.
- The sign of the perpendicular electric field pulse associated with ESWs depends on which side of the spacecraft the structure passes.
- Since most of the ESWs have the same polarity in the perpendicular direction, all pass by the same side of the spacecraft
- This suggests the structures are somewhat ordered in the direction perpendicular to **B** as shown.

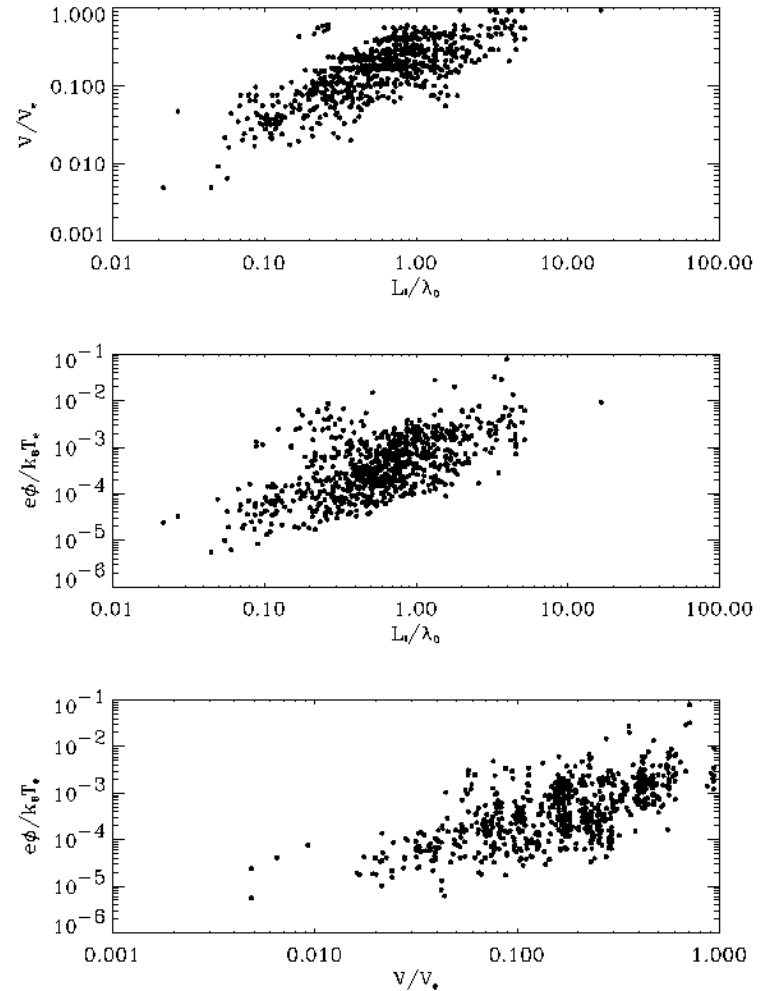
PROPERTIES OF ELECTRON PHASE-SPACE HOLES OBSERVED BY POLAR

[From Franz, Kintner, Pickett et al., *JGR*, 2005]

Cusp



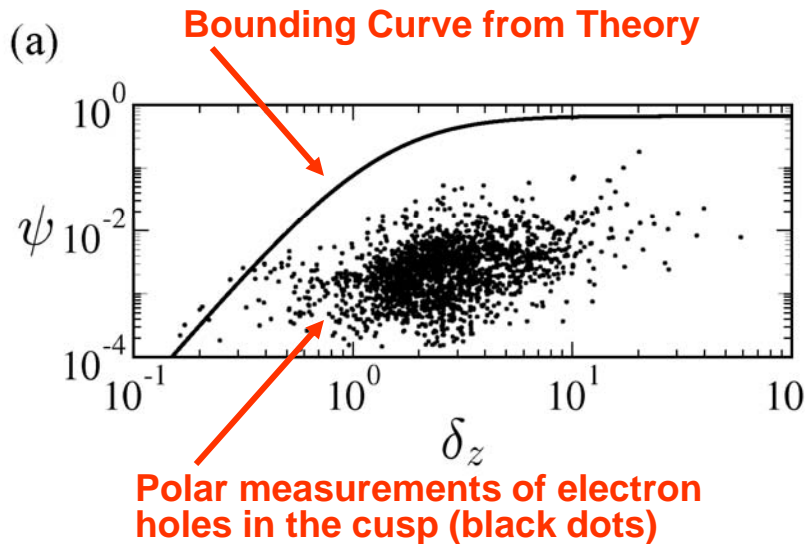
Plasmasheet



General trends for both regions: 1) larger scale structures tend to have larger velocities, 2) larger amplitude ESW structures have larger scale sizes, and 3) larger-amplitude structures have larger velocities.

A THEORY TO EXPLAIN POLAR OBSERVATIONS

[From Chen, Pickett et al., *JGR*, 2005]



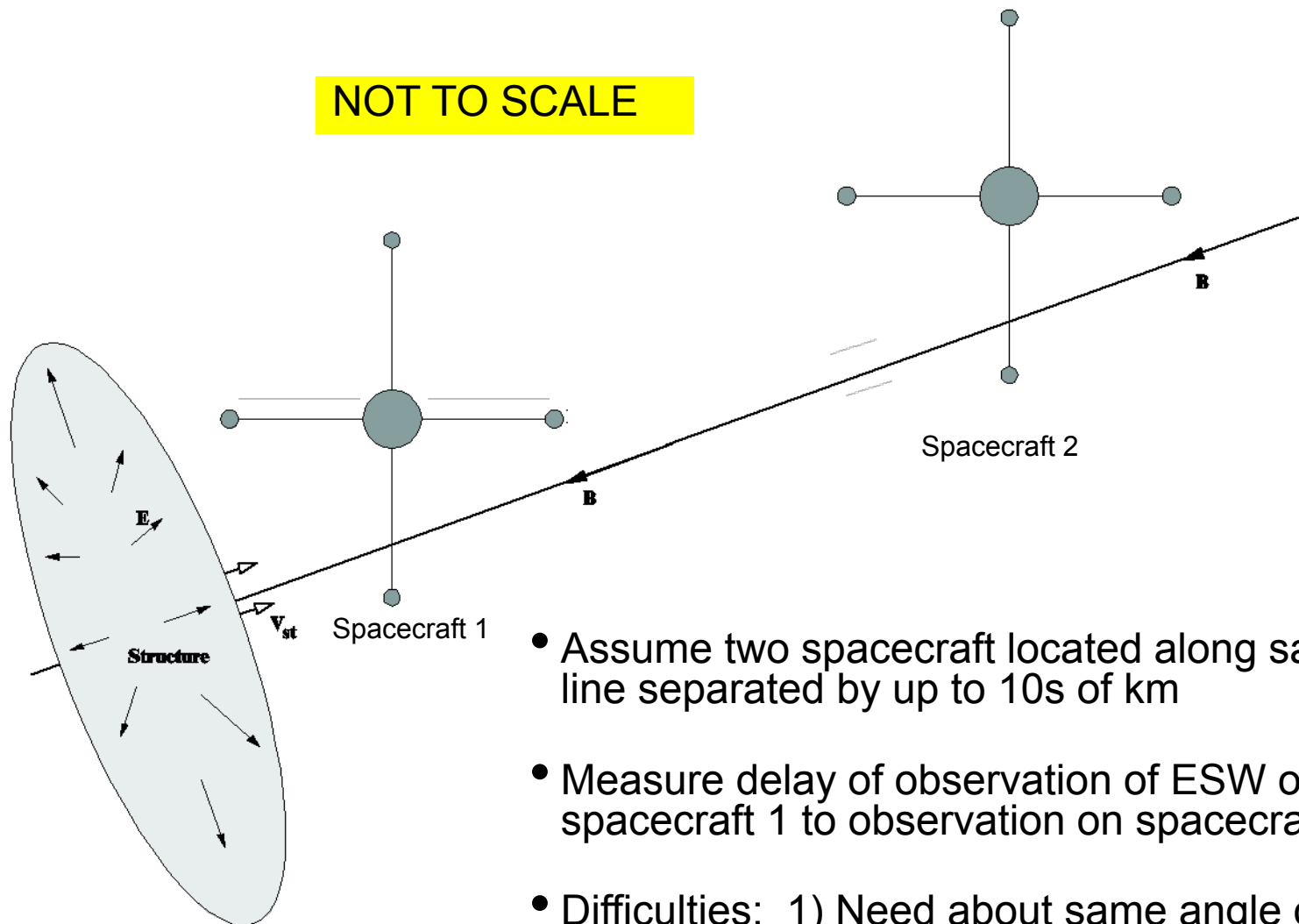
- Electron and ion phase space holes are solitary-wave solutions to the nonlinear Vlasov-Poisson equations in a collisionless plasma that involve trapping of electrons and ions, respectively.
- These solitary wave solutions are also called BGK solitary waves after Bernstein, Greene and Kruskal, who were the first to obtain the exact, time-stationary solutions for the 1-D nonlinear Vlasov-Poisson equations.
- Width-amplitude relations for one-dimensional and three-dimensional electron holes are derived to be inequalities that allow the existence of the holes in regions to one side of a bound.
- The inequality nature is independent of specific functional forms of the solitary potential and ambient plasma distribution functions.
- Ion dynamics and effects of finite hole velocity and finite perpendicular size are subsequently included.



Propagation and Stability of ESWs Using Multi-Spacecraft Measurements

ESW VELOCITY/SIZE DETERMINED WITH CLUSTER MULTI-SPACECRAFT

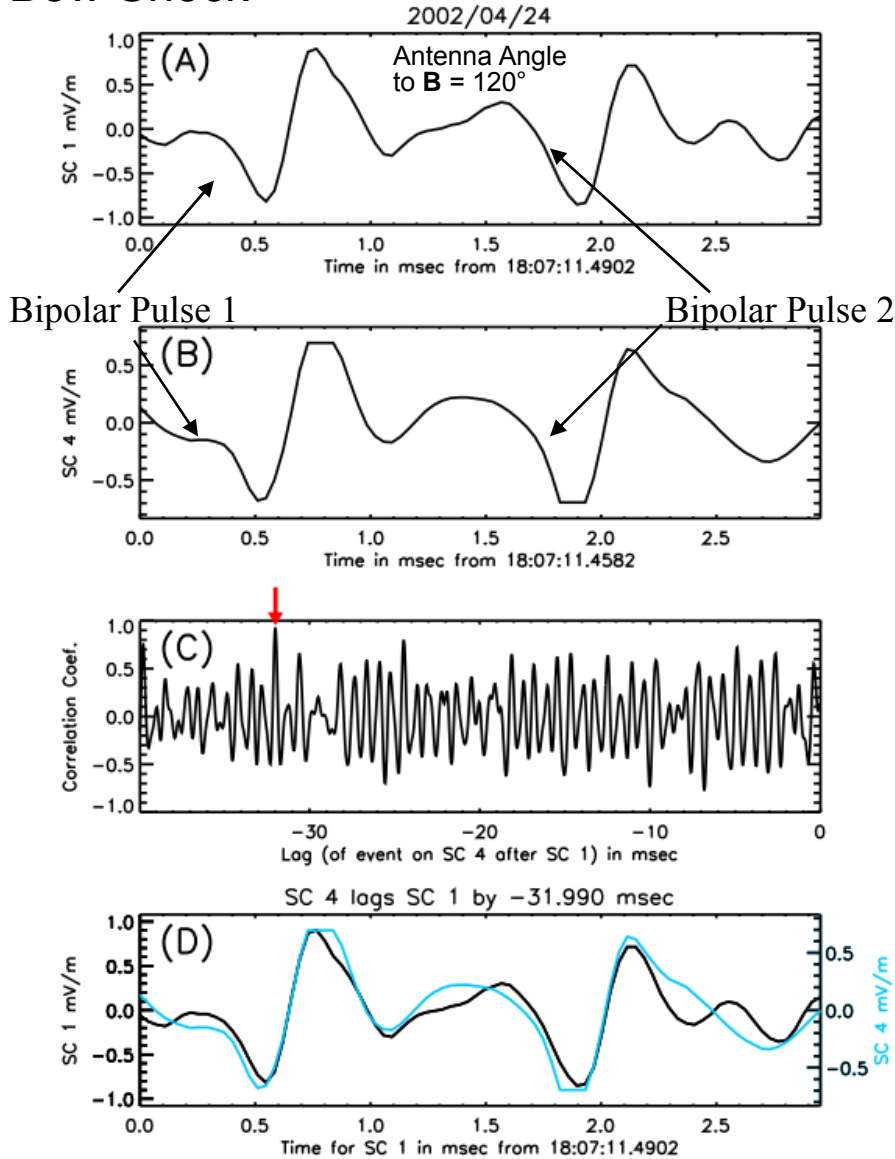
NOT TO SCALE



- Assume two spacecraft located along same field line separated by up to 10s of km
- Measure delay of observation of ESW on spacecraft 1 to observation on spacecraft 2
- Difficulties: 1) Need about same angle of antenna to B-field 2) Need isolated, series of pulses; 3) structures may be traveling in different directions and/or at different speeds

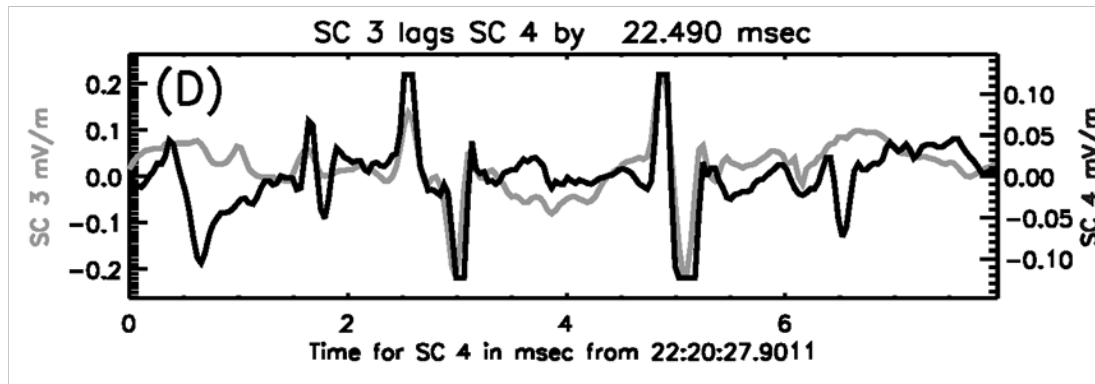
PROPAGATION AND STABILITY OF ESWs- EXPERIMENTAL

Bow Shock



- Two bipolar pulses of ~0.8 ms time duration and 1.8 mV/m amplitude observed on SC1 and SC4 at about the same antenna angle to **B** (panels A and B) near the bow shock.
- Correlation coefficient of 0.93 at about 32 ms lag of SC1 from SC4 (panel C)
- Plotting SC1 and SC4 3 ms waveforms on top of each other using 32 ms lag gives good fit of both bipolar pulses (Panel D)
- Based on 13.6 km separation along B and 83 km across B: $v=424$ km/s away from the bow shock toward earth, parallel size of 0.33 km and perpendicular size of at least 83 km
- If propagating obliquely, using line-of-sight separation we get $v=2,632$ km/s with size along this direction of 2.1 km

PROPAGATION AND STABILITY OF ESWs- EXPERIMENTAL



Cluster observations showing ESW propagation from spacecraft 4 to spacecraft 3 (away from the magnetopause) in the magnetosheath (Case 1 in table below)

- Figure shows for first time ESW stability in the magnetosheath over 22 ms time, with $L_{\text{perp}} > 30$ km ($\sim 1000 \lambda_D$), $V \sim 1334$ km/s, $L_{\text{par}} \sim 0.8$ km ($\sim 25 \lambda_D$) [Pickett et al., JASR, 2008]
- Table below shows 6 cases of ESW propagation in the magnetosheath close to the magnetopause

Date	Time (UT)	Cluster spacecraft	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

PROPAGATION AND STABILITY OF ESWs- EXPERIMENTAL

From *Pickett et al., JASR, 2008*]

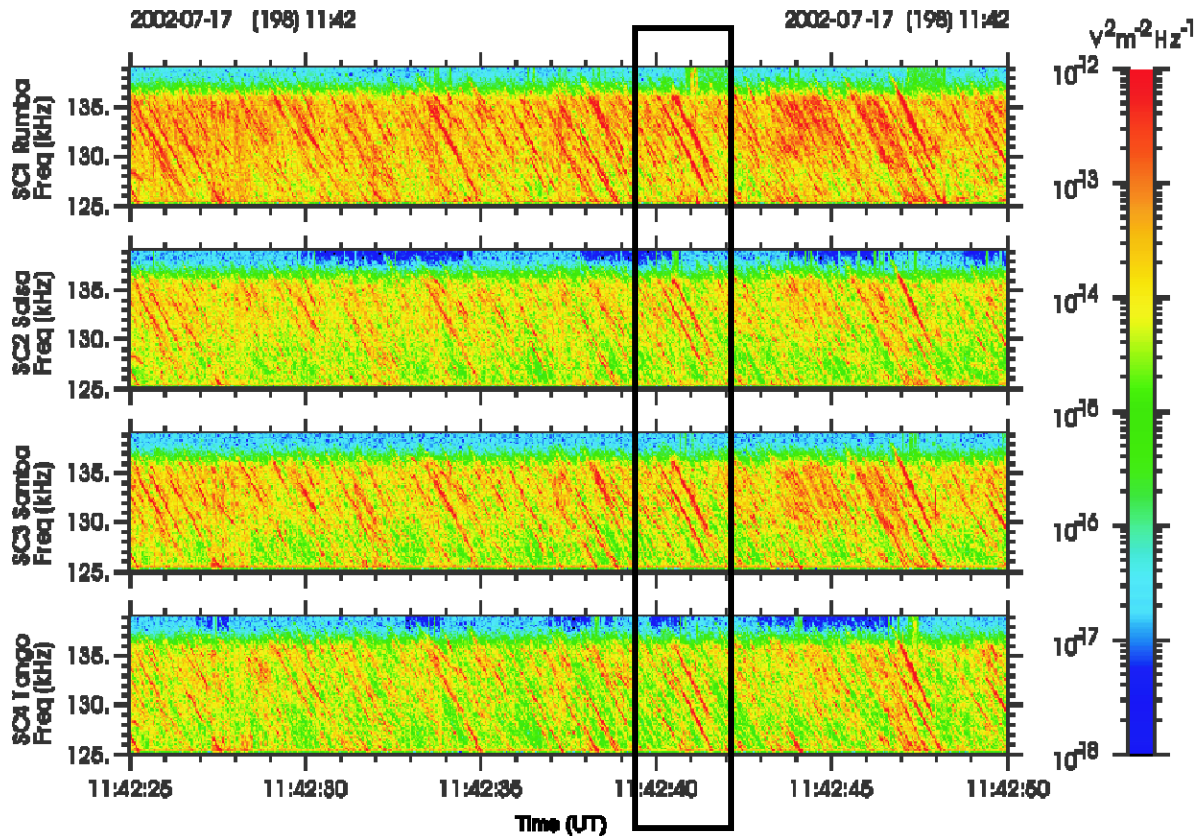


Fig. 6

- Auroral Kilometric Radiation showing fine-structured, negative-sloped striations correlated across all 4 Cluster spacecraft.
- The striations are believed to be tracers of ion or electron holes or EMIC waves propagating in the auroral acceleration region and perturbing the “horseshoe” electron velocity distribution.
- Analysis of the beaming pattern from these multi-spacecraft measurements allows us to obtain beam size (< 10 deg.), location of generation and lifetimes of the propagating structures

PROPAGATION AND STABILITY OF ESWs- EXPERIMENTAL AND THEORETICAL

From *Pickett et al., JASR, 2008*]

	E-Field (mV/m)	Time Duration (ms)	Velocity (km/s)	Lifetime (ms)	Lpar (km)	Lperp (km)
AURORAL FIELD LINES/ PLASMASHEET AT 5-8 R _E (ELECTRON SOLITARY WAVES)						
Single Spacecraft Interferometry (in situ)	1	0.5 - 1.0	500- 2,500	≥ 0.08	0.1 - 1.0	> 0.1-1.0
Multispacecraft (in situ)	0.2 - 3	0.5 - 1.0	900 - 2,800	≥ 20-22	0.7 - 4.5	> 30-250
Theory/Simulation	----	----	----	----	----	----
MAGNETOSHEATH						
Single Spacecraft Interferometry (in situ)	0.2 - 1.0	0.03 – 0.25	----	----	----	----
Multispacecraft (in situ)	0.1	0.075	1,334	22.5	0.8	> 40
Theory/Simulation[1]	----	----	----	----	.01–.05	----
AURORAL ACCELERATION REGION (ION SOLITARY WAVES)						
Single Spacecraft Interferometry (in situ)	10 - 500	3 - 10	75-300 at 5500-7000 km	≥ 10	2 - 4	3 - 4
Multispacecraft (remote sensing)	>100	----	75-400	Few 1,000	O(1)	----
Theory/Simulation[2]	----	----	200-300	5 - 75	2	2

- Table highlights the longer lifetimes obtained through multi-spacecraft analysis
- Shows that ESW can be stable over distances of 1 km and greater, something unknown from single spacecraft measurements

[1] Electron acoustic soliton model (Pickett et al., this paper)

[2] Simulations using a 2 spatial and 3 velocity dimension electrostatic code with one electron and two ion species (Crumley et al. 2001)



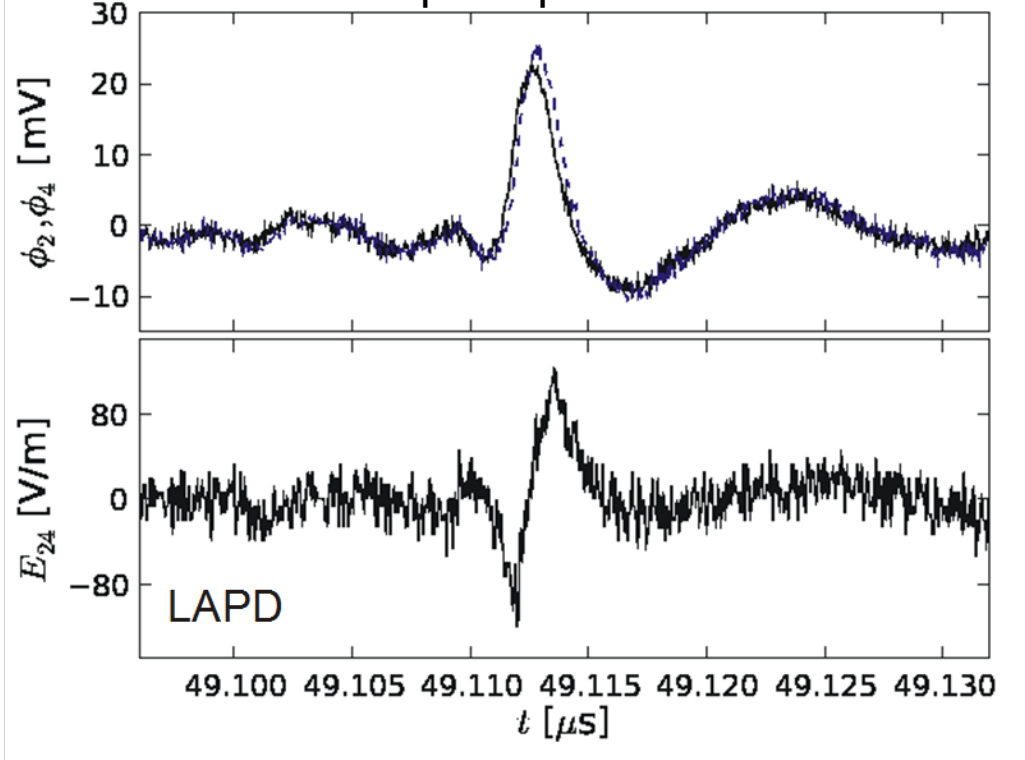
LAPD/Laboratory Experiments and Comparison to Space Observations

LAPD EXPERIMENT SETUP and PLASMA CHARACTERISTICS

- Helium plasma column, 60 cm diameter, 17.5 m long, pulsed at 1 Hz
 - $B \approx 75\text{--}750\text{ G}$
- Electron beam source is a hot wire + voltage bias
 - $n_e \approx 7 \times 10^8\text{--}3 \times 10^9\text{ cm}^{-3}$
 - $T_e \approx 0.13\text{--}0.22\text{ eV}$
 - $W_{beam} \approx 30\text{--}100\text{ eV}$
- Electric probe with 10 μm tips, 20 and 60 μm gap, 20 GHz sampling rate. Can be set either \parallel or \perp to **B**. 30 cm away from source.
 - $n_b \approx 0.1n_e$ or lower
 - $\lambda_{De} \approx 60\text{--}128\ \mu\text{m}$
 - $r_{ge} \approx 13\text{--}132\ \mu\text{m}$
 - $\lambda_{ee} \approx 0.08\text{--}10\text{ m}$
 - $f_{pe} \approx 240\text{--}490\text{ MHz}$
 - $f_{ce} \approx 210\text{--}2100\text{ MHz}$
- Different plasma densities and magnetic fields can be set

COMPARISON of ESWs in Current Layers: Laboratory and in Space - 2

Both LAPD and space plasma are collisionless



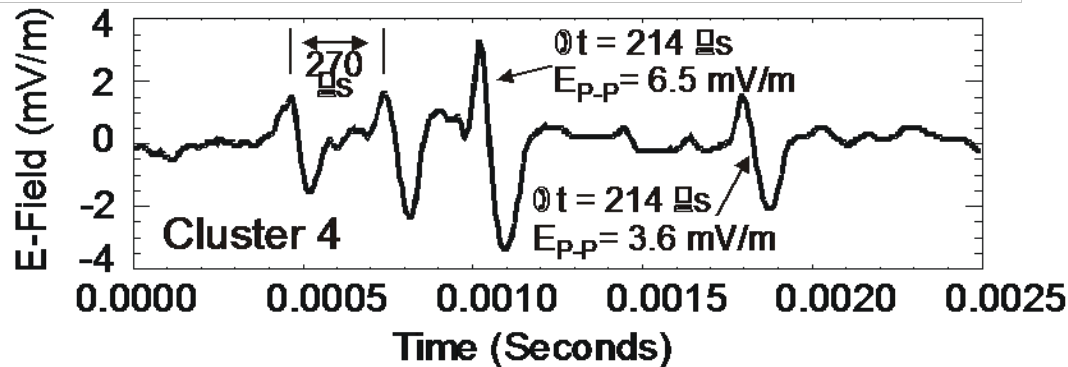
LABORATORY: LAPD with 90 eV field-aligned electron beam

Top Panel: Potential measured at each of Probes 2 and 4

Second Panel: Electric field between Probes 2 and 4: 240 V/m

ESW Duration: 0.0029 μs

Plasma Period: 0.0025 μs



SPACE: Plasmasheet at 18.8 RE at super-substorm onset with field-aligned electron beams

Electric field: 6 mV/m

ESW Duration: 200 μs

Plasma Period: 90 μs

From Pickett et al., NPG, in press, 2009

COMPARISON of ESWs in Current Layers: Laboratory and in Space - 3

- Laboratory ESW travels away from the beam source at a speed of 300 km/s or 1.21 electron thermal speed.
- Laboratory ESW has size of $8.8 \lambda_{De}$ ($1 \lambda_{De} = 56 \mu\text{m}$)
- Shape, velocity and charge are consistent with electron holes
- Generation mechanism is not the two-stream instability

CONCLUSIONS

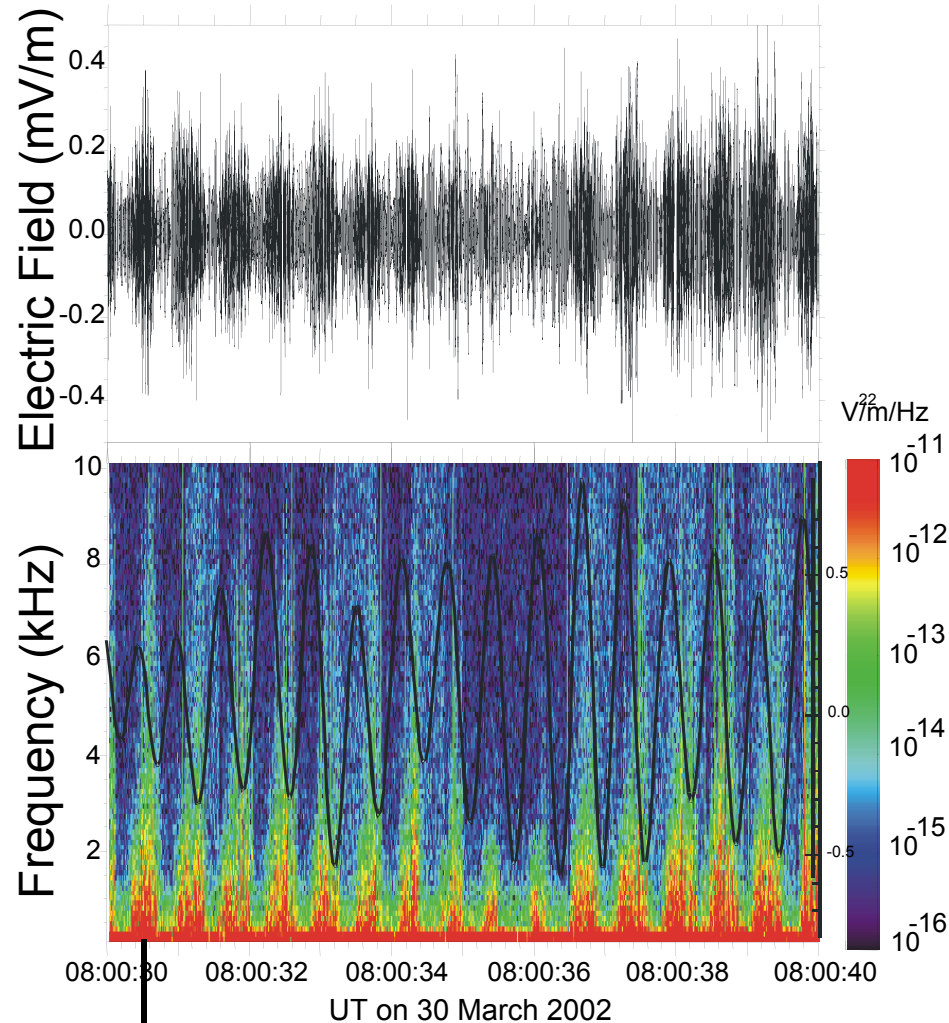
- The time durations of both the laboratory and space ESWs are only slightly larger than the electron plasma period, suggesting they are both electron-mode solitary waves
- LAPD ESWs represent the first laboratory measurements of Debye-scale solitary structures' electric field



Modulation of ESWs at 1.5 Hz

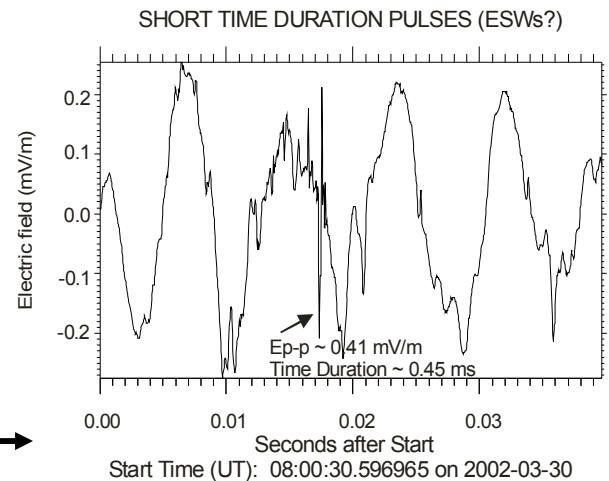
MODULATION OF ESWs AT 1.5 HZ -1

CLUSTER 4 WBD



Top panel: Electrostatic bursts in the frequency range 100 Hz – 9.5 kHz are modulated at ~ 1.5 Hz

Bottom panel: Spectrum of the waveforms shown in the top panel. Overplotted black line is STAFF-SC By waveform in MFA coordinate system. A phase shift is observed.



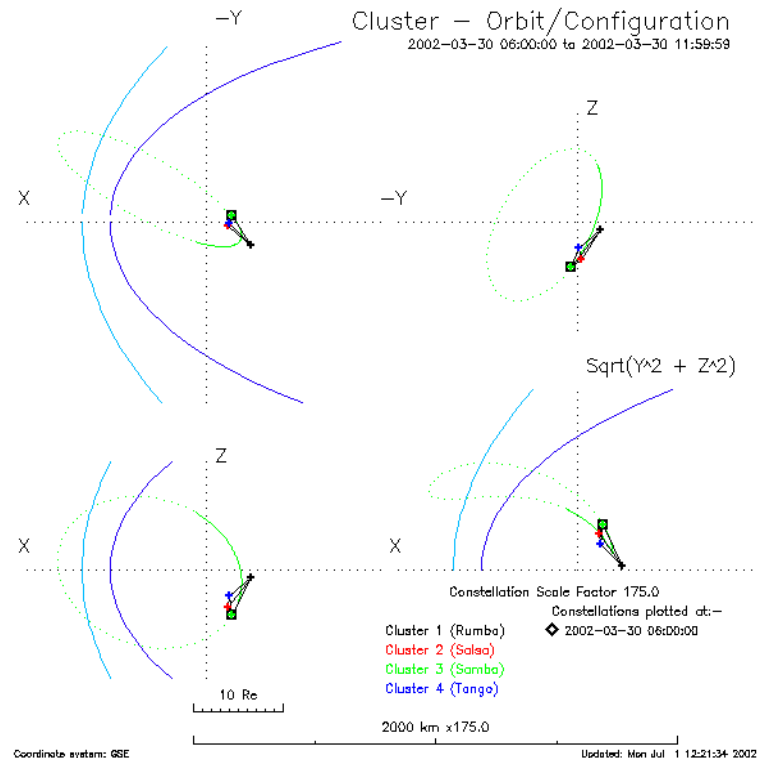
MODULATION OF ESWs AT 1.5 HZ - 2

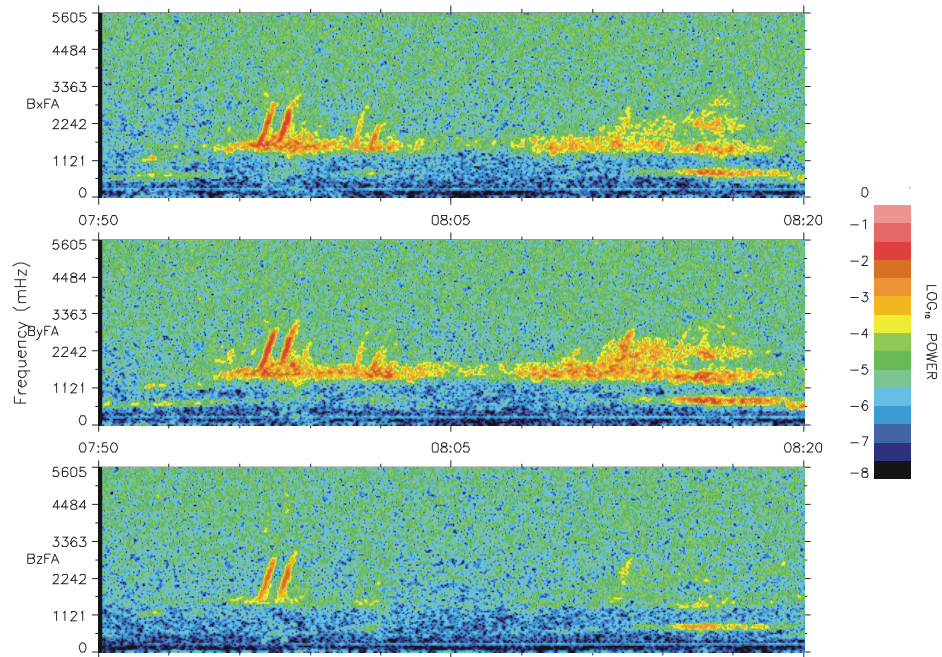
LOCATION AND CONTEXT

At 07:55-08:20 UT the Cluster spacecraft were located at ~ 4.5 RE, 2200 MLT and -7.5 deg. MLat

A pressure pulse ~ 11 hours earlier more than doubled the solar wind pressure from about 4 to 9 nPa

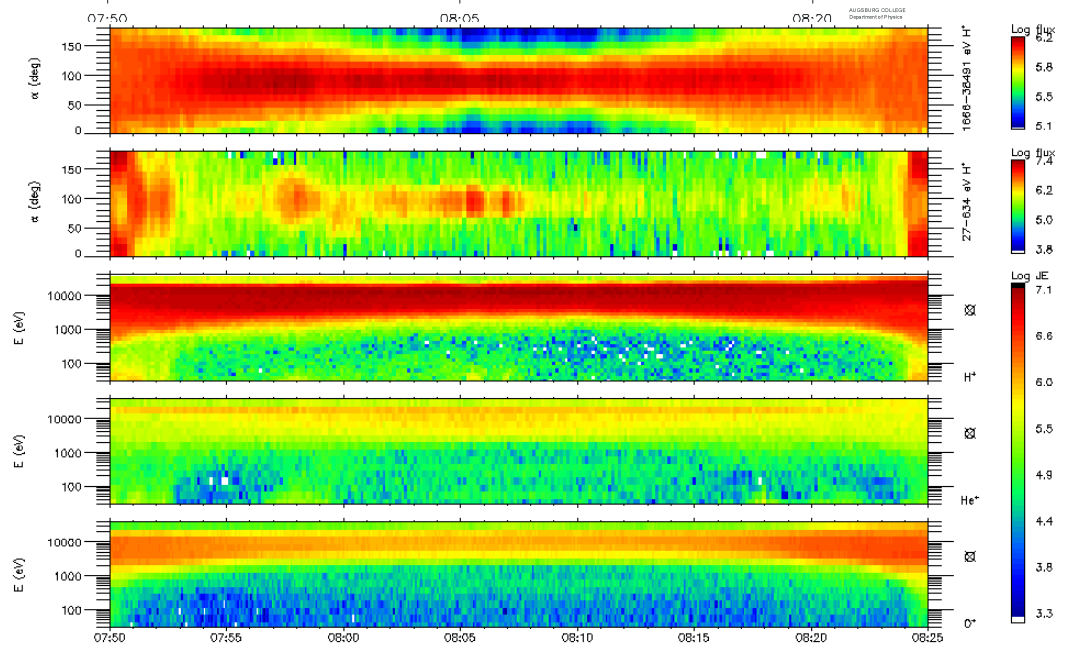
Kp was moderate at 3-4 and Dst was positive (45 nT) at the time of the pressure pulse.



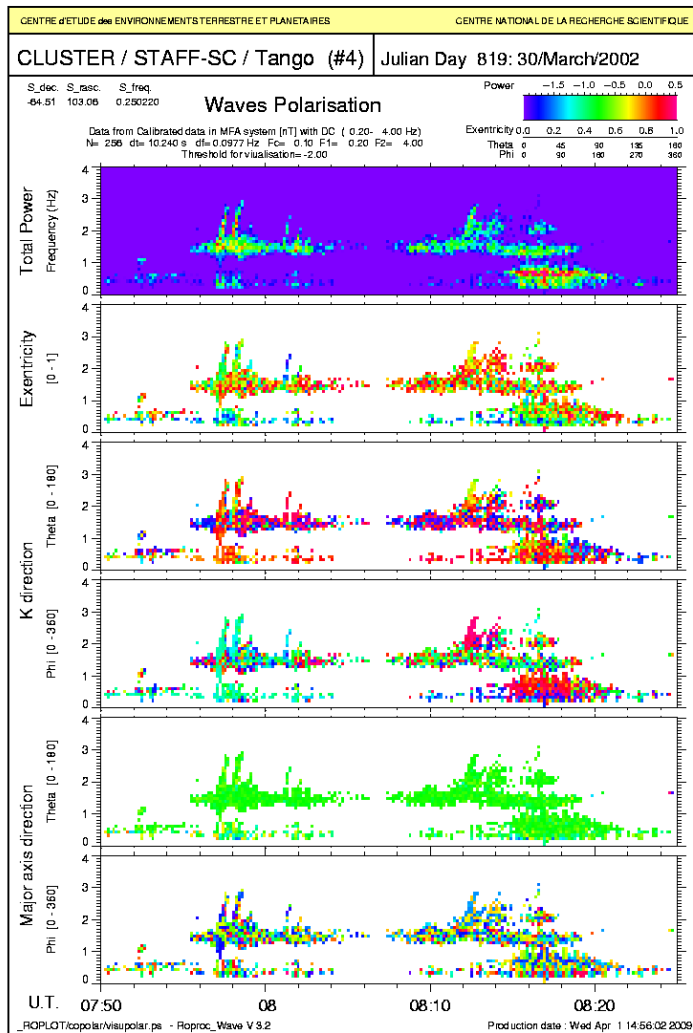


MODULATION OF ESWs AT 1.5 HZ -3

Top plot: FGM magnetic field data showing a wave at ~ 1.5 Hz, almost exclusively perpendicular to DC magnetic field. Risers appear to be triggered from this wave

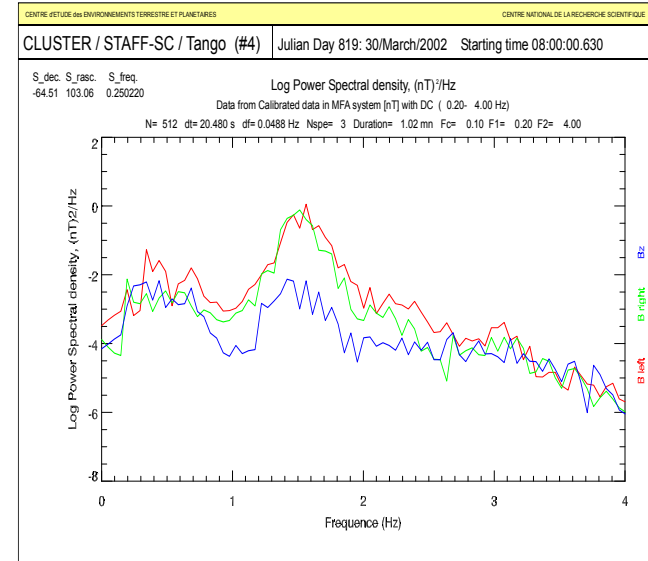


Bottom plot: CIS-Codif ion data showing high and low energy H+ at 90 degrees (top two panels) and H+, He+ and O+ flux.



MODULATION OF ESWs AT 1.5 HZ - 4

1.5 HZ INTENSITY PEAK



STAFF-SC data: Analysis of the 1.5 Hz waves shows eccentricity near 1, implying linear polarization. Wave vector is parallel to the magnetic field.

Left, right and parallel to B components of the low frequency waves, showing an intensity peak at 1.5 Hz. Similarity of the left and right components showing the coherent and transverse nature of the waves, all consistent with Pc1 magnetic pulsations.



ESW GENERATION MECHANISMS - 1

- **Beam or two-stream instability.** These would represent potential structures (phase space holes) and be BGK mode. A beam mode was suggested by Bale et al. [*Astrophys. J.*, 2002] for the shock ramp (electron holes) and MTSI suggested by Hobara et al. [*JGR*, 2008] for the foot of a quasi-perpendicular shock (ion holes). See also Omura et al., *JGR*, 1996 (beam) and Goldman et al., *GRL*, 1999 (two stream).
- **Kinetic Buneman instability.** As proposed by Goldman et al., *NPG*, 2003, slow moving ion and electron holes (ESWs) result from saturation via trapping of the kinetic Buneman instability driven by the interaction of accelerated ions with unaccelerated electrons.
- **Excitation of plasma by a localized, time dependent modulation of the electron distribution function (heating of electrons).** As proposed by Briand et al., [*JGR*, 2008], these would also represent potential structures and be BGK mode.
- **Spontaneous generation out of turbulence.** These would be BGK mode.
- **Acoustic mode instability (electron or ion).** These would represent density structures (enhancements or depressions). See Douboloz et al. *GRL*, 1991; Berthomier et al., *POP*, 2000; Singh et al., *PSS*, 2001; Ghosh et al., *JGR*, 2008; Lakhina et al., *POP & NPG*, 2008a,b)



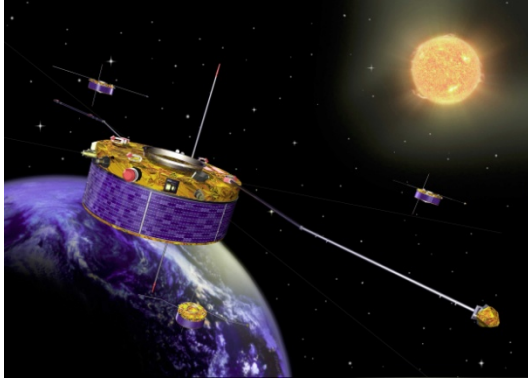
ESW GENERATION MECHANISMS - 2

- **Product of Magnetic Reconnection.** In the magnetotail using Cluster and Geotail data (Cattell et al., *JGR*, 2005; Deng et al., *ASR*, 2005); in association with dayside reconnection through observations in the cleft on Viking (Pottelette and Treumann, *JGR*, 1998; and in the magnetopause boundary using Geotail data (Matsumoto et al., *GRL*, 2003).
- **Multi-step Process:** As proposed by Lakhina et al. (*NPG*, 2004) and Tsurutani et al. (*NPG*, 2003) using data from the Polar spacecraft for a magnetic hole event in the polar cap boundary layer:
 - ❑ Low frequency waves (Alfvén and/or obliquely propagating proton cyclotron waves) provide free energy for electron heating.
 - ❑ Electron heating produces electron currents to drive some much higher frequency instabilities (LH, IAC, bi-stream or counter-streaming electron, and EIC instabilities).
 - ❑ These instabilities saturate in 100-400 plasma periods by trapping electrons.
 - ❑ Electron trapping leads to generation of electron phase space holes.



CONCLUSIONS

- Electrostatic solitary waves (solitary structures) are observed at many locations in the Cluster and Polar orbits, as well as on other spacecraft, primarily in regions of turbulent or mixing plasmas.
- Some aspects of the observations are consistent with ESW generation through beam-type or kinetic Buneman instabilities (BGK mode) and some aspects are consistent with acoustic mode.
- In situ multi-spacecraft observations of propagating ESWs are just starting to be made, but provide more insight about lifetimes and stability of ESWs than single spacecraft observations.
- ESWs in space have been found to be stable over several Debye lengths
- Most ESWs observed by Cluster and Polar outside the auroral acceleration region are flat structures, with small extent along the field and large extent cross-field.
- Laboratory generated ESWs by means of beam injection have time periods consistent with the electron plasma period, similar to those observed by Cluster and Polar
- Combining observations of ESWs from space and from the laboratory with theory and simulations, is the subject of future work with the aim of establishing an ESW generation mechanism for certain current layers



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