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SHEDDING NEW LIGHT ON SOLITARY WAVES OBSERVED IN SPACE

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PRIOR TO 1985

- Broadband Electrostatic Noise (BEN) was first reported by Scarf et al. (1974) and Gurnett et al. (1976) using observations made 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 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. (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-rendering of solitary waves.

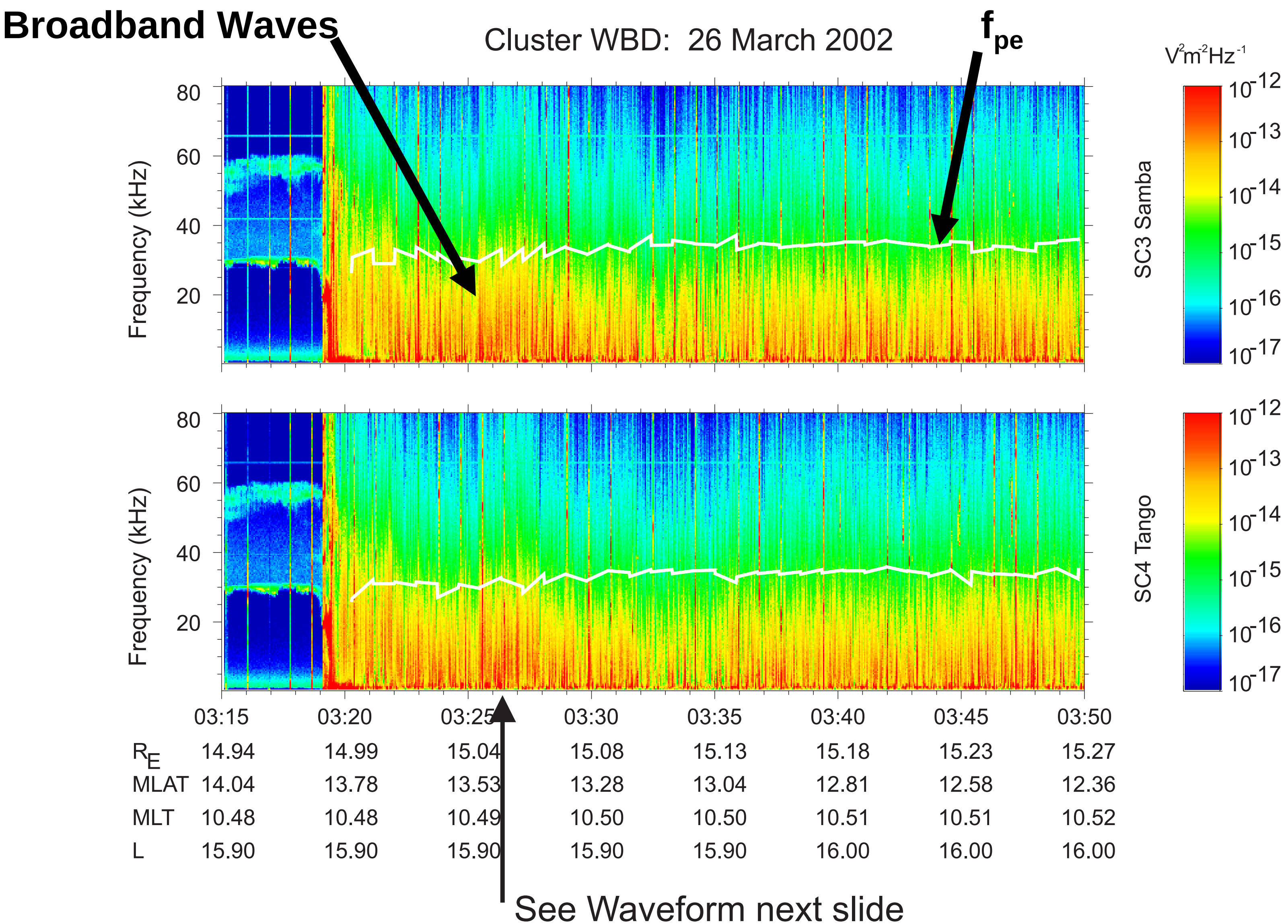
AFTER 1985

- 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.
- Matsumoto et al. (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 (one positive peak and one negative peak), have time durations on the order of 2-5 ms and peak-to-peak amplitudes of a few tenths mV/m.
- The observational breakthroughs came primarily with the sophistication of waveform receivers with high time resolution and having the waveform data available in digital form.

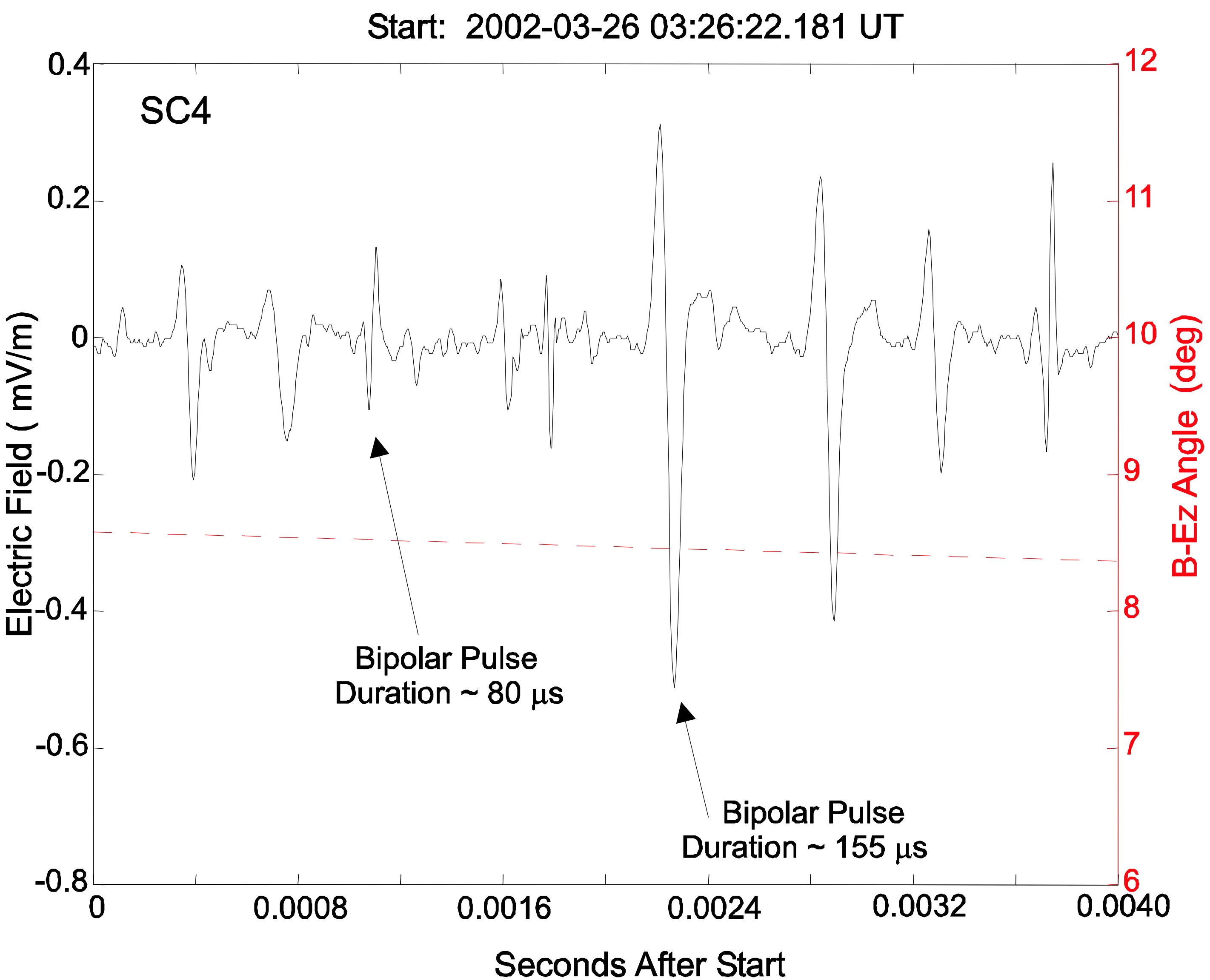
AFTER 1985 (Continued)

- The solitary waves reported to date have often been interpreted as holes in electron or ion phase space (potential structures) that move along magnetic field lines and arise out of beam instabilities (so-called Bernstein-Greene-Kruskal, or BGK, mode).
- For the auroral acceleration region, they have in one case been identified as electron acoustic solitons growing out of the electron acoustic instability.
- Some of the three-peaked solitary waves, currently referred to as tripolar pulses, have been interpreted as weak double layers in the solar wind and along auroral field lines.
- 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.

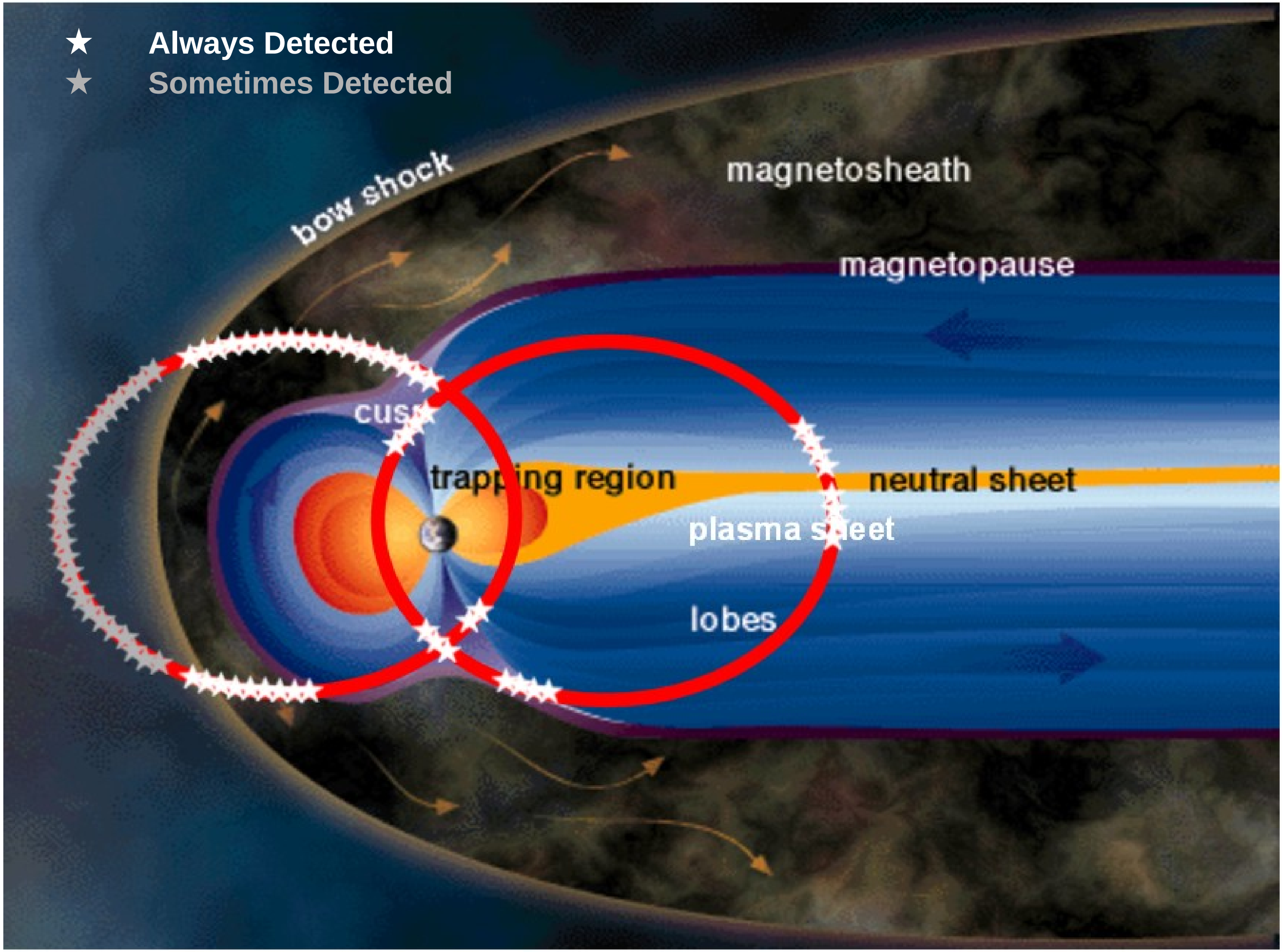
Quasi-perpendicular Bow Shock Crossing and Magnetosheath



Magnetosheath Solitary Waves

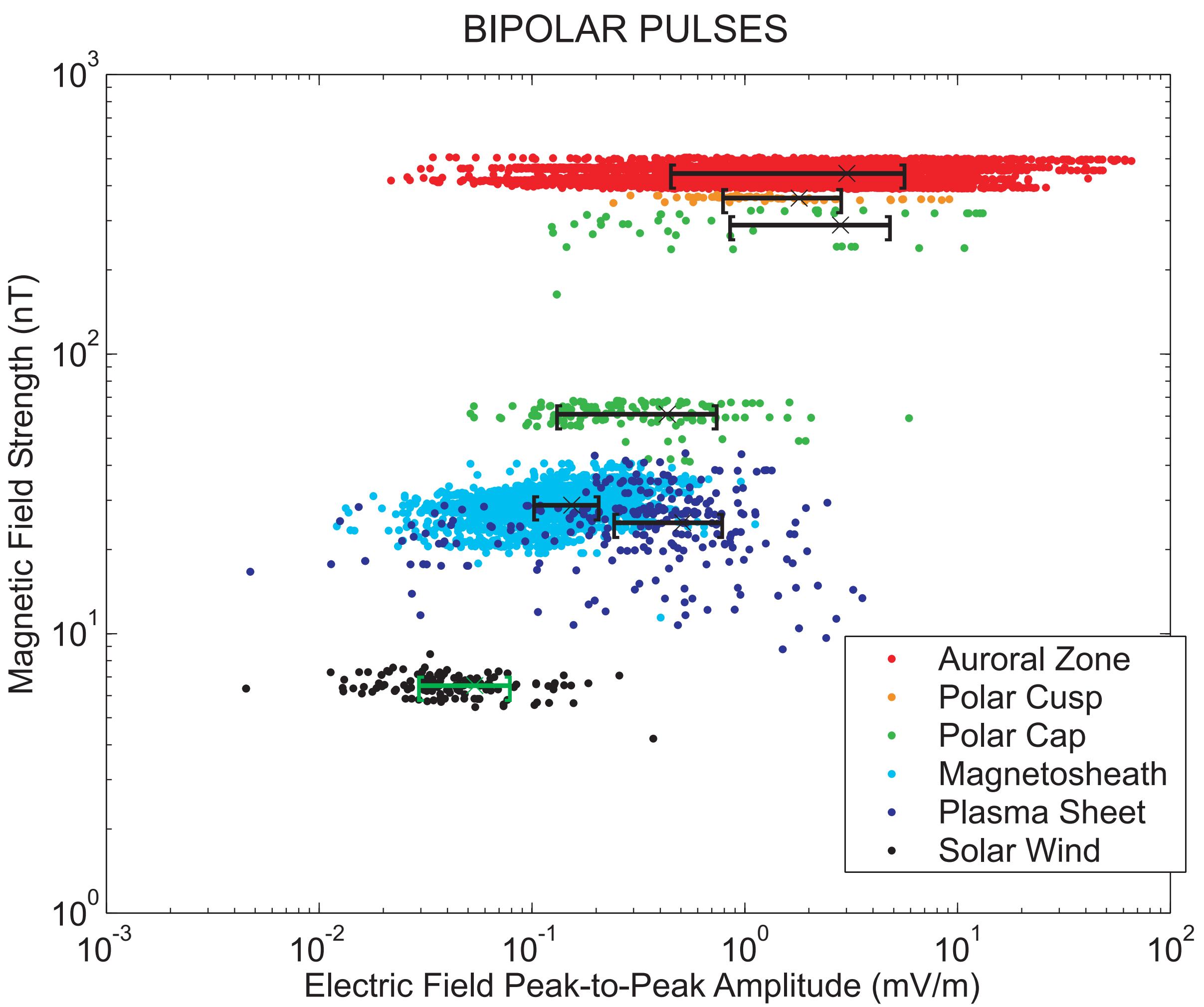


LOCATION OF SOLITARY WAVE DETECTIONS IN CLUSTER'S ORBIT



ELECTROSTATIC SOLITARY WAVE SURVEY

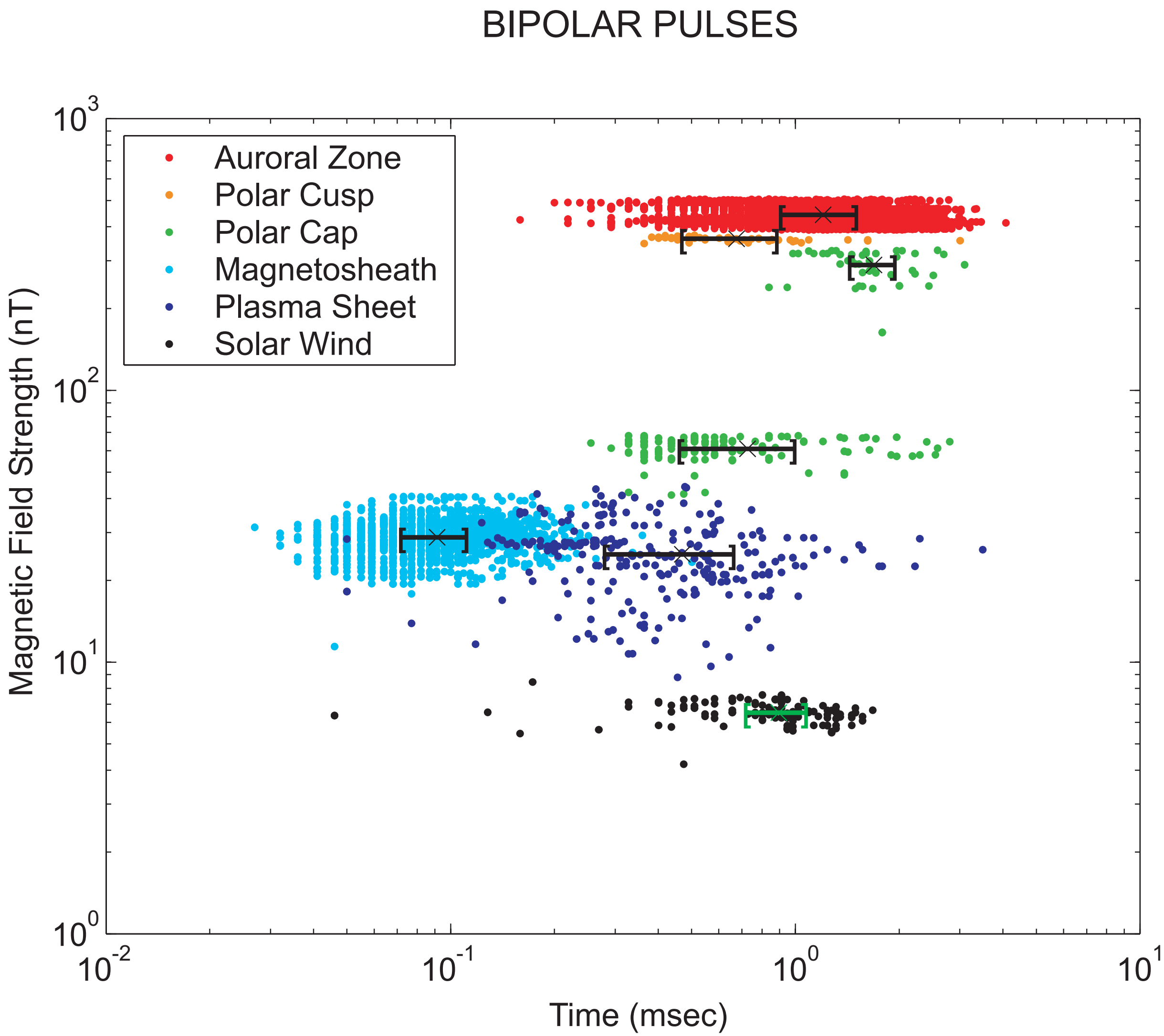
- ESWs cover 4 orders in amplitude over 2 orders of magnetic field strength
- General trend for ESW amplitude to increase with magnetic field strength, consistent with stability requirements of the BGK mode in finite magnetic fields.



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

ELECTROSTATIC SOLITARY WAVE SURVEY

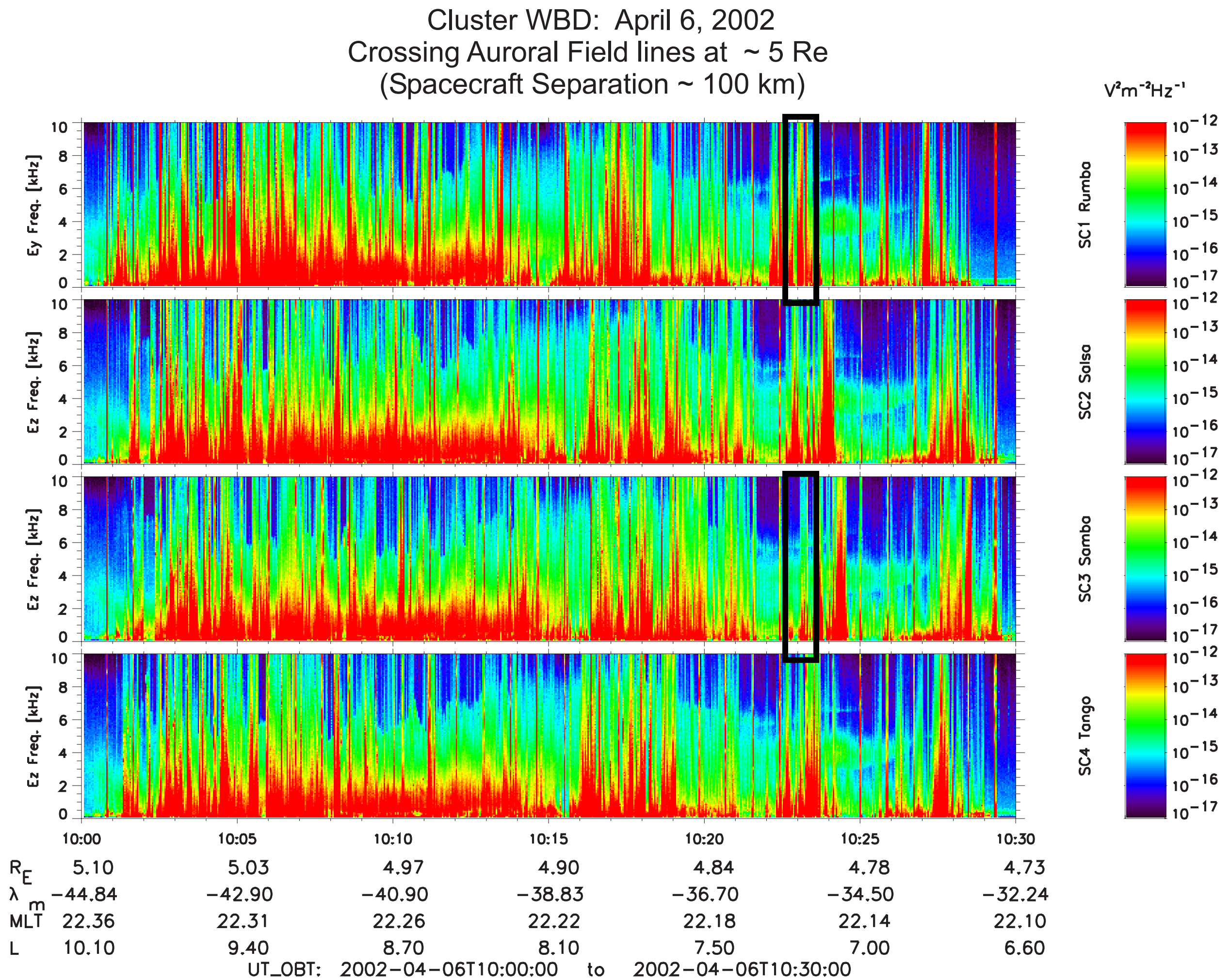
- ESWs COVER 2.5 orders magnitude in time duration over 2 orders of |B|.
- No Trend EXCEPT magnetosheath ESW appear to be of different class.

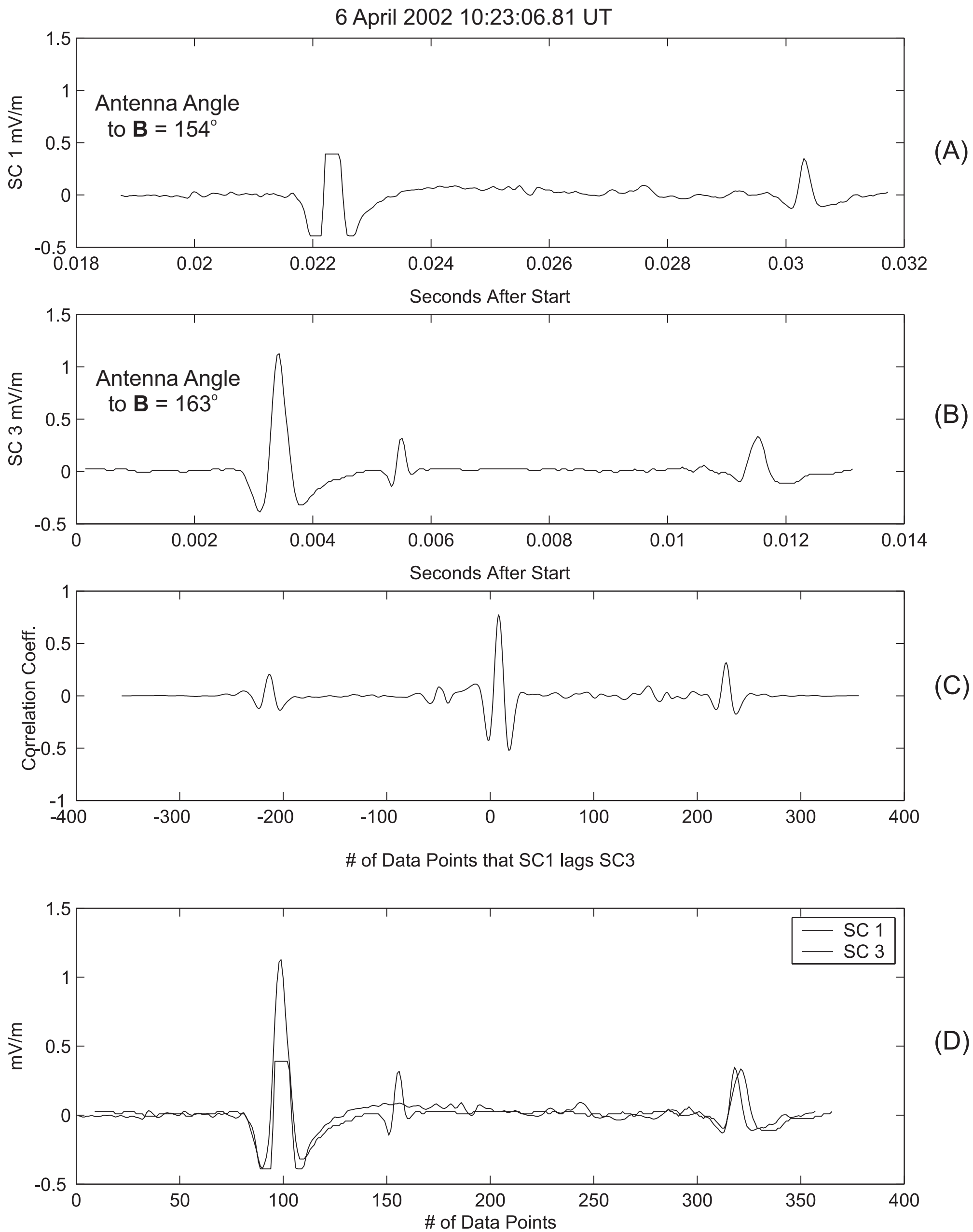


[From Pickett et al., Ann. Geophys., 2004]

AURORAL ZONE: ESW PROPAGATION STUDY

- Cross correlation was carried out for the waveforms contained within the boxed areas of SC1 and SC3.



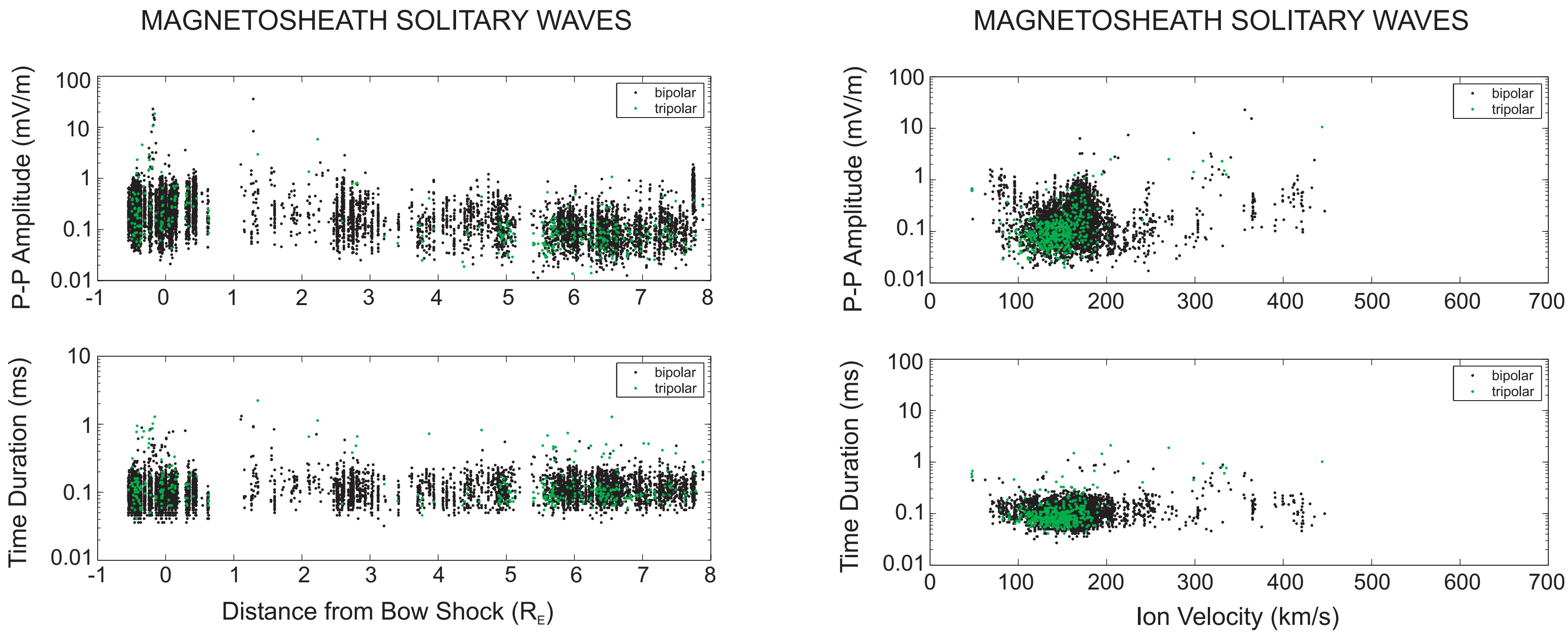


[From Pickett et al., NPG, 2004a]

AUORAL ZONE: ESW PROPAGATION STUDY

- Tripolar pulse ~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)
- SC1 and SC3 13 ms waveforms plotted on top of each other using 10 lags
- 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



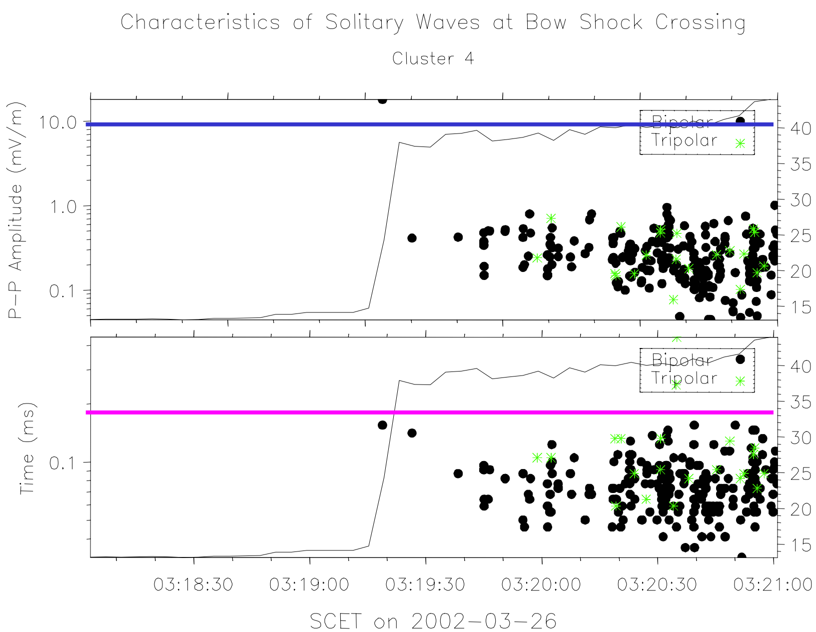
<u>Distance from Bow Shock</u>

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

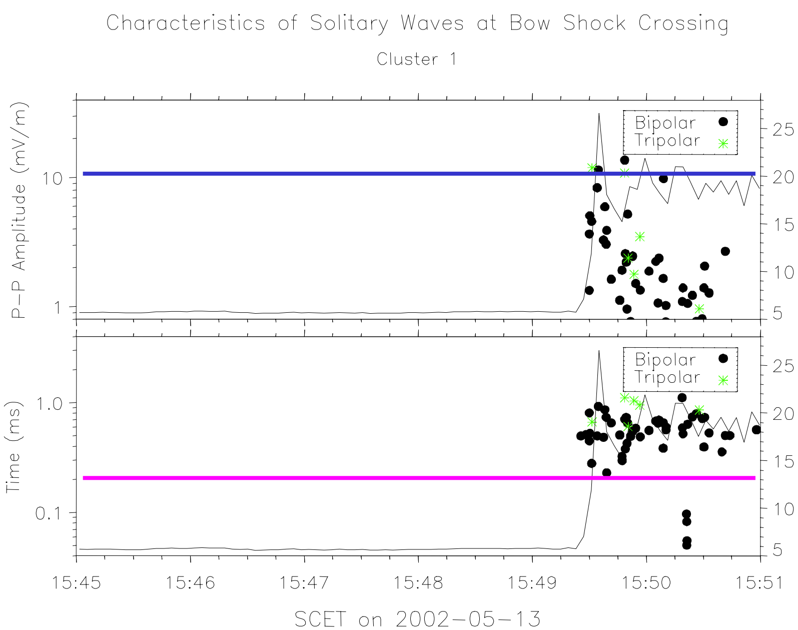
<u>Dependence on Ion Velocity</u>

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

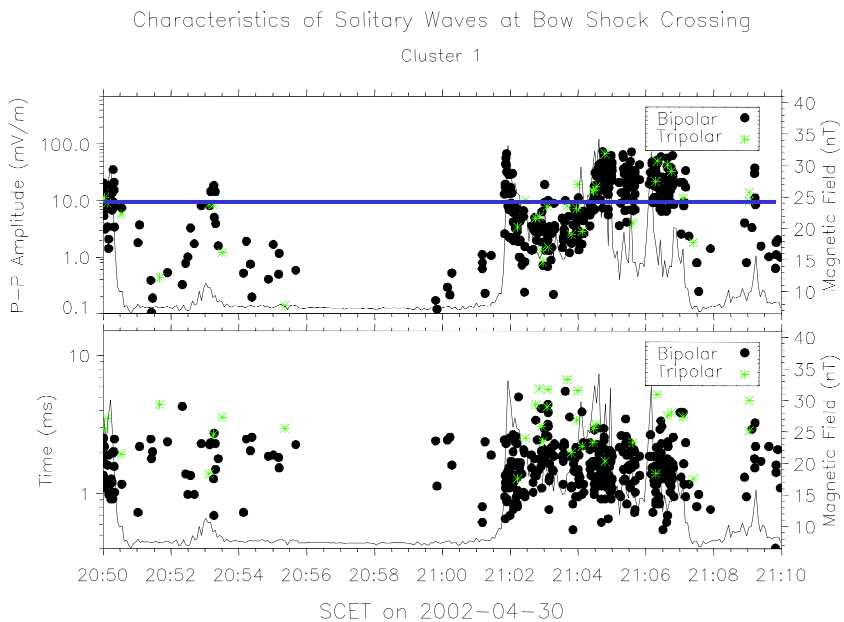
[From Pickett et al., NPG, 2004b]



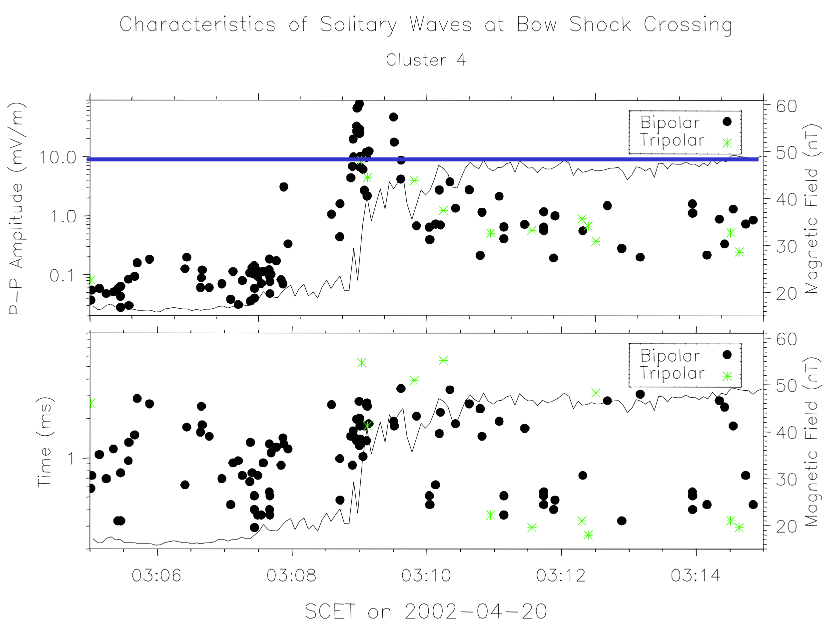
- Quasi-perpendicular, $\theta_{BN} \sim 85^{o}$
- $\beta \sim 0.29$
- $M_A \sim 6.4$
- Almost total absence of ESWs in transition region, as well as upstream; numerous downstream but of very short duration



- Quasi-perpendicular, $\theta_{BN} \sim 52^{o}$
- $\beta \sim 2.4$
- $M_A \sim 13.5$
- Nearly an absence of ESWs upstream, but longer time duration SWs detected in transition region and downstream

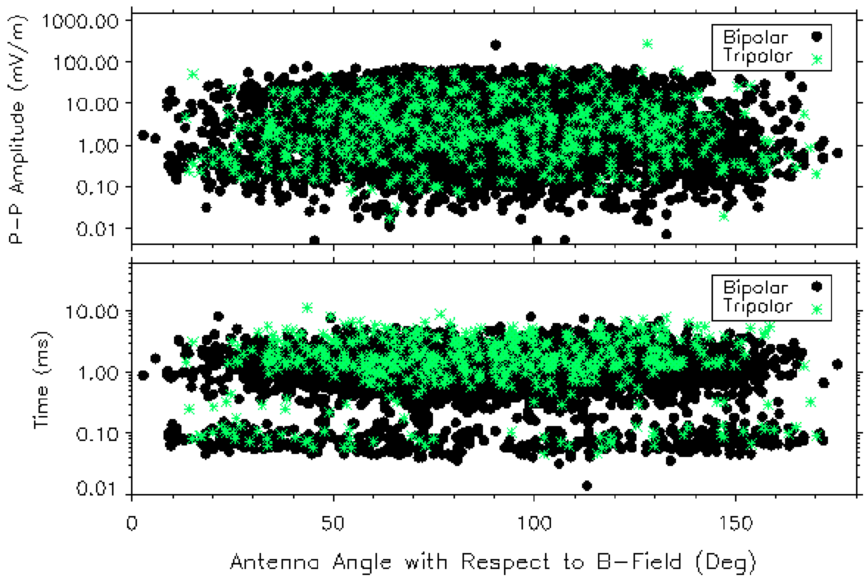


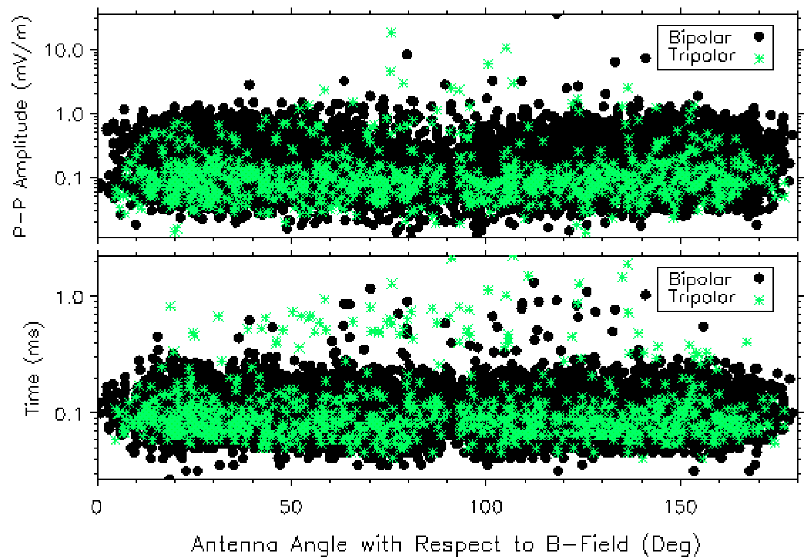
- Quasi-perpendicular, $\theta_{BN} \sim 73^o$
- $\beta \sim 1.4$
- $M_A \sim 8.2$
- Most ESW time durations > 1 ms; amplitude related to magnetic field strength



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

Comparison of Solitary Wave Characteristics by Region





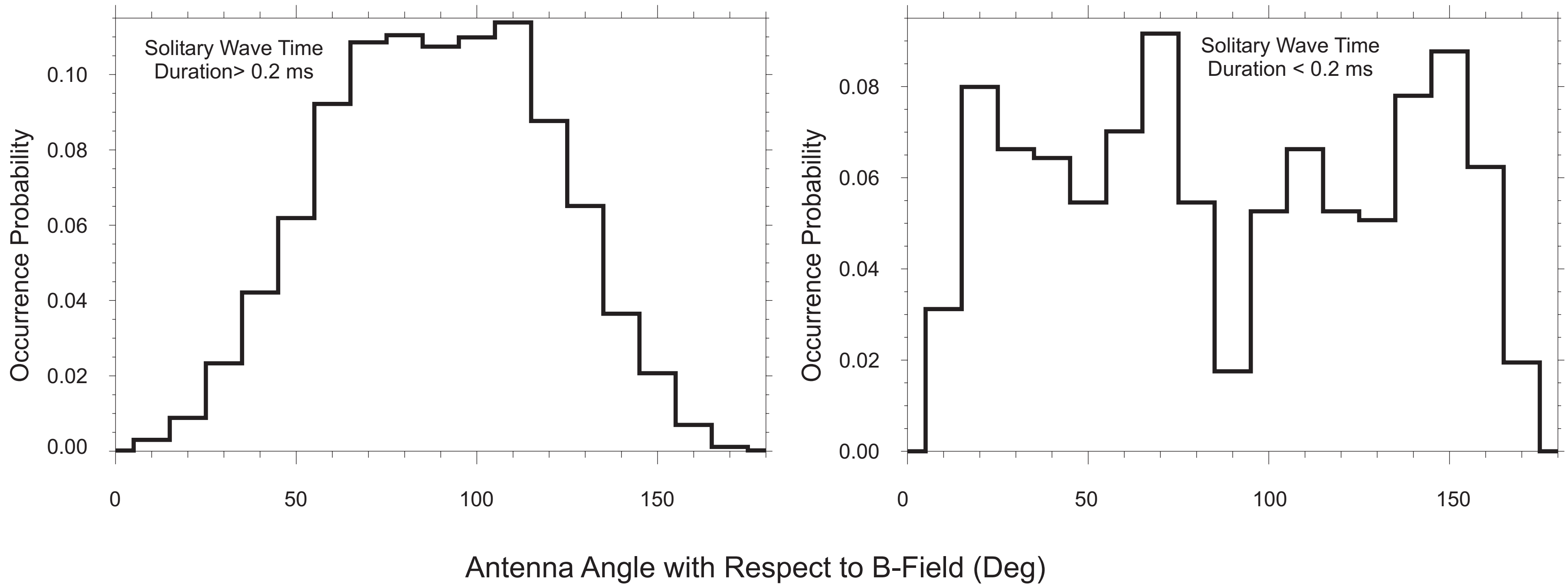
BOW SHOCK

- 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) at angles other than 90º and 2) time duration > 0.2 ms at all angles with peak at 90º

MAGNETOSHEATH

- Amplitudes usually no greater than 1 mV/m P-P
- **One distinct population:** time duration < 0.2 ms at angles other than 90º, order of electron plasma period

SOLITARY WAVE OCCURRENCE AT THE BOW SHOCK



<u>Solitary Wave Time Duration **> 0.2 ms**</u>

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

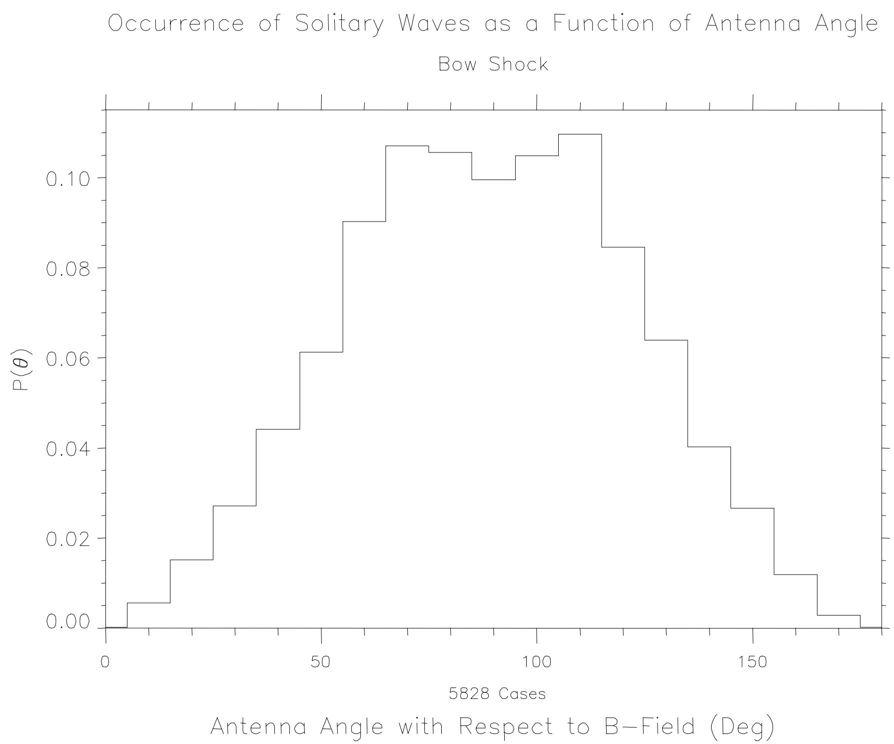
- Suggests that this major population does not propagate along the magnetic field and most likely related to ions.

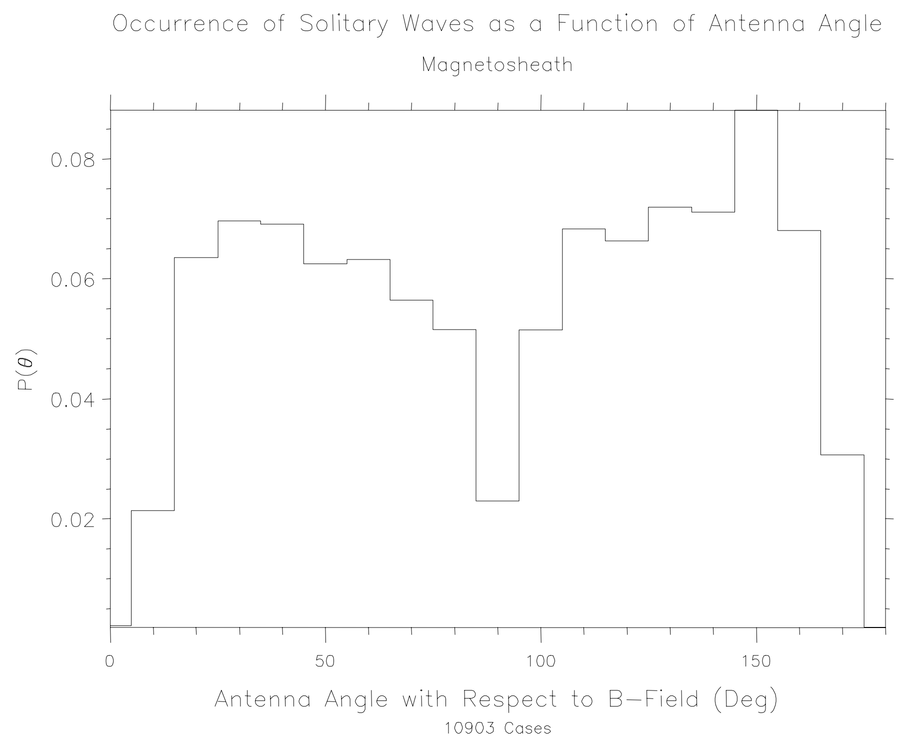
<u>Solitary Wave Time Duration **< 0.2 ms**</u>

- Nearly total absence of SWs at 90º

- Suggests this minor population propagates along the magnetic field and may be related to electrons

Comparison of Solitary Wave Occurrence by Region





BOW SHOCK

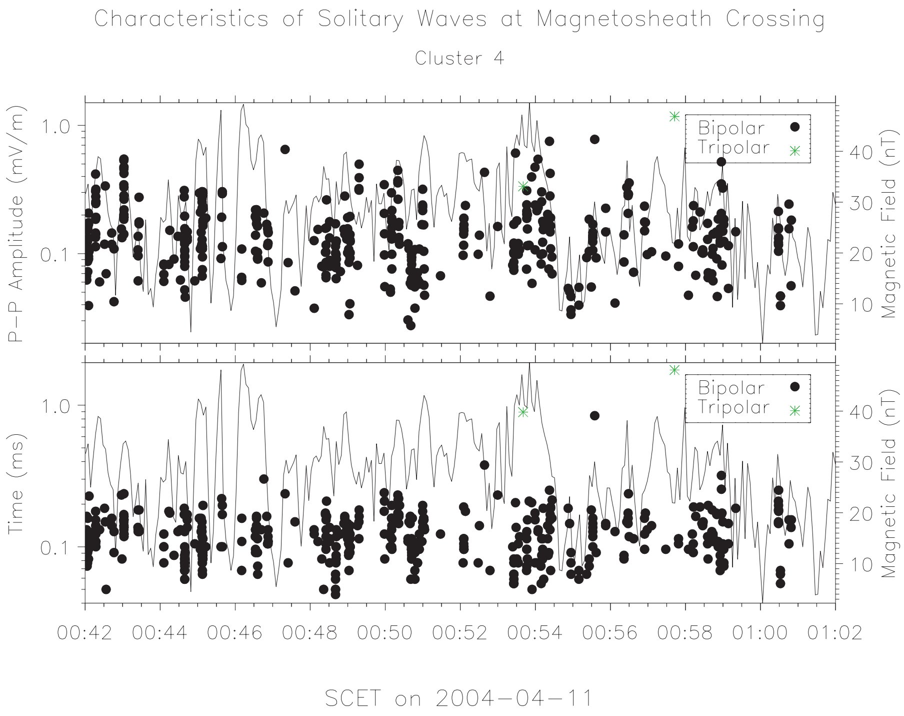
- Angle occurrence peaks around 90º
- Suggests that most SWs do not propagate along the magnetic field

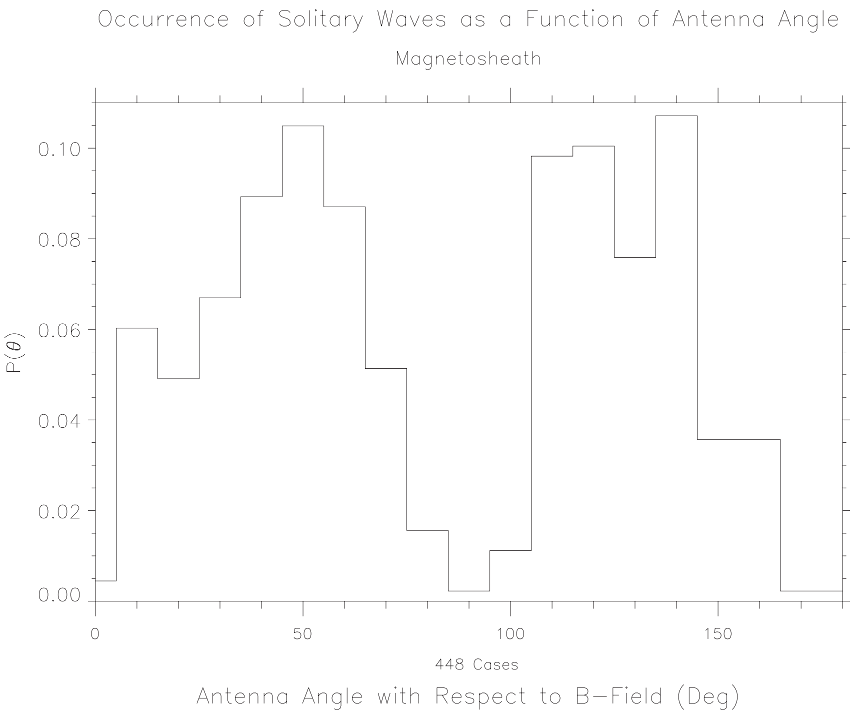
MAGNETOSHEATH

- Angle occurrence nearly equal at all angles except 90º
- Suggests that structures propagate along the magnetic field

MAGNETOSHEATH MUTUAL IMPEDANCE TEST

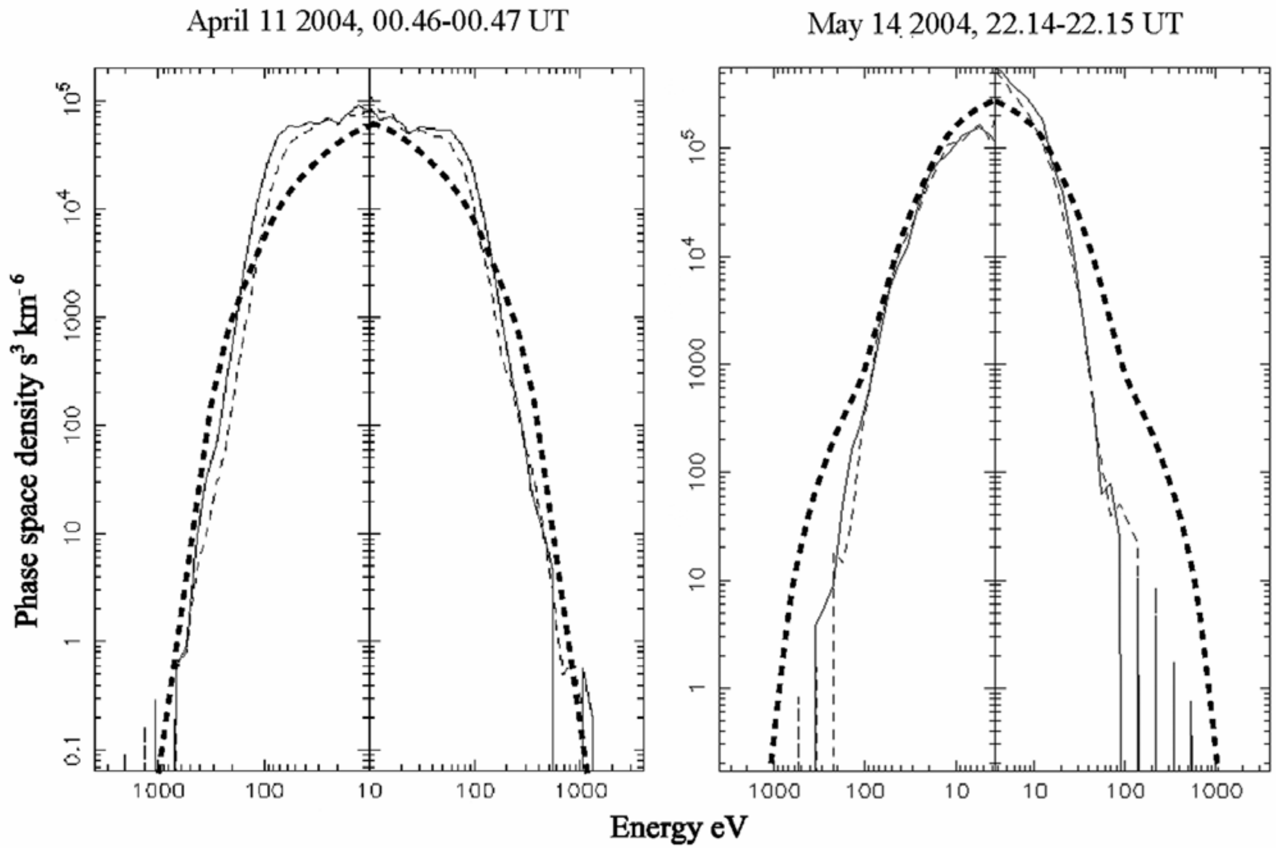
- ESW have amplitudes less than 1 mV/m and time durations less than 0.3 ms.
- Virtually no ESW observed at 90 degrees





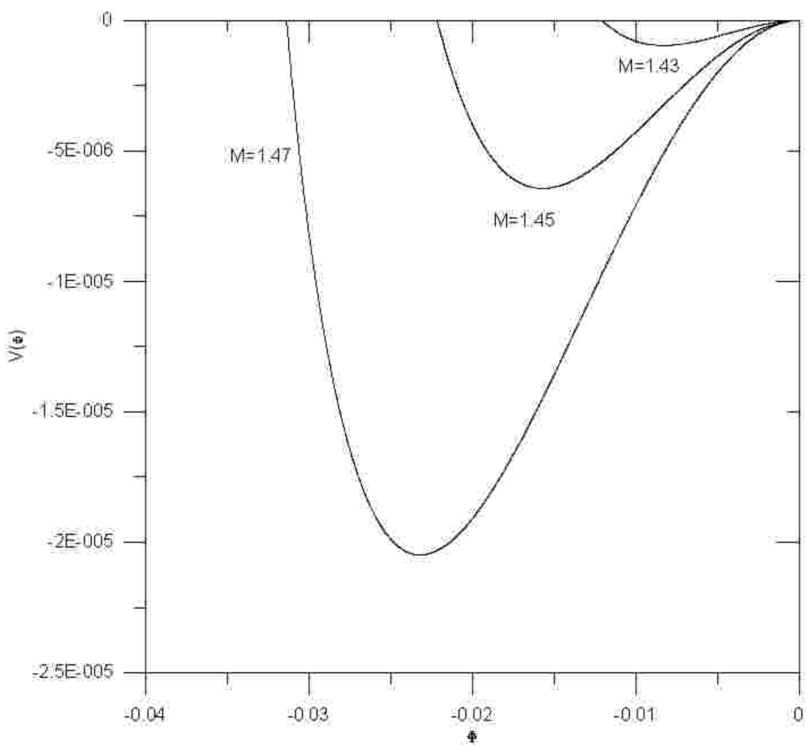
MAGNETOSEHATH MUTUAL IMPEDANCE TEST

- Using the WBD and Whisper data from the Magnetosheath MI test (left panel) and modeling of Cluster's electric antennas, Béghin et al. (Radio Science, 2005) have determined that n_c = 16 cm^{-3}, T_c ~ 39 eV, n_h = 8 cm^{-3}, T_h ~ 79 eV assuming modified Debye length of 11m
- Comparison of analytic model (bold dashed line) to PEACE data (solid and thin lines at 1-minute intervals) of the distribution function shows good agreement.

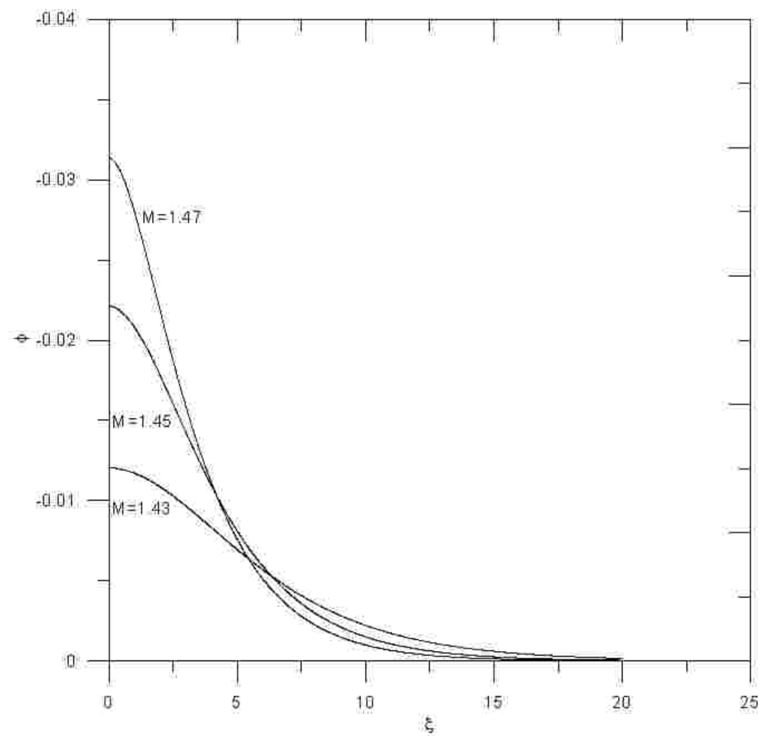


MAGNETOSHEATH MUTUAL IMPEDANCE TEST

- Electron Acoustic Instability Simulations carried out with data obtained from Beghin et al. (2005)
- Only negative potential structures are observed; positive potential structures are possible only in the presence of electron beams, in addition to cold and hot electrons (still under investigation).
- Typical normalized soliton potential amplitudes are 0.01-0.03 and typical soliton widths are 1-5 hot electron Debye lengths.



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



Normalized Potential Amplitude vs. Size

GENERATION MECHANISM

- Hard to determine since particle measurements are made at much lower time resolution than the waveform measurements.
- Three likely possibilities:
  - Beam instability such as the counterstreaming instability, which has possibilities in the magnetosheath and auroral zone since counterstreaming electrons are observed during major ESW events. These would be BGK mode.
  - Spontaneous generation out of turbulence since ESW are observed most abundantly in turbulent regions. These too would be BGK mode.
  - Acoustic mode (electron or ion), which in the case of electron acoustic mode would require a cold and hot population as well as an ion population, which is possible in the magnetosheath and solar wind. These would be fluid solitons.
- We need to carry out more studies using particle data in order to see if we can get around the time resolution problem with statistics; more importantly, we need simulations to be run of various instabilities.

SUMMARY

- Electrostatic solitary waves (solitary structures) are observed at many locations in Cluster's orbit, primarily regions of turbulent or mixing plasmas.
- These ESW 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 amplitude with increasing magnetic field strength consistent with BGK modes
- If BGK mode, the bipolar ESW would imply trapping of one of electrons or ions, whereas the tripolar ESW would imply trapping of both.

FUTURE WORK

- Compile a larger statistical base of bow shock and magnetosheath crossings using the Cluster WBD 77 kHz bandwidth filter in conjunction with EFW snapshots and do a more systematic cross spacecraft correlation study.
- From an experimental perspective explore the various generation mechanisms for all regions where ESW are observed using observed particle and field inputs to models (in collaboration with various theory groups).

Acknowledgments:

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