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ANALYSIS OF THE CHARACTERISTICS AND POSSIBLE GENERATION MECHANISMS OF ELECTROSTATIC SOLITARY WAVES OBSERVED BY CLUSTER FROM THE INNER MAGNETOSPHERE TO THE SOLAR WIND

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XVIII General Assembly of International Union of Radio Science (URSI)
Vigyan Bhavan, New Delhi, India
23 – 29 October 2005

Acknowledgments: NASA/Goddard Space Flight Center, Jet Propulsion Laboratory, National Science Foundation, Deep Space Network, ESA, ESOC, JSOC, Cluster Bow Shock Working Group

PRIOR TO 1985

- Broadband Electrostatic Noise (BEN) was first reported by Scarf et al. (*GRL*,1974) and Gurnett et al. (*JGR*,1976) using observations made by IMP7 and IMP8, respectively, in the Earth's distant tail.
- BEN was characterized as being
  - Bursty, and
  - consisting of broadband spectral features usually extending from the lowest frequencies measured up to as high as the plasma frequency with the BEN intensity decreasing with increasing frequency.
- Subsequently, BEN was reported by several investigators for several regions of Earth, e.g., near Earth solar wind, bow shock, magnetosheath, magnetopause boundary layer, cusp, plasmasheet boundary layer, along auroral field lines and auroral acceleration region.
- Observations of solitary waves and double layers reported by Temerin et al. (*Phys. Rev. Lett*.,1982) using S3-3 waveform data were not presented in spectral form and thus no link was made with BEN.
- Several theories were put forth to try to explain these broad spectral features, but none suggested they were simply the FFT-renderings of solitary waves.

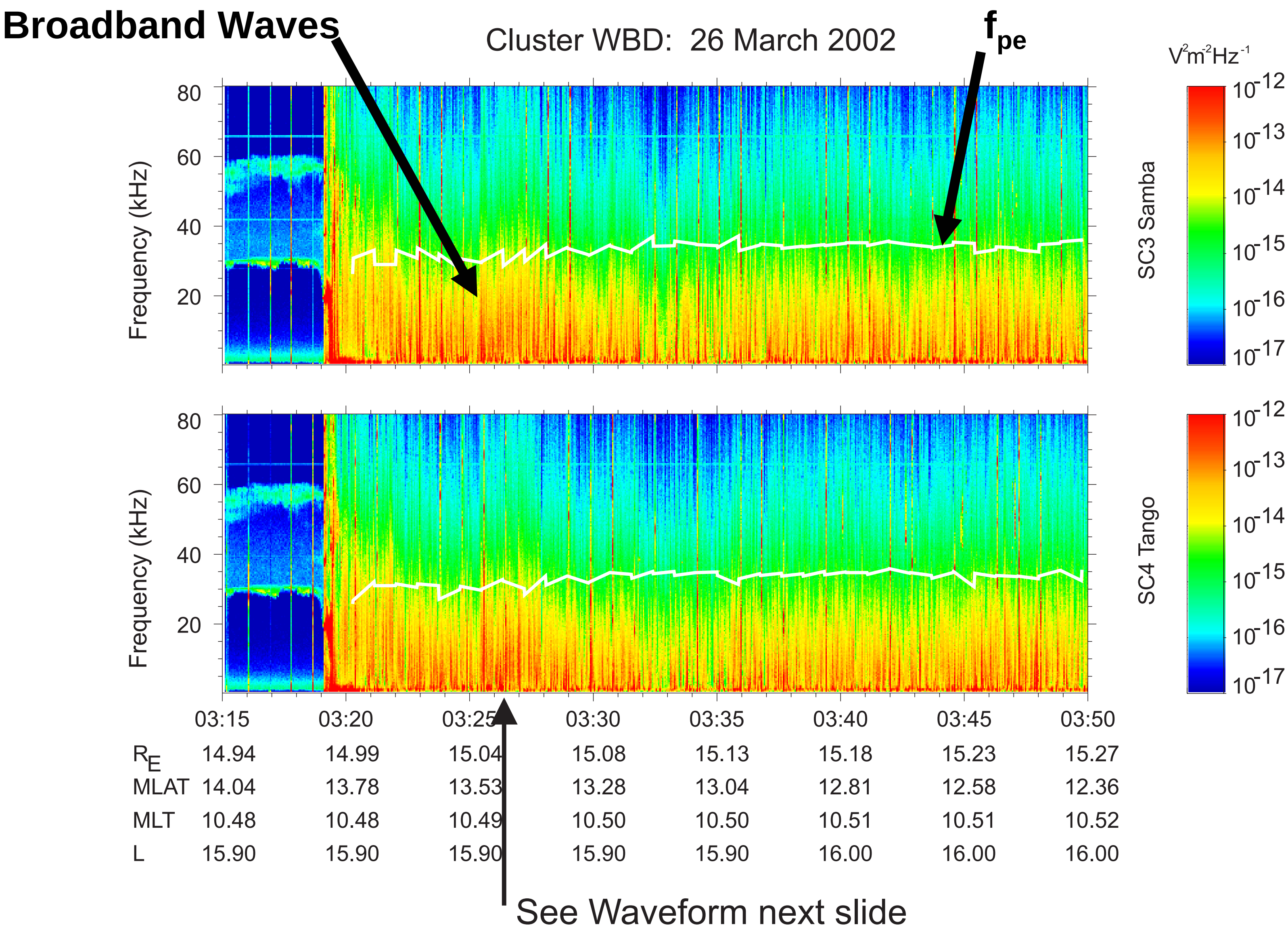
1985 AND LATER

- A theoretical investigation by Nishida et al. (1985) pointed out that certain kinds of potential structures could explain the broad frequency spectra
- A subsequent theoretical investigation by Dubouloz et al. (1991) showed that electron acoustic solitons passing by a satellite would generate spectra that could explain the high frequency part of BEN, consistent with Viking observations.
- Matsumoto et al. (*GRL*,1994) was the first to link the observations of solitary waves with BEN for the distant magnetotail:
  - Geotail PWI instrument waveform data (4 kHz bandwidth, 8.7 s snapshots every 5 minutes) show that several modes are present in the ac electric field measurements of the broadband electrostatic noise, one of the most surprising being the "Electrostatic Solitary Wave", or ESW.
  - ESWs are in the form of bipolar pulses (half sinusoid-like cycle followed by a similar half cycle of opposite sign), have time durations on the order of 2-5 ms and peak-to-peak amplitudes of a few tenths mV/m.
- A nonlinear BGK (Bernstein-Greene-Kruskal) potential mode was proposed by Omura et al. (*GRL*, 1994) as the ESW generation mechanism.

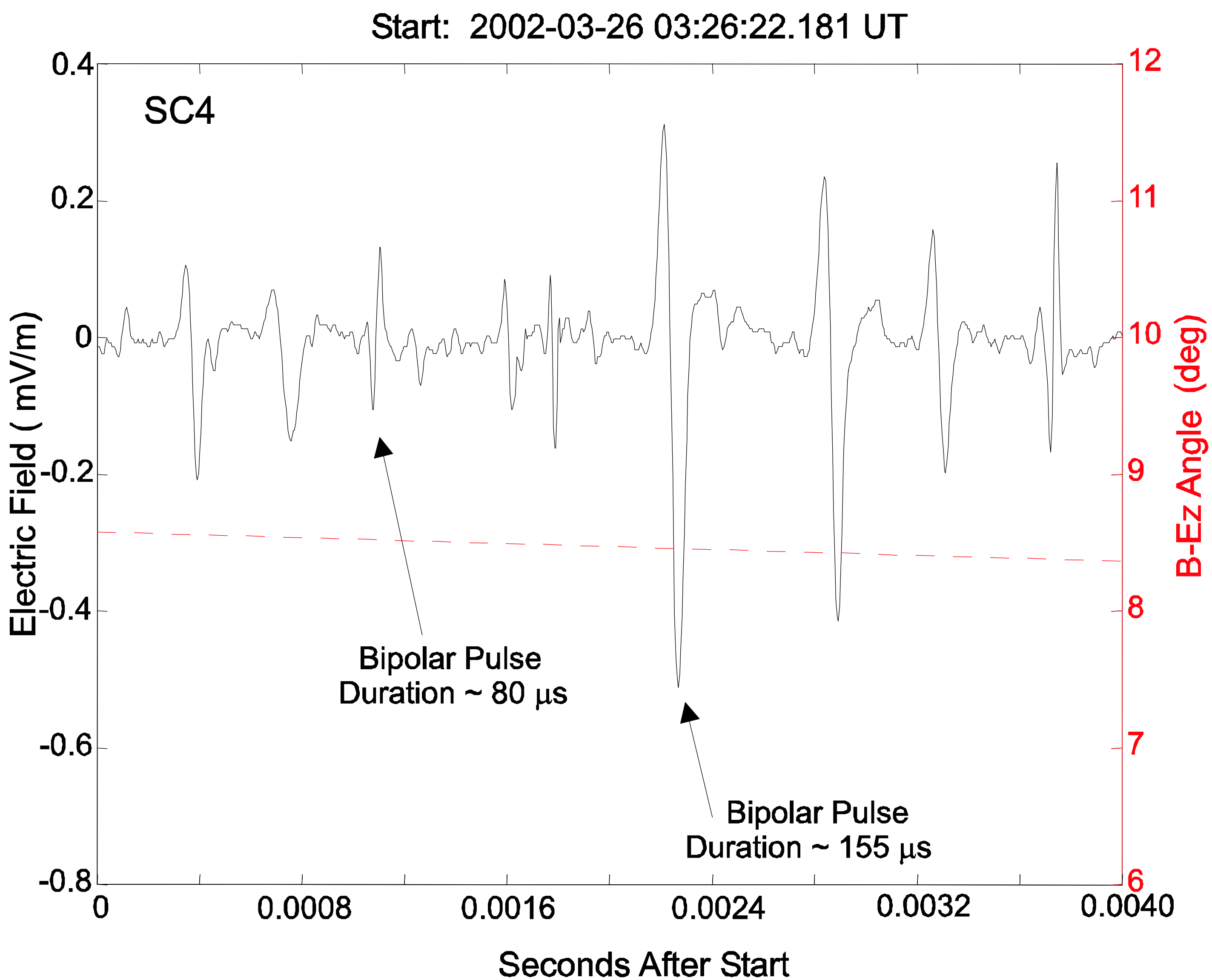
1985 AND LATER (Continued)

- Most of the ESW observations reported to date have been interpreted as holes in electron or ion phase space (potential structures) that move along magnetic field lines and arise out of beam instabilities (see Franz et al., *JGR*, 2005 for a review), similar to the mechanism proposed by Omura et al. (1994).
- For the auroral parallel acceleration region, the ESWs have in one case been identified as modulated electron acoustic solitons growing out of the electron acoustic instability (Pottelette et al., *GRL*, 1999).
- Some of the three half sinusoids (two of one polarity and one of the other), currently referred to as tripolar pulses, have been interpreted as weak double layers in the solar wind and along auroral field lines (Mangeney et al., *Ann. Geophys*, 1999; Pickett et al., *NPG*, 2004).
- Pairs of monopolar (one half sinusoid) pulses of opposite polarity and offset bipolar pulses were interpreted as electron holes that are split and broadened, respectively (Tsurutani et al., *GRL*, 1998)
- Since the Cluster orbit traverses almost all regions of Earth where solitary waves are observed, this provided WBD, due to its extensive amplitude range and high sampling rate, with an excellent opportunity to carry out surveys for comparison by region.

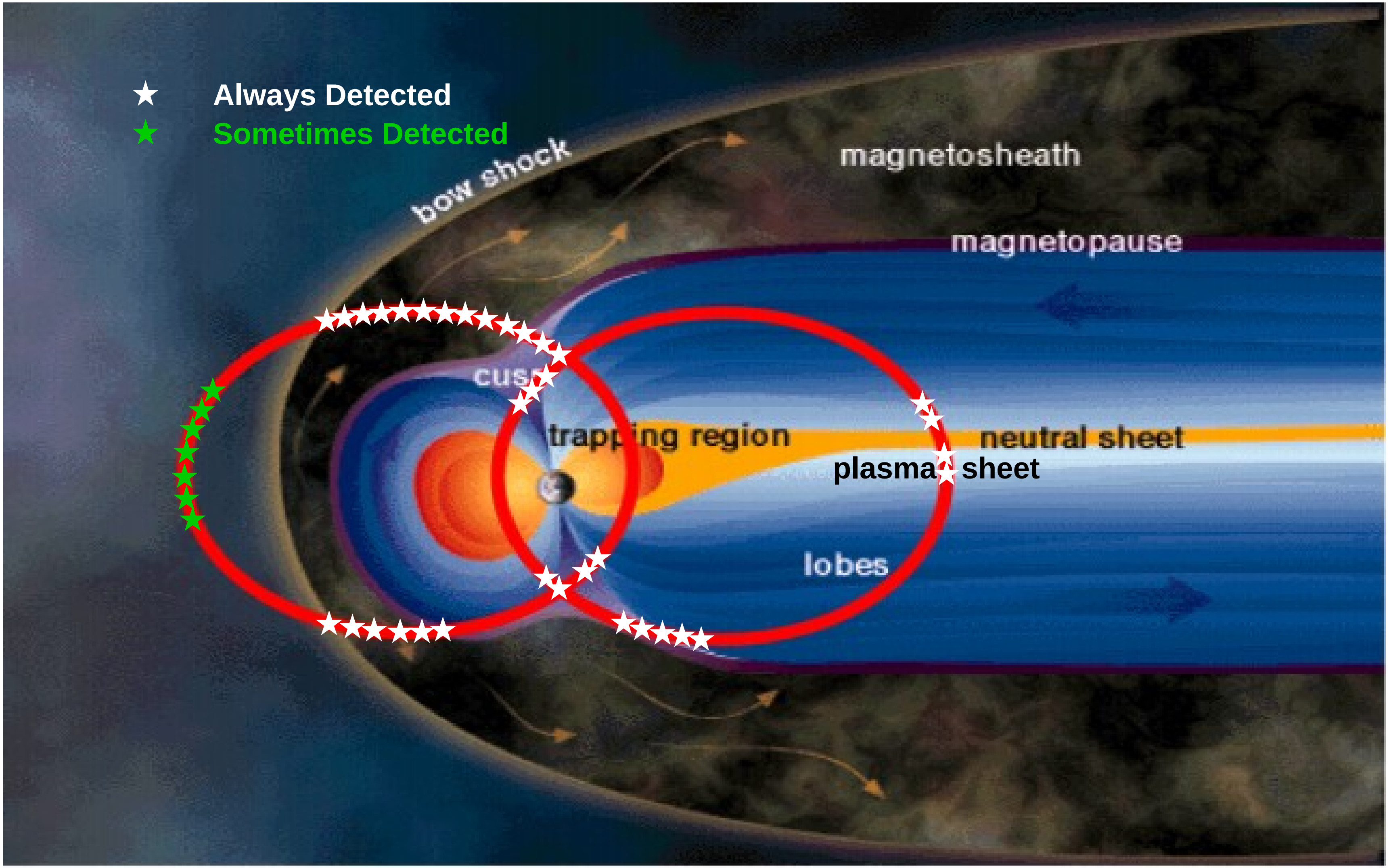
QUASI-PERPENDICULAR BOW SHOCK CROSSING AND MAGNETOSHEATH



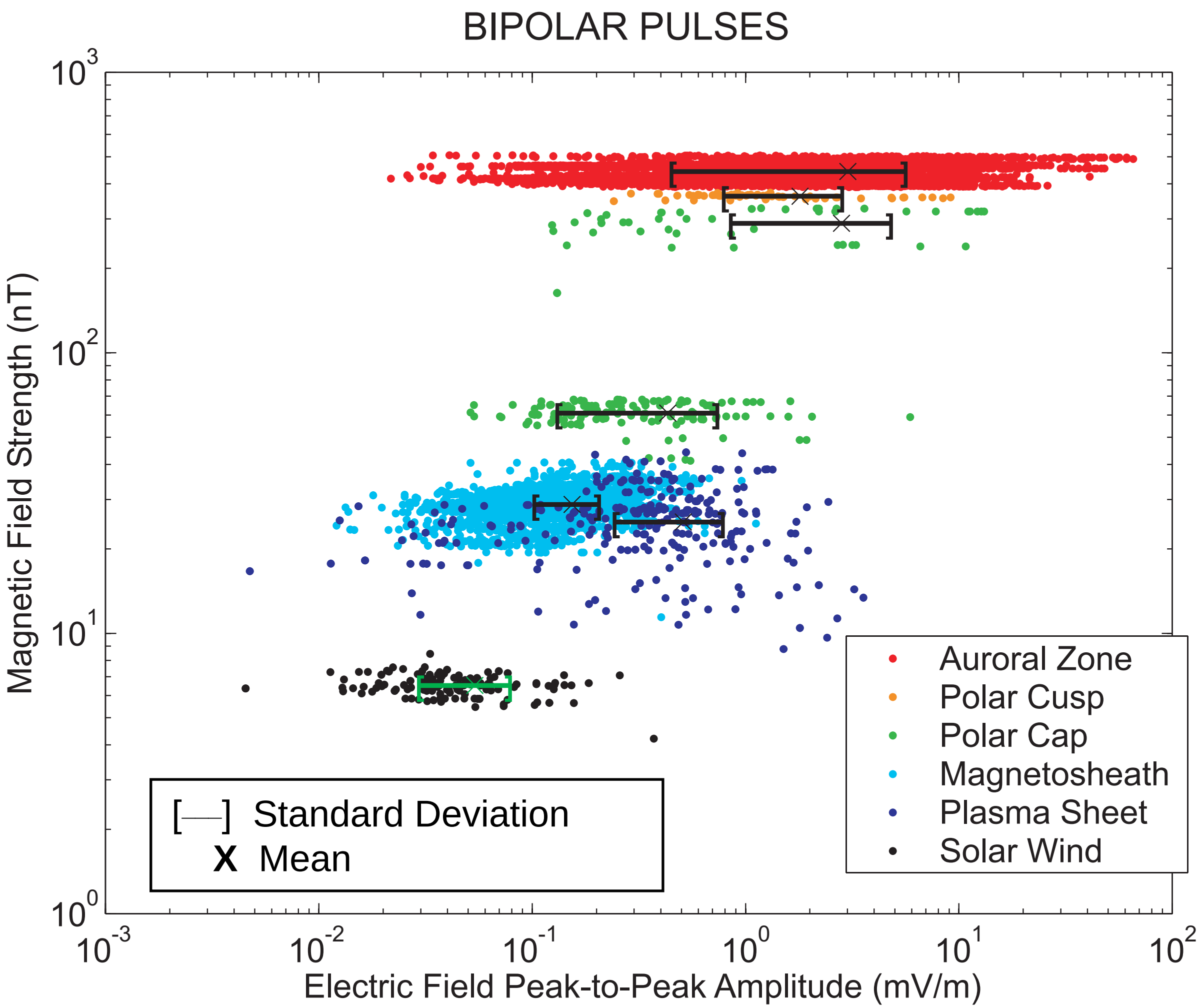
MAGNETOSHEATH SOLITARY WAVES



LOCATION OF SOLITARY WAVE DETECTIONS IN CLUSTER’S ORBIT



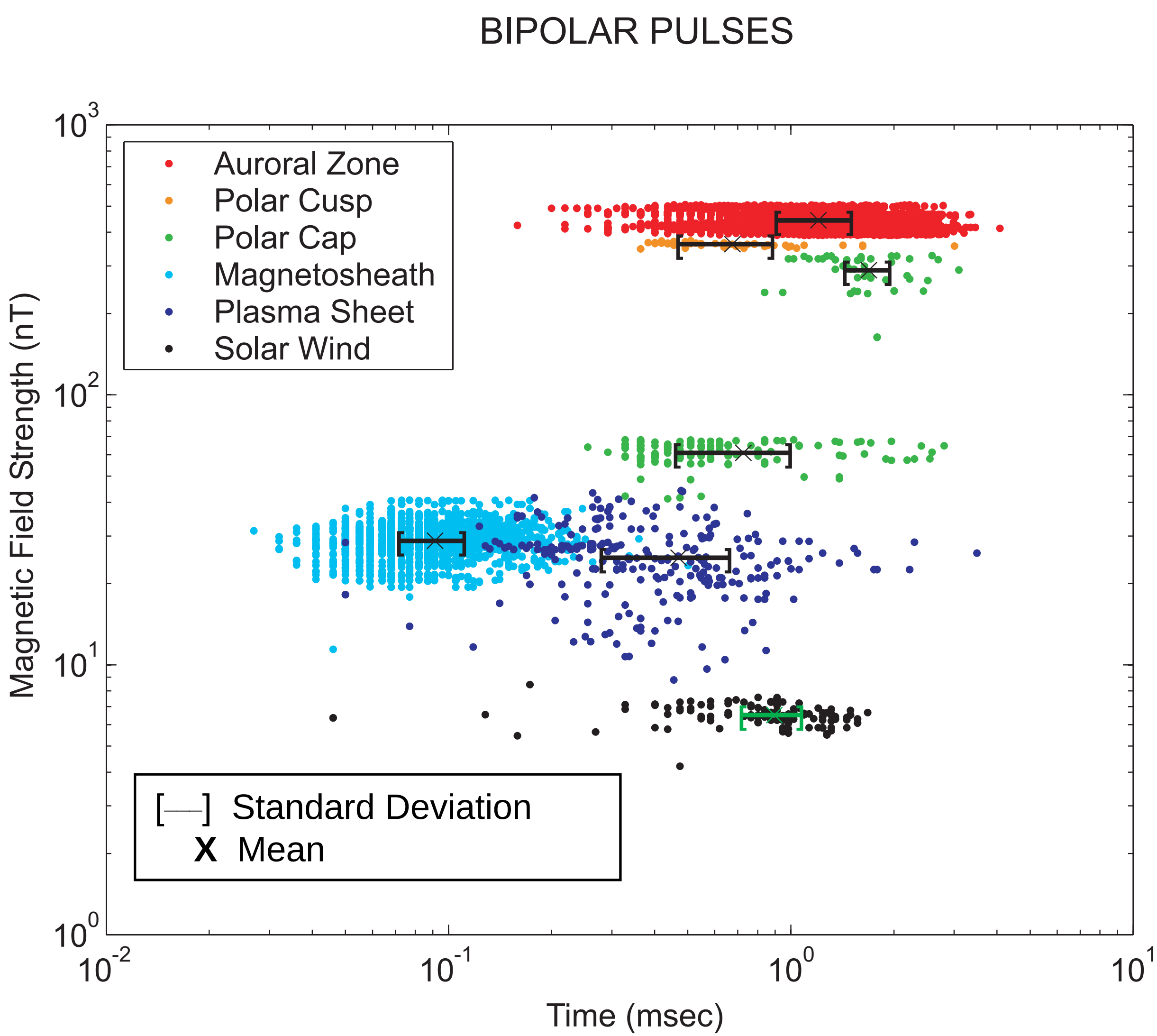
ELECTROSTATIC SOLITARY WAVE SURVEY



[From Pickett et al., Ann. Geophys., 2004]

- Automatic detection algorithm used to identify bipolar and tripolar ESWs.
- ESWs span 4 orders in amplitude over 2 orders of magnetic field strength
- General trend for ESW amplitudes to increase with magnetic field strength, consistent with stability requirements of the BGK mode in finite magnetic fields (Chen et al., *Phys Rev. E*, 2004).

ELECTROSTATIC SOLITARY WAVE SURVEY

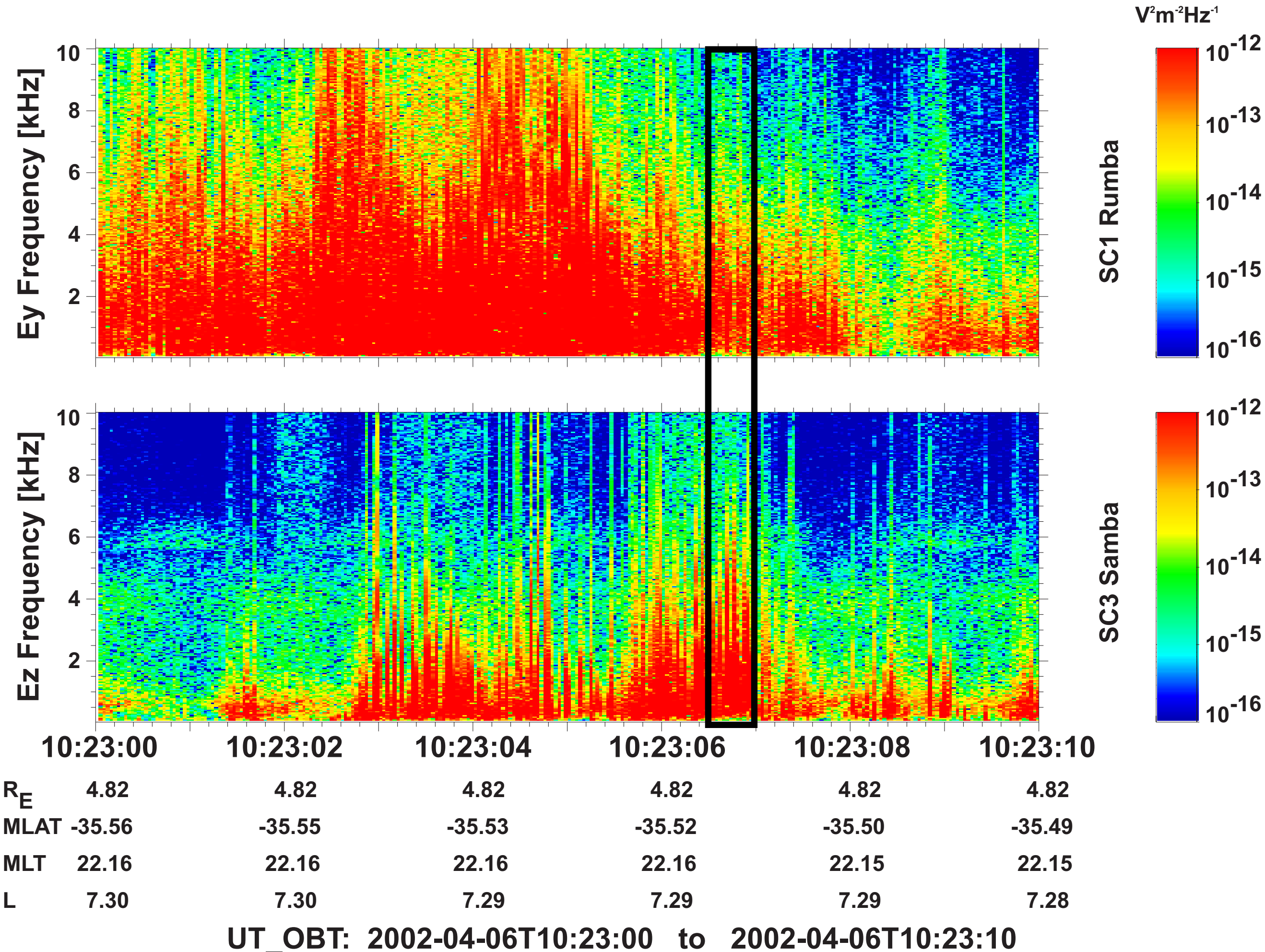


[From Pickett et al., Ann. Geophys., 2004]

- ESWs span 2.5 orders of magnitude in time duration over 2 orders of magnetic field strength.
- No trend EXCEPT magnetosheath ESW appear to be of different time class (much shorter).
- Suggests magnetosheath ESWs generated from different mechanism or plasma parameters are vastly different if common generation mechanism.

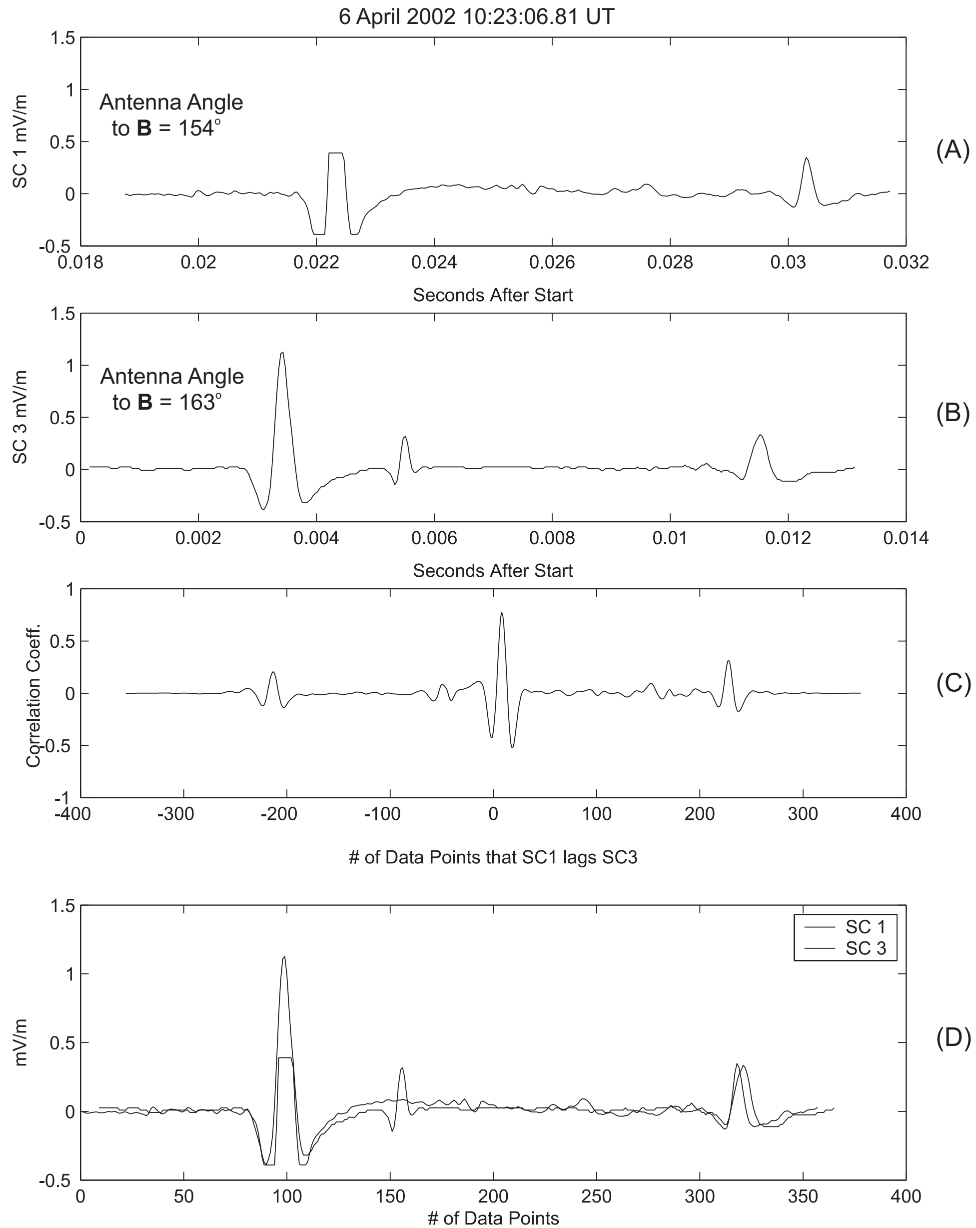
AURORAL ZONE: ESW PROPAGATION STUDY

Cluster WBD: 06 April 2002



Cross correlation was carried out for the waveforms contained within the black box area (smallest separation along **B** of few 10s kms)

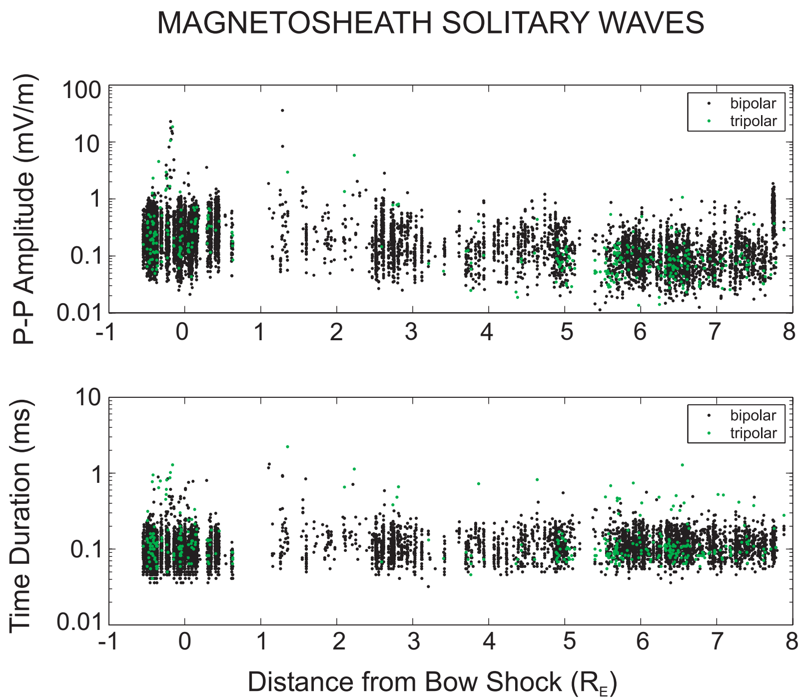
AUORAL ZONE: ESW PROPAGATION STUDY

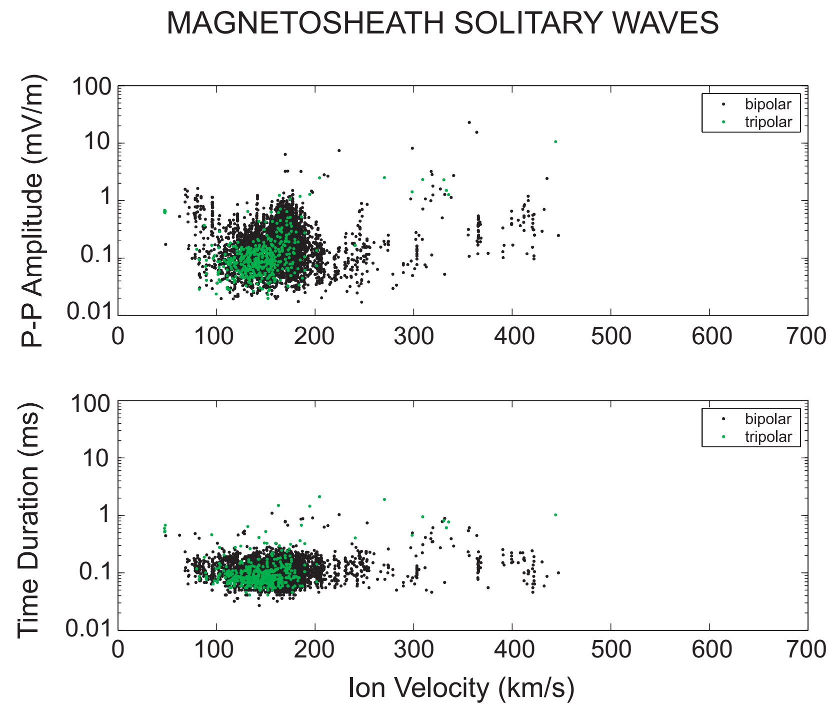


[From Pickett et al., NPG, 2004a]

- Two tripolar pulses of ~1.6 ms time duration observed on SC1 and SC3 at about the same antenna angle to **B** (panels A and B)
- Correlation coefficient of 0.78 at about 10 lags of SC1 from SC3 (panel C)
- Plotting SC1 and SC3 13 ms waveforms on top of each other using 10 lags gives good fit of both tripolars (Panel D)
- Based on 56 km separation along B and 251 across B: v=2800 km/s away from Earth, parallel size of 4.5 km and perpendicular size of at least 251 km

MAGNETOSHEATH ESW GENERATION STUDY





Distance from Bow Shock

- No dependence for amplitude or time duration
- Suggests local generation at multiple locations in the magnetosheath rather than generation at bow shock

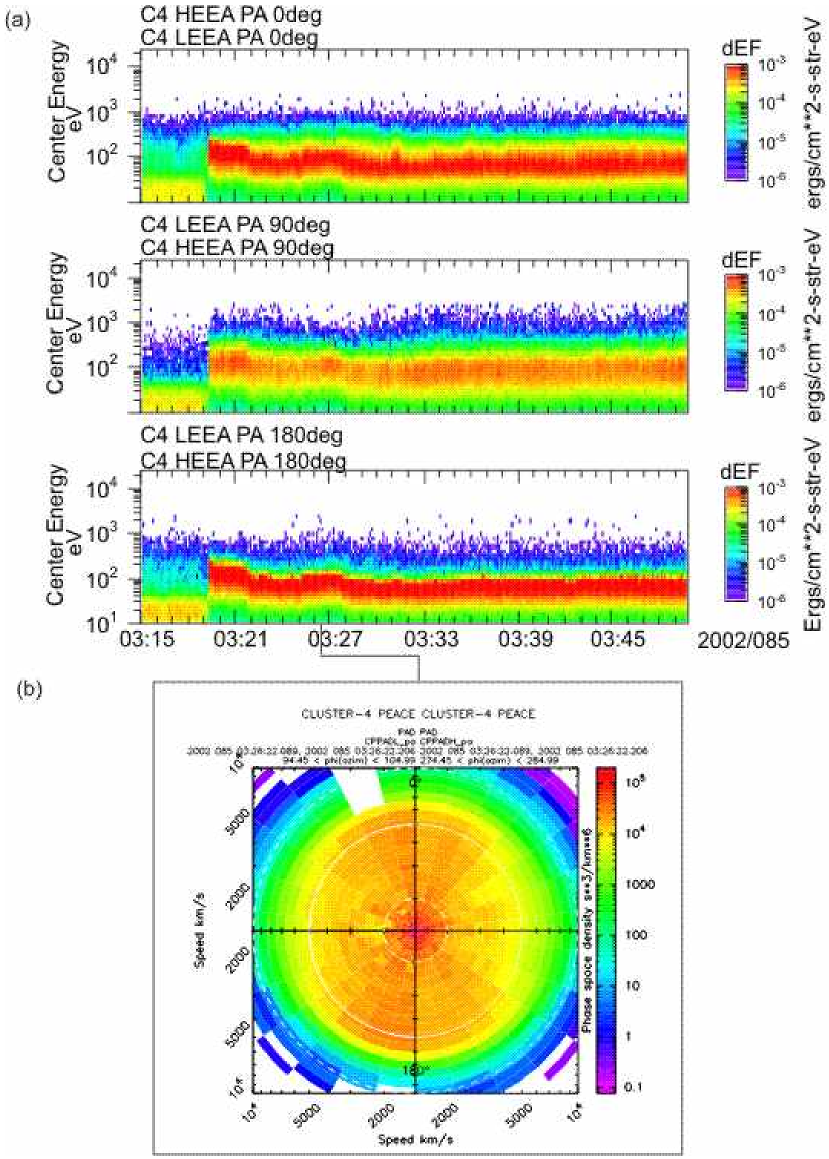
Dependence on Ion Velocity

- Slight trend for larger amplitudes at larger velocities, but no dependence for time duration
- Suggests ions not solely responsible for creation

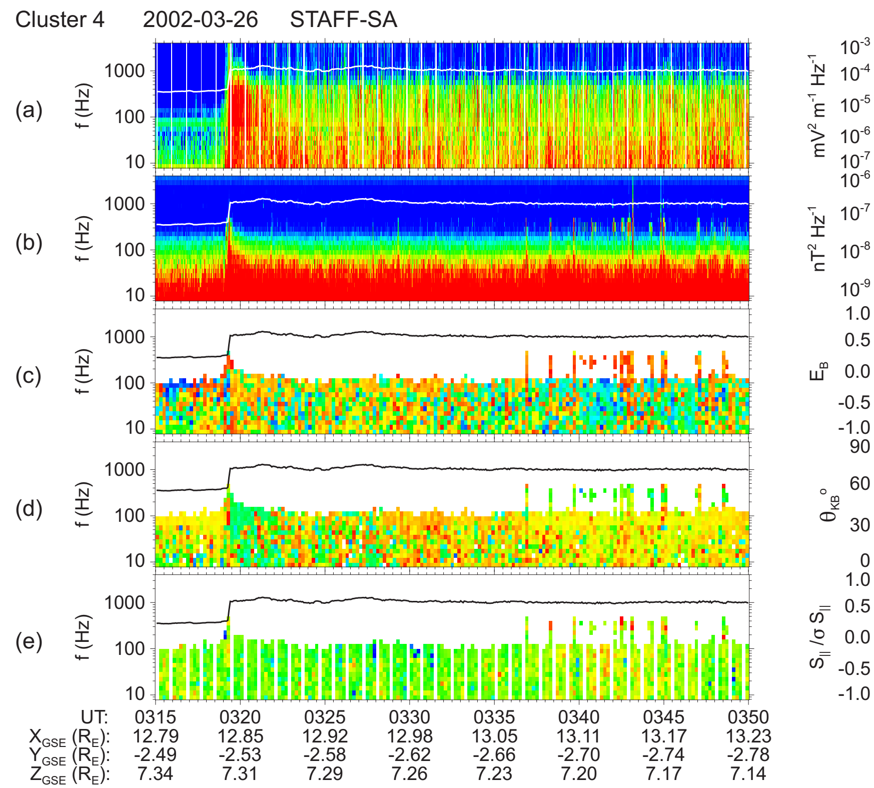
[From Pickett et al., NPG, 2005]

MAGNETOSHEATH ESW GENERATION STUDY

PEACE ELECTRON DATA



STAFF-SA WAVE DATA

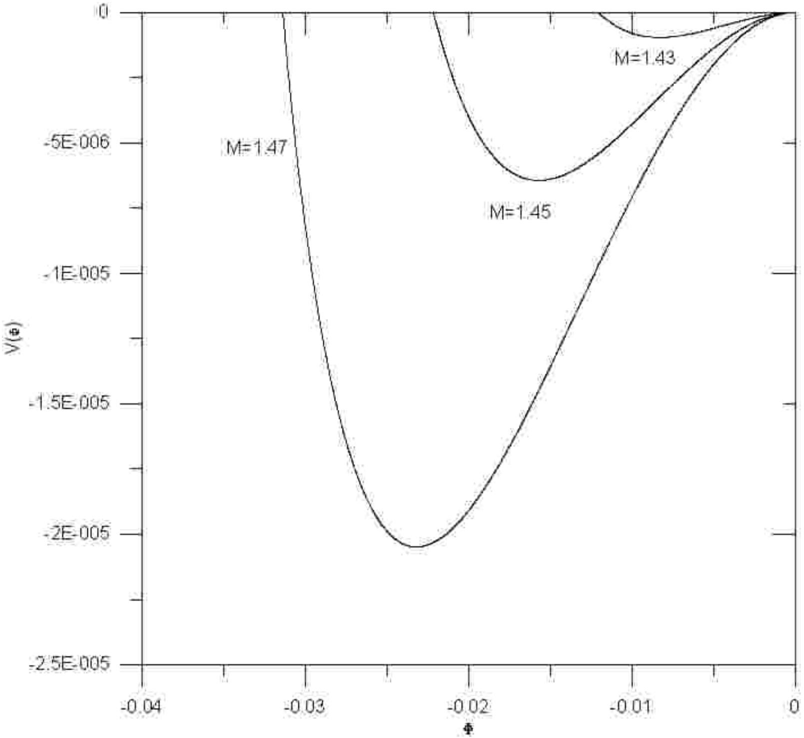


Possible Generation Mechanisms

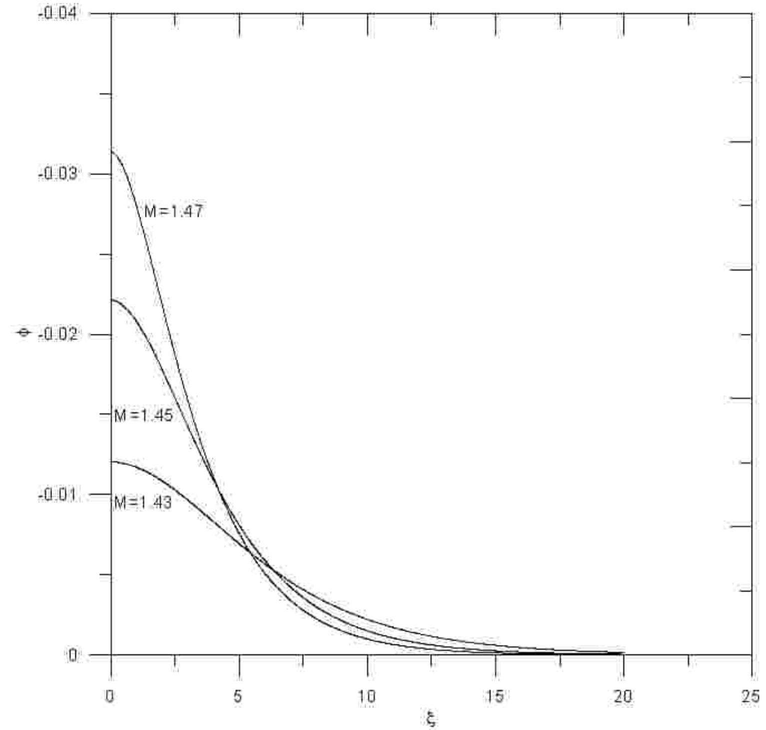
- Beam instability, such as two-stream, based on electron data
- Spontaneously out of turbulence, based on magnetic wave data
- Electron Acoustic Instability (next slide)

[From Pickett et al., NPG, 2005]

MAGNETOSHEATH ESW GENERATION STUDY



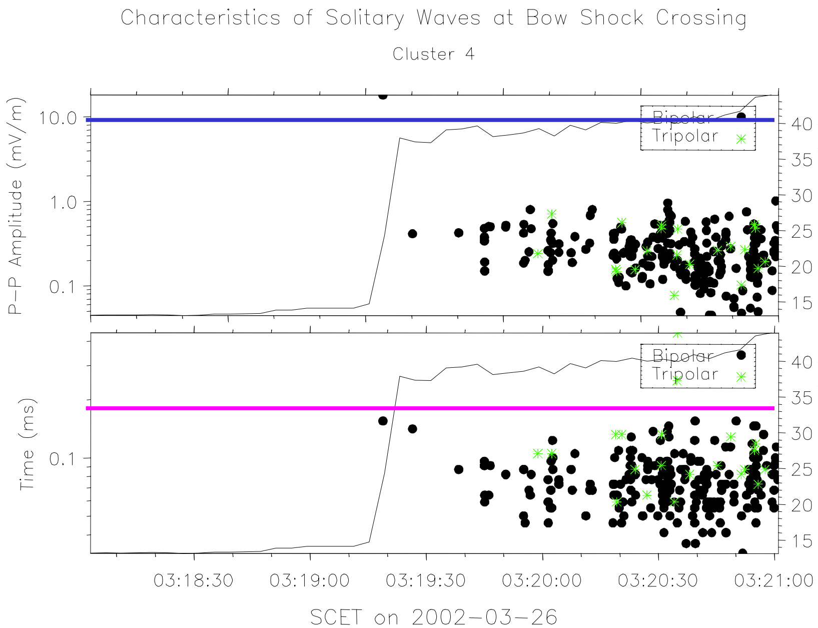
Sagdeev potential versus Normalized Potential (with respect to hot electron temperature)



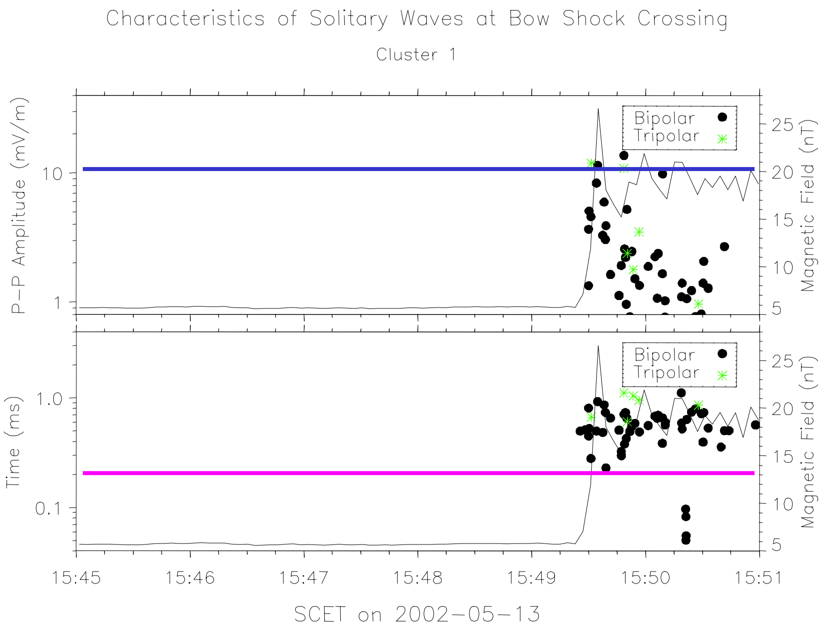
Normalized Potential Amplitude vs. Size

- Preliminary Electron Acoustic Instability simulations carried out with input data obtained from antenna modeling by Beghin et al. (Rad. Sci., 2005) using Whisper/WBD Mutual Impedance test data results (T_{ec}, T_{eh}, n_{ec}, n_{eh}, ion beam)
- Only negative potential structures are observed; (still under investigation by Lakhina, Singh and Reddy).
- Typical normalized soliton potential amplitudes are 0.01-0.03 and typical soliton widths are 1-5 hot electron Debye lengths.

ESW CHARACTERISTICS FOR TWO QUASI-PERPENDICULAR SHOCKS

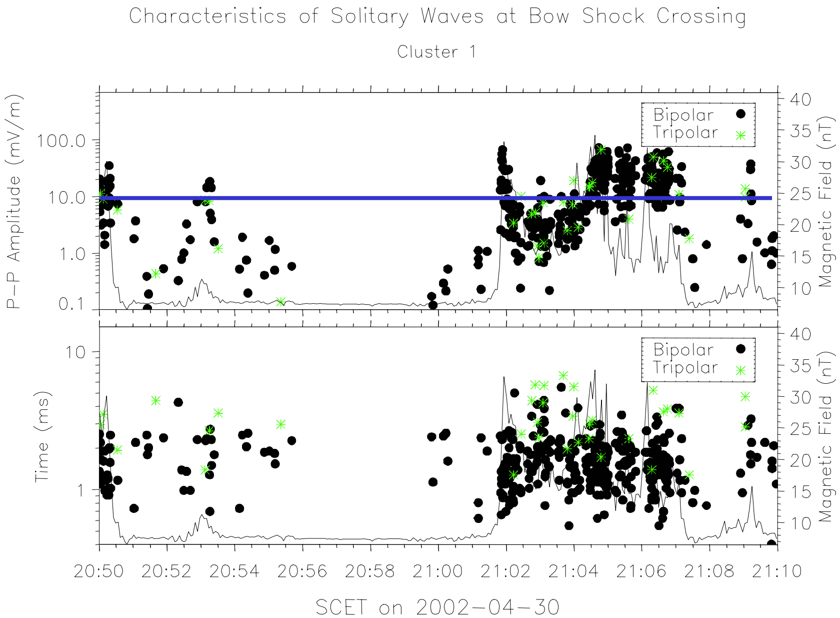


- Quasi-perpendicular, $\theta_{BN} \sim 85^{\circ}$
- $\beta \sim 0.29$
- $M_A \sim 6.4$
- Almost total absence of ESWs in transition region, as well as upstream; numerous downstream but of very short duration

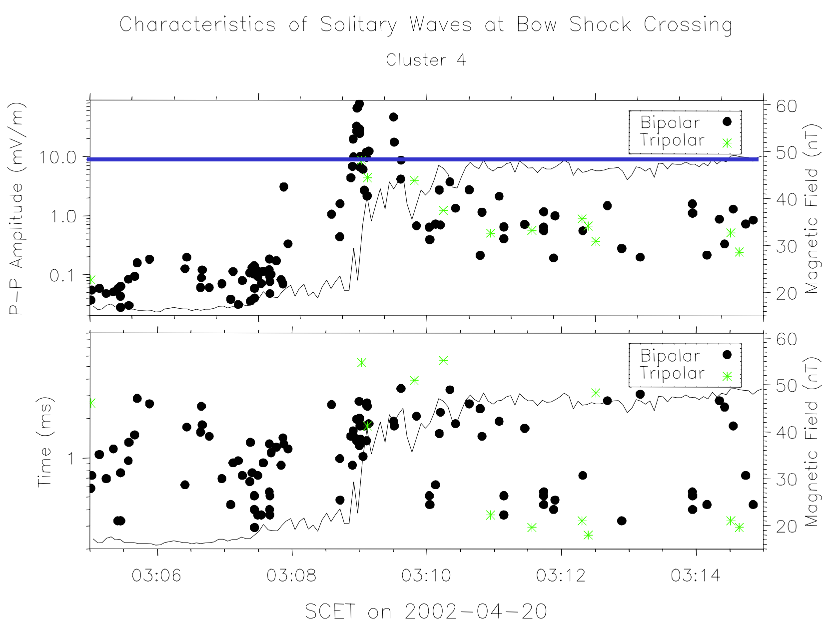


- Quasi-perpendicular, $\theta_{BN} \sim 52^{\circ}$
- $\beta \sim 2.4$
- $M_A \sim 13.5$
- Absence of ESWs upstream possibly due to low **B**, but longer time duration ESWs detected in transition region and downstream.

ESW CHARACTERISTICS FOR DIFFERENT KINDS OF SHOCKS

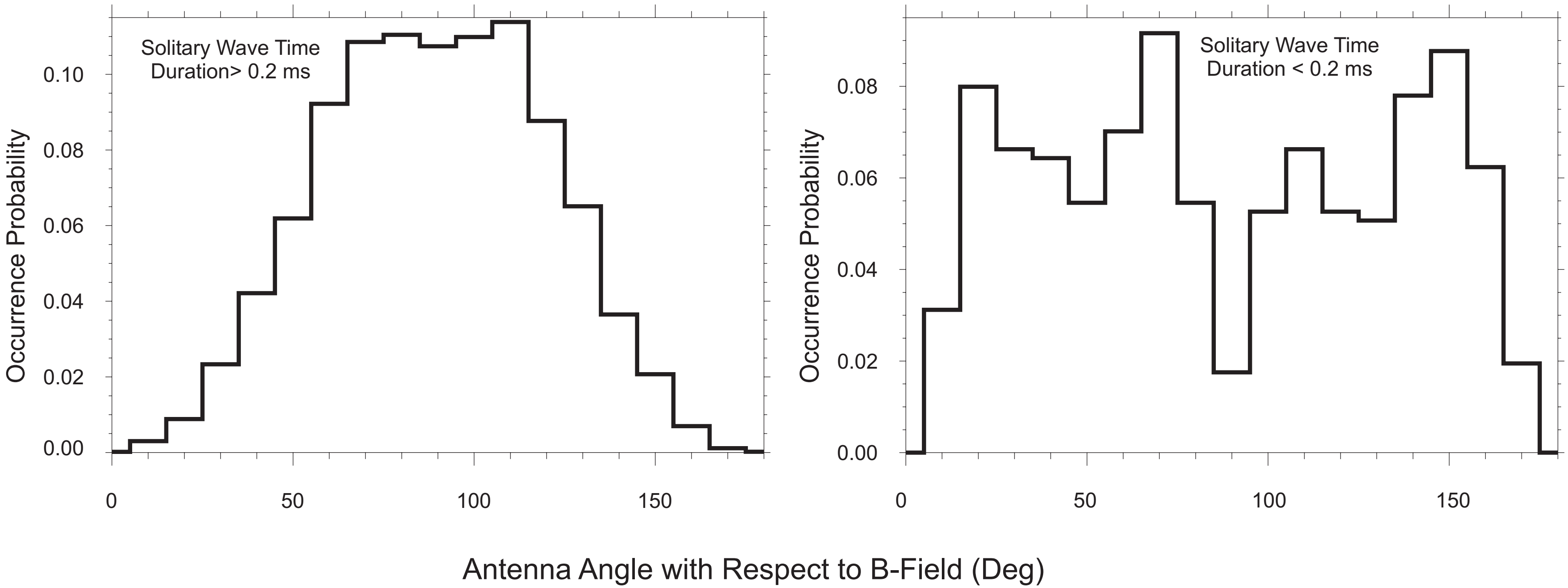


- Quasi-perpendicular, $\theta_{BN} \sim 73^o$
- β ~1.4
- $M_A \sim 8.2$
- Most ESW time durations > 1 ms; amplitude related to magnetic field strength



- Quasi-parallel, $\theta_{BN} \sim 33^o$
- β ~0.06
- $M_A \sim 2.8$
- Many ESW detected at all locations near the bow shock; amplitudes greatest on the ramp

SOLITARY WAVE OCCURRENCE AT THE BOW SHOCK



Solitary Wave Time Duration **> 0.2 ms**

- Angle occurrence greatest at 90º +/- 15º

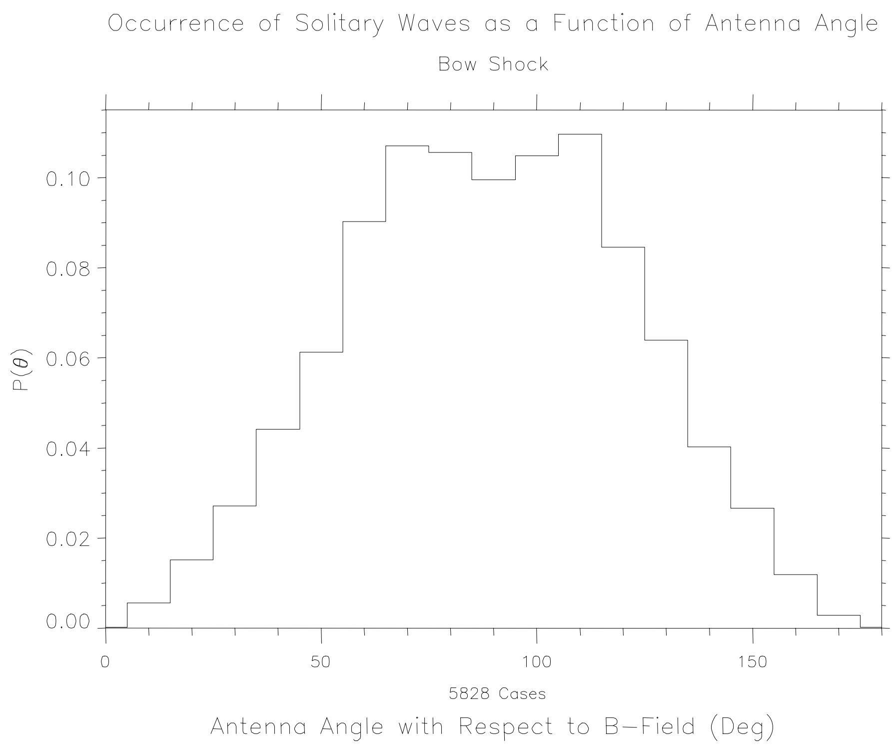
- Suggests that this major population does not propagate along the magnetic field and most likely related to ions.

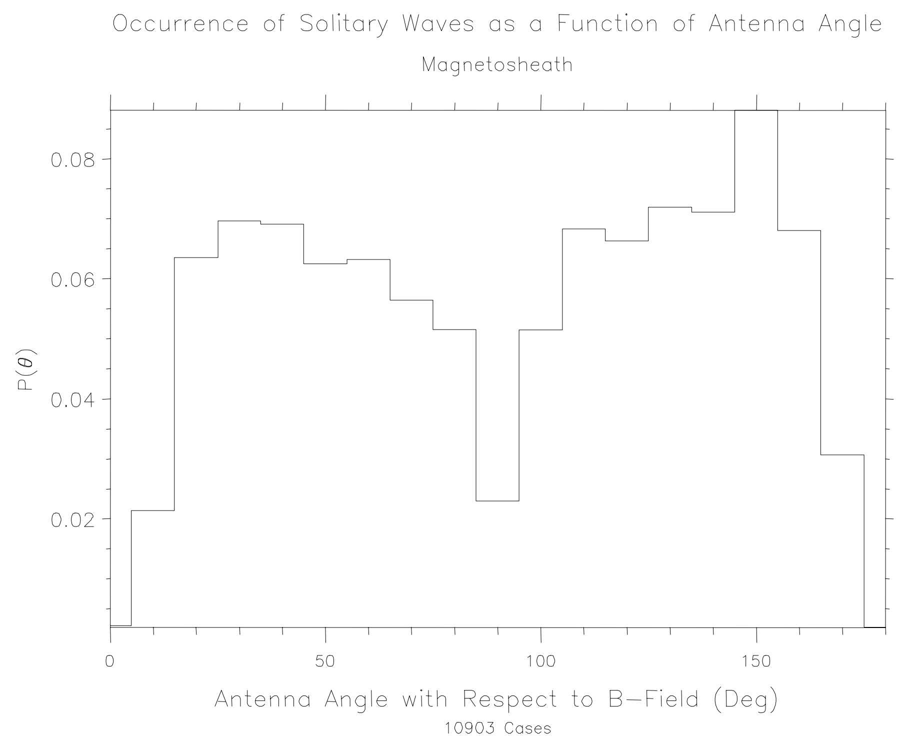
Solitary Wave Time Duration **< 0.2 ms**

- Nearly total absence of ESWs at 90º

- Suggests this minor population propagates along the magnetic field and most likely related to electrons

COMPARISON OF SOLITARY WAVE OCCURRENCE BY REGION





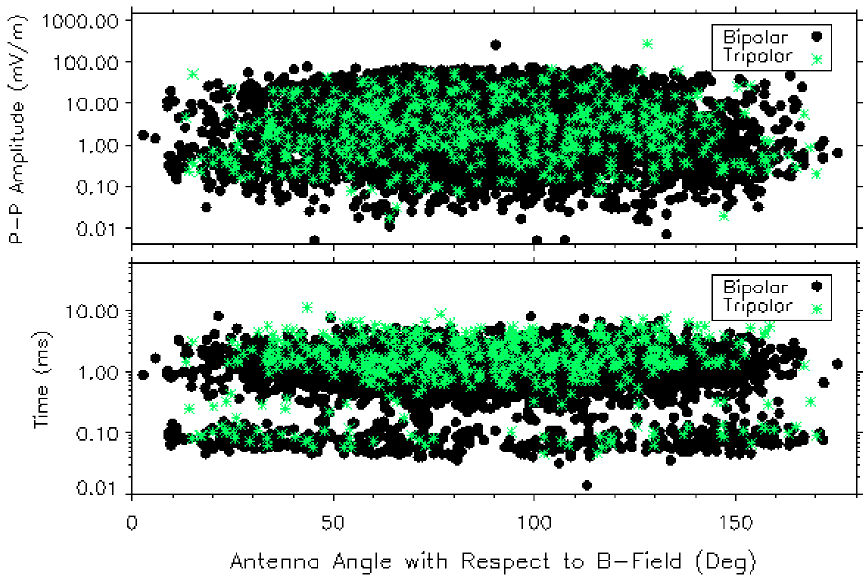
BOW SHOCK

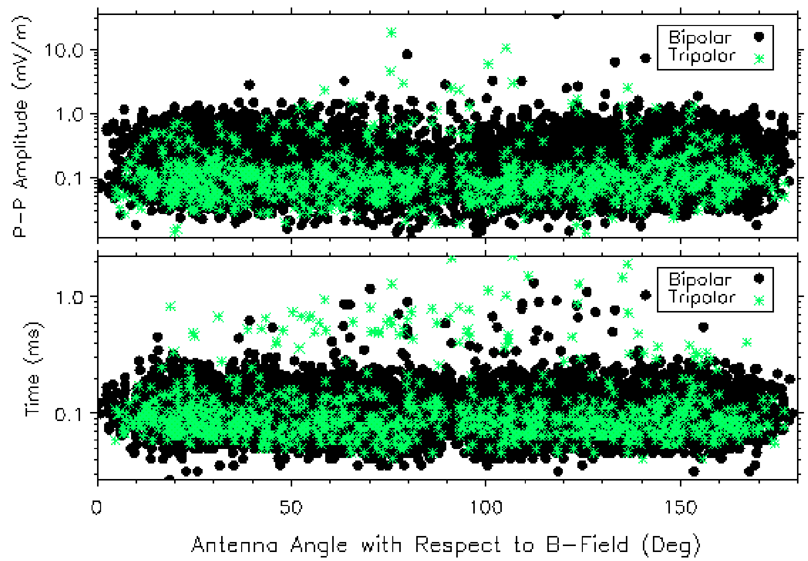
- Angle occurrence peaks around 90º
- Follows angle occurrence for all time periods, or sin(theta), irrespective of ESW occurrence

MAGNETOSHEATH

- Angle occurrence nearly equal at all angles except 90º
- Favors angles near 0º and 180º since all angles follow sin(theta), irrespective of ESW occurrence

COMPARISON OF SOLITARY WAVE CHARACTERISTICS BY REGION





BOW SHOCK

- Amplitudes as great as 100 mV/m P-P, WBD upper cutoff for most gain states
- **Two distinct populations:** 1) time duration < 0.2 ms (order of electron plasma period) AND not 90º, 2) time duration > 0.2 ms at almost all angles

MAGNETOSHEATH

- Amplitudes usually no greater than 1 mV/m P-P
- **One distinct population:** time duration < 0.2 ms (order of electron plasma period) AND not 90º

GENERATION MECHANISM

- Beam instabilities are likely in some of the regions sampled by Cluster; unfortunately, particle measurements are made at much lower time resolution than the waveform measurements and counter-streaming electron **beams** have not been observed simultaneously with ESWs in most cases.
  - Counter-streaming electrons, often not beamed, are observed during major ESW events in the magnetosheath and auroral zone; still under investigation for bow shock.
  - Still need to investigate the possibility of a beam instability driven by low-frequency, wave-accelerated bi-streaming electrons similar to that proposed by Lakhina et al. (NPG, 2004; Phys. Scripta, 2005) for the cusp turbulent boundary layer.
- Magnetic turbulence is almost always observed in regions where ESWs are present, but we have not yet begun to investigate ESW spontaneous generation out of turbulence.
- Electron acoustic instability is a possibility in the magnetosheath where we have confirmed the presence of hot and cold electrons in the presence of an ion beam; still needs investigation for the bow shock.

SUMMARY

- Electrostatic solitary waves (solitary structures) are observed at many locations in Cluster's orbit, primarily regions of turbulent or mixing plasmas.
- These ESWs have time durations that vary from ~ 20 microseconds to a few milliseconds (shortest in magnetosheath), P-P amplitudes of 0.01 to 100 mV/m, and follow a general trend of increasing ESW amplitude with increasing magnetic field strength consistent with BGK modes.
- If BGK mode, the bipolar ESWs would imply trapping of electrons or ions, whereas the tripolar ESWs would imply trapping of both.
- ESWs have been observed in a limited number of cases to propagate from one spacecraft to another over distances of a few 10s of kms.
- Magnetosheath ESWs are probably locally produced within the magnetosheath as opposed to some fixed location such as the bow shock; however, upstream and bow shock parameters might influence the nature and occurrence of the ESWs by affecting downstream parameters.
- There are two distinct types of ESWs at the bow shock, i.e., those with time durations less than 0.2 ms and those greater than 0.2 ms.
- The ESW generation mechanisms under consideration are beam instabilities, acoustic instabilities and spontaneous generation out of turbulence.