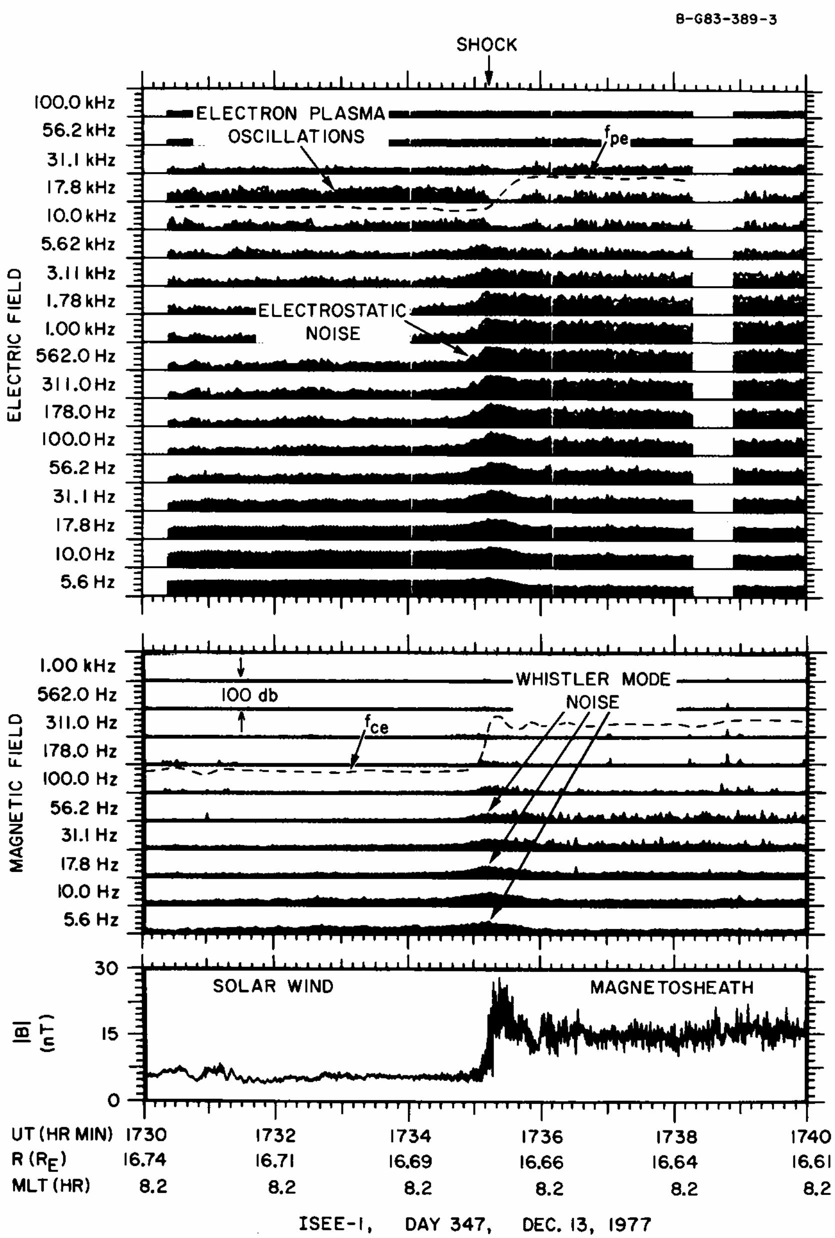
University of Iowa

SOLITARY WAVES OBSERVED BY THE CLUSTER SPACECRAFT AT AND NEAR THE EARTH'S BOW SHOCK

J. S. Pickett, L.-J. Chen, S. N. Walker, R. Behlke, J. Williams, D. A. Gurnett, C. A. Cattell, M. L. Goldstein, R. Kessell, B. T. Tsurutani, and G. Lakhina

IGPP 4th Annual International Astrophysics Conference
on the Physics of Collisionless Shocks
Palm Springs, CA, USA
26 February – 03 March 2005



[From D. Gurnett, *Collisionless Shocks in the Heliosphere*, 1985]

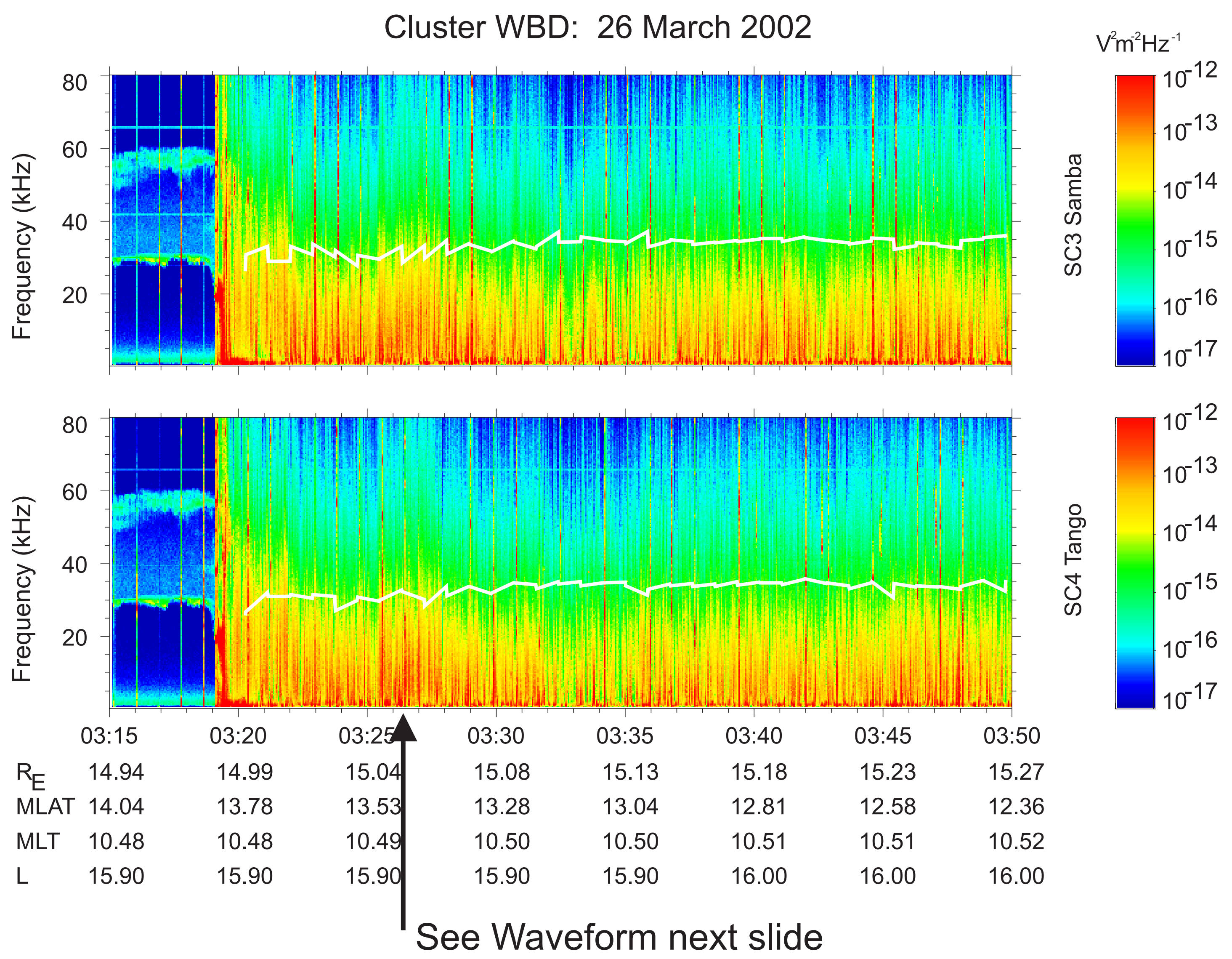
PRIOR TO 1997

- Earth's bow shock was explored through wave observations made by sweep frequency receivers and multi-channel analyzers (waveforms not available) or analog waveform receivers (difficult to extract waveforms for analysis).
- Various electromagnetic and electrostatic waves are observed upstream, in the shock transition region and downstream.
- Determining the mode of the electrostatic waves was difficult due to their broad, often featureless frequency extent.
- It was recognized that high time resolution digital waveforms were required to untangle the the various modes.

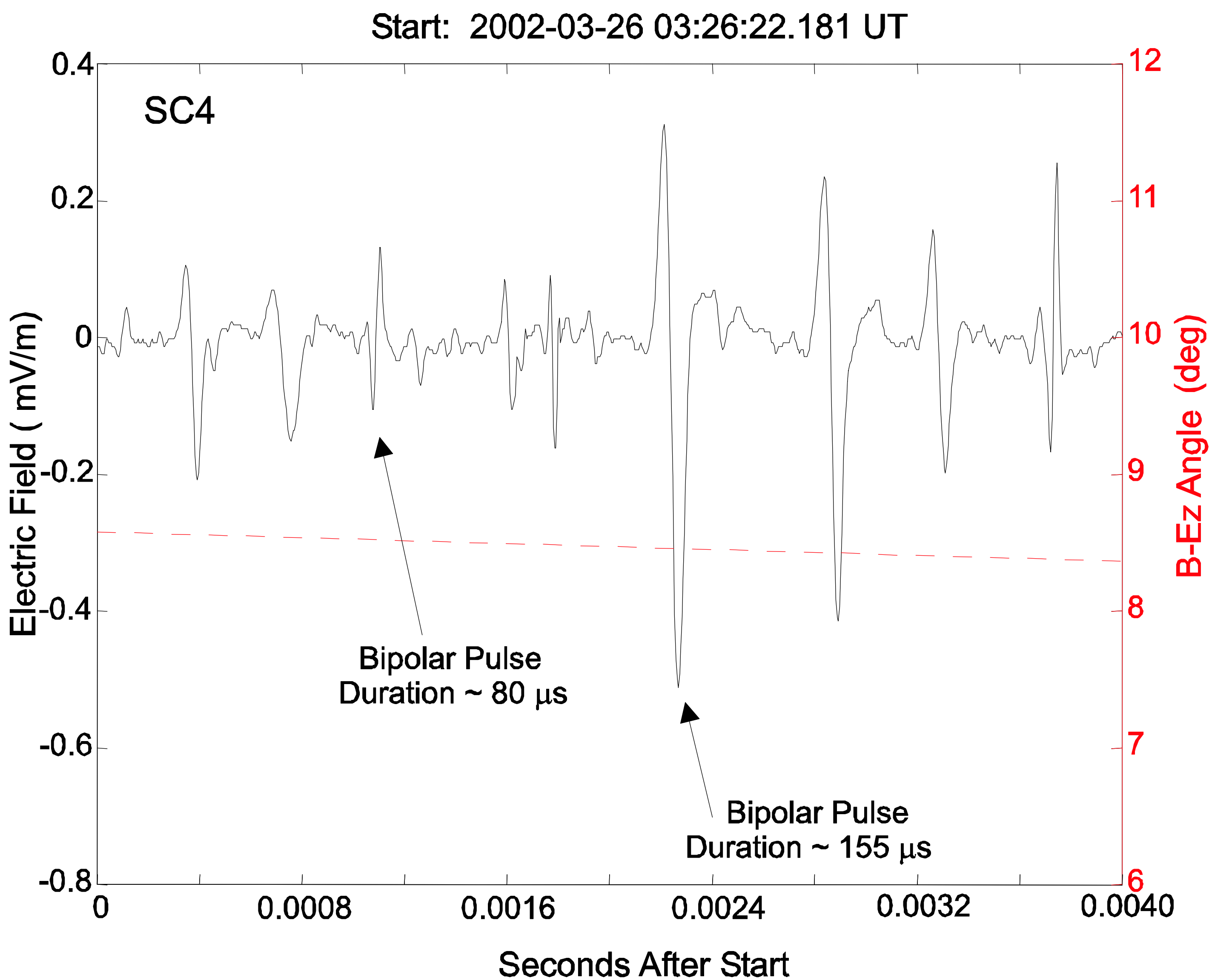
AFTER 1997

- Matsumoto et al. (Adv. Space Res., 1997)
  - 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 1-2 ms and peak-to-peak amplitudes of 60 mV/m in the transition region and 20 mV/m just downstream.
- Bale et al. (Geophys. Res. Lett., 1998)
  - WINDS WAVES TDS (120,000 samples/s, 17 ms snapshots) observes ESWs with time durations of ~ 0.1 ms and amplitudes > 200 mV/m in the shock transition region
  - Suggested that these ESW were Bernstein-Greene-Kruskal (BGK) modes in the form of electron phase space holes.
- On to Cluster …

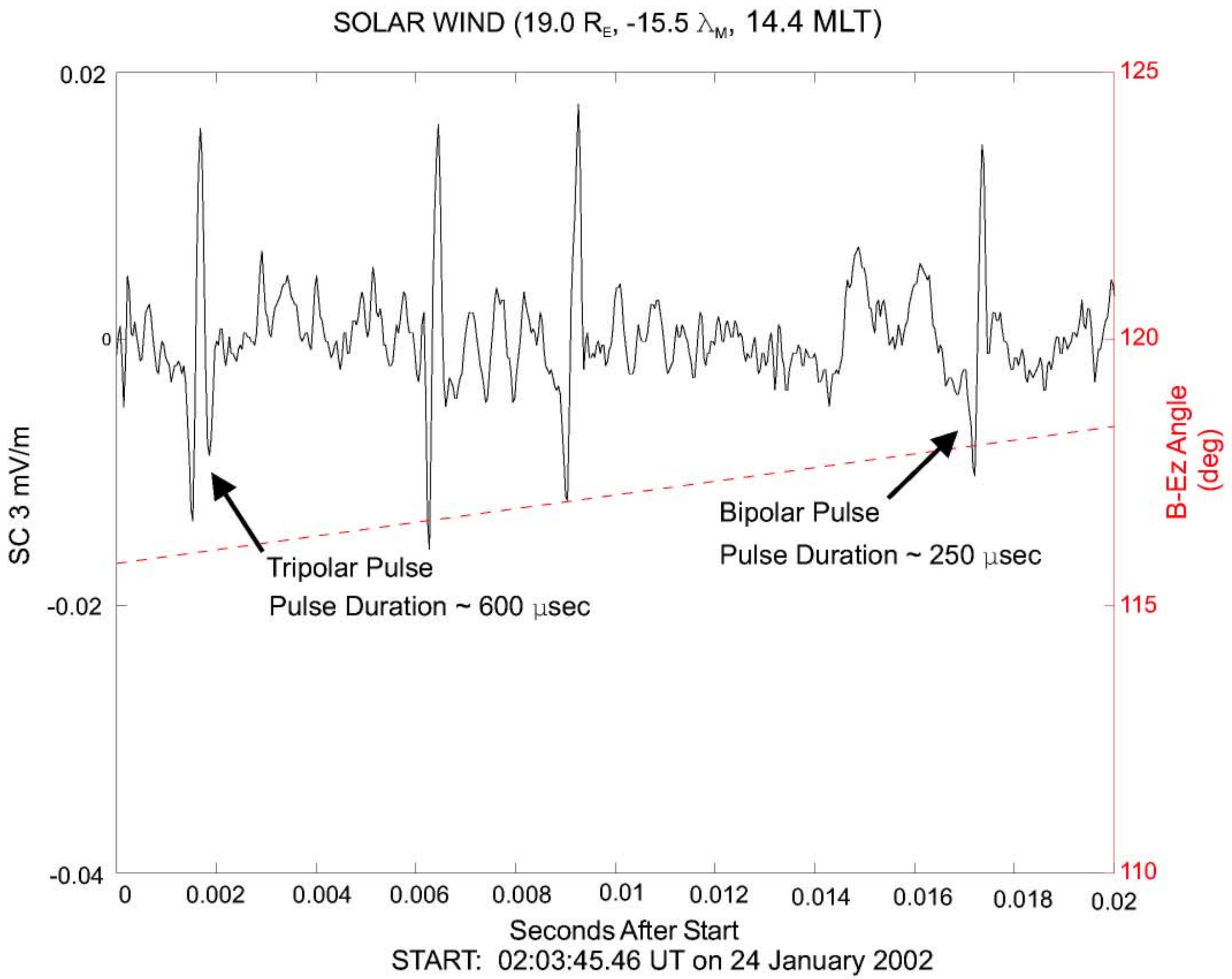
Quasi-perpendicular Bow Shock Crossing and Magnetosheath



Magnetosheath Solitary Waves

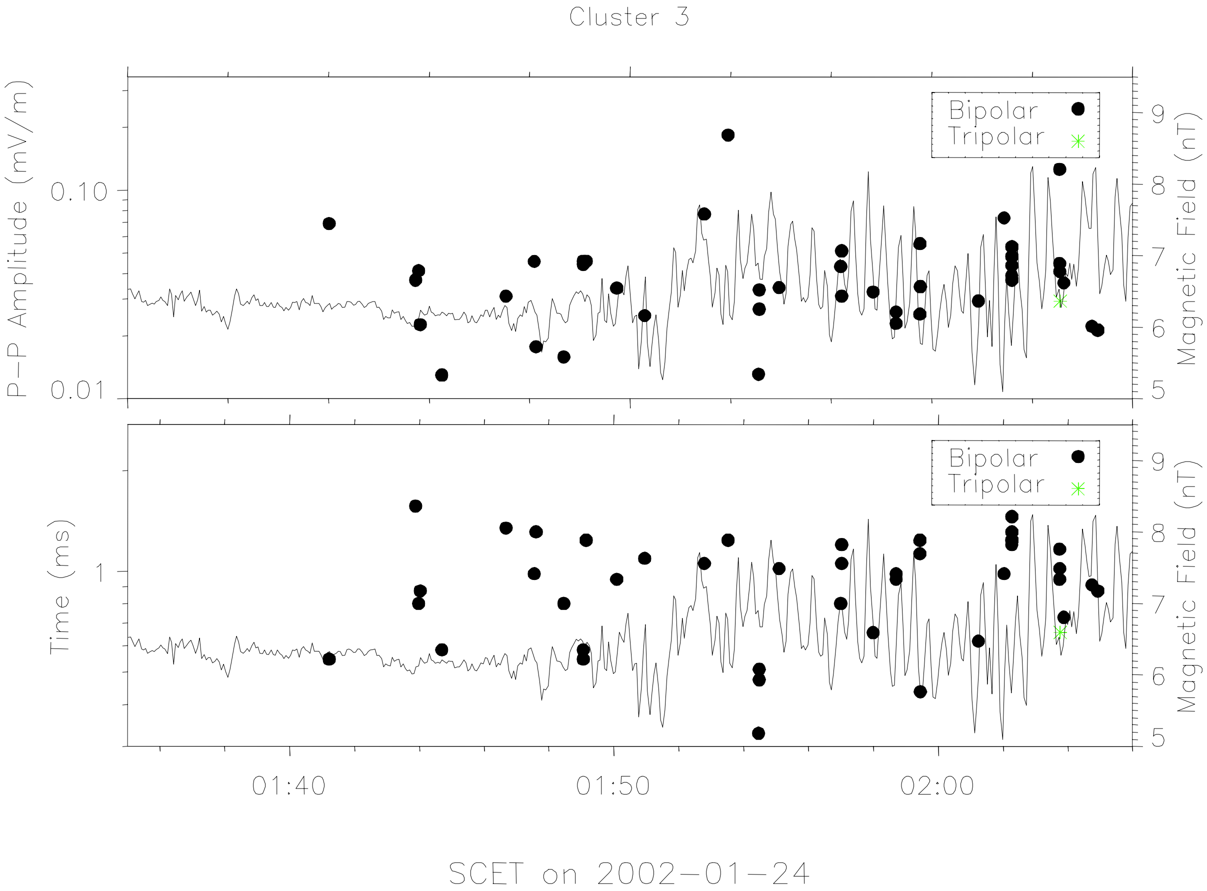


Solar Wind Solitary Waves

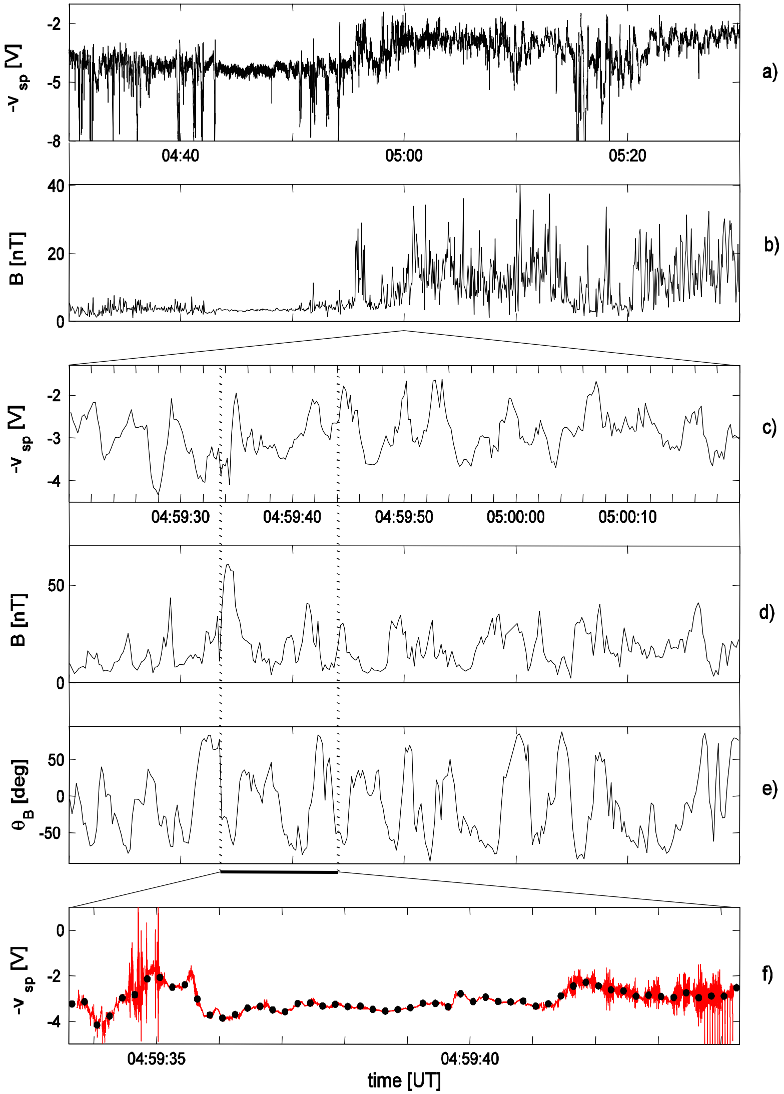


UPSTREAM – SOLAR WIND

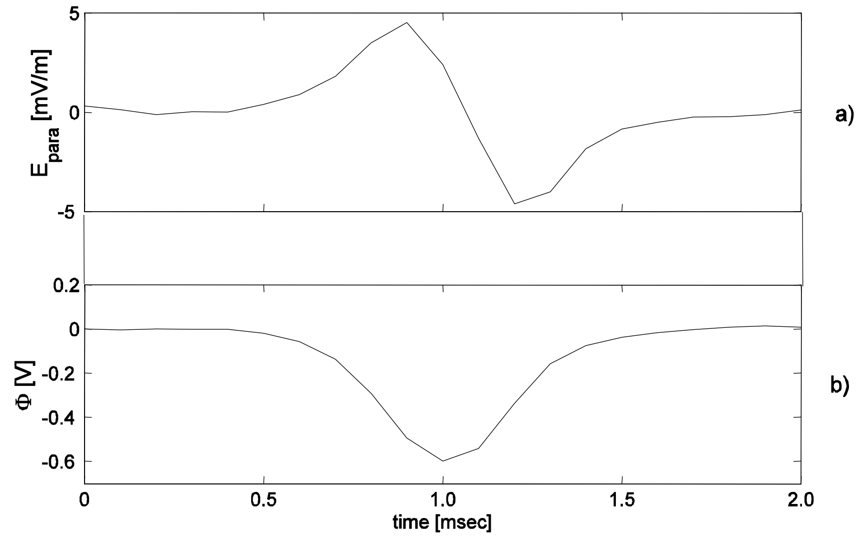
- ESWs typically a few tenths to 1 ms in duration and 0.01 to 0.1 mV/m in amplitude, but need to look at more cases with a wider bandwidth.
- ESWs are most often observed during periods of magnetic fluctuations.



SOLITARY WAVES IN SLAMS, EFW DATA [From Behlke et al., GRL, 2004]



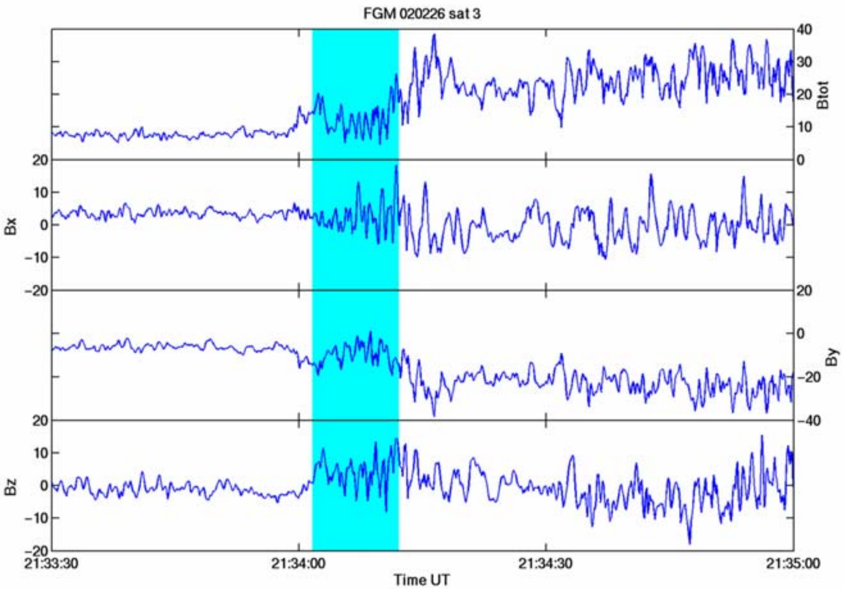
February 3, 2002

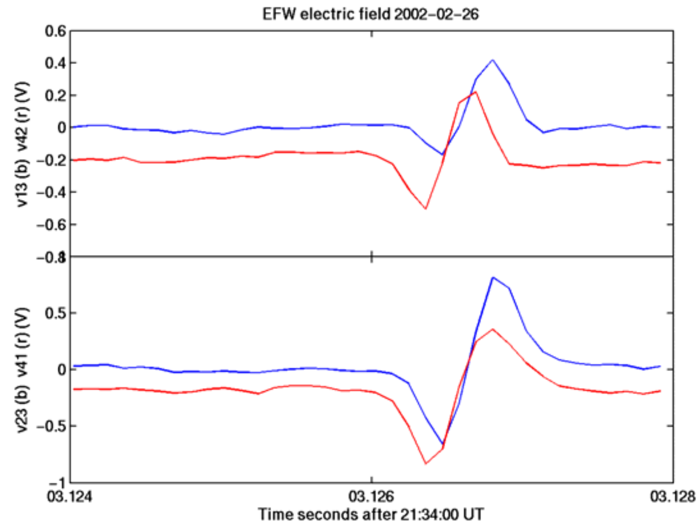


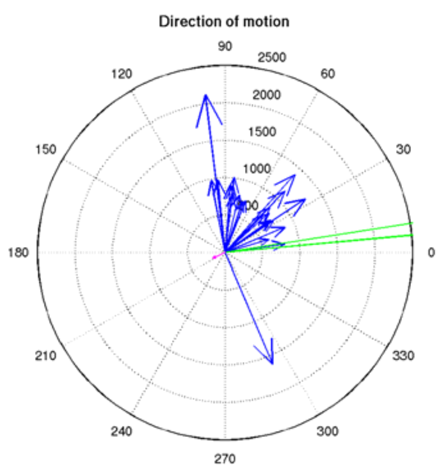
UPSTREAM OF QUASI-PARALLEL SHOCK IN SLAMS

- ESWs are on the order of 1 ms in duration and 5-65 mV/m amplitude with parallel velocity 400 – 1200 km/s
- These ESW are consistent with some features of BGK ion phase space holes.

Analysis Provided by S. Walker using Cluster EFW and FGM Data

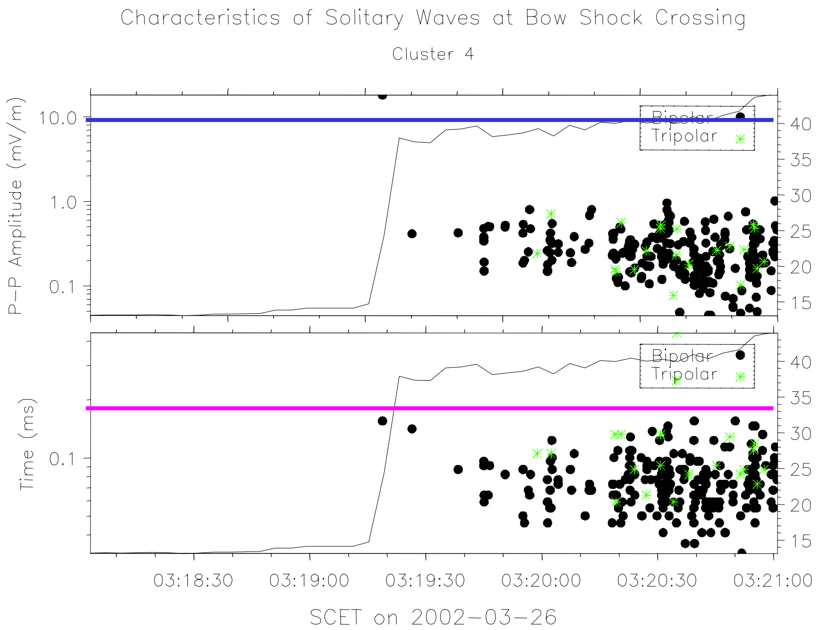




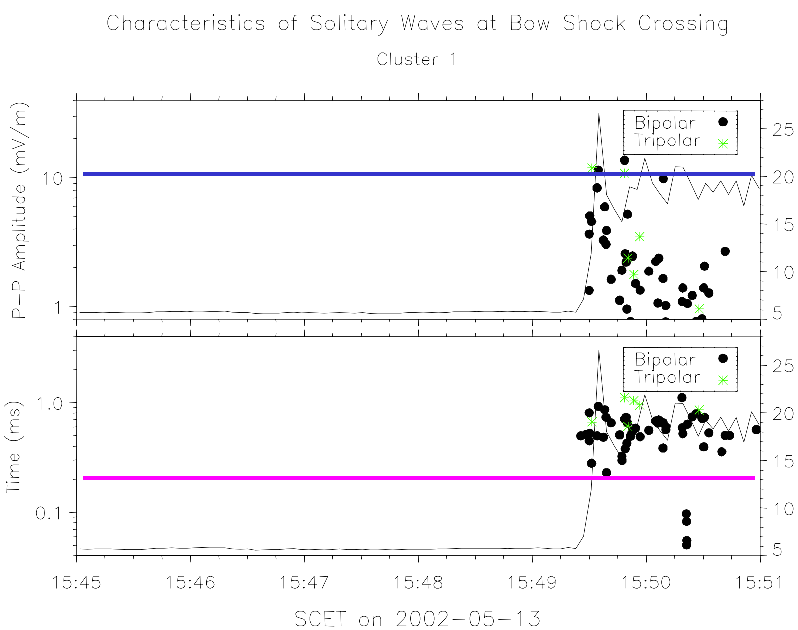


SHOCK FOOT

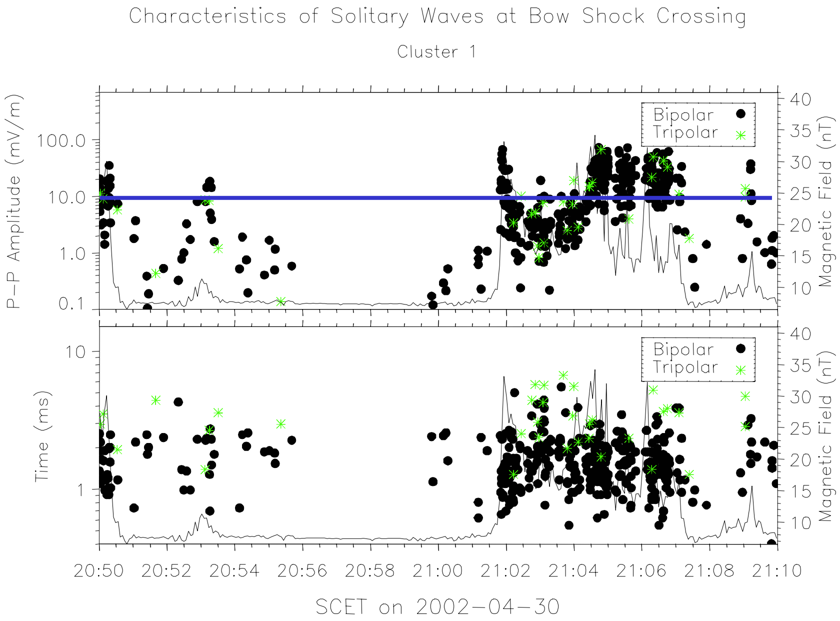
- ESWs are typically about 1ms in duration
- Interferometry used to determine velocity of solitary waves.
- Waves determined to be propagating primarily upstream at typical speed of 1000 km/s.



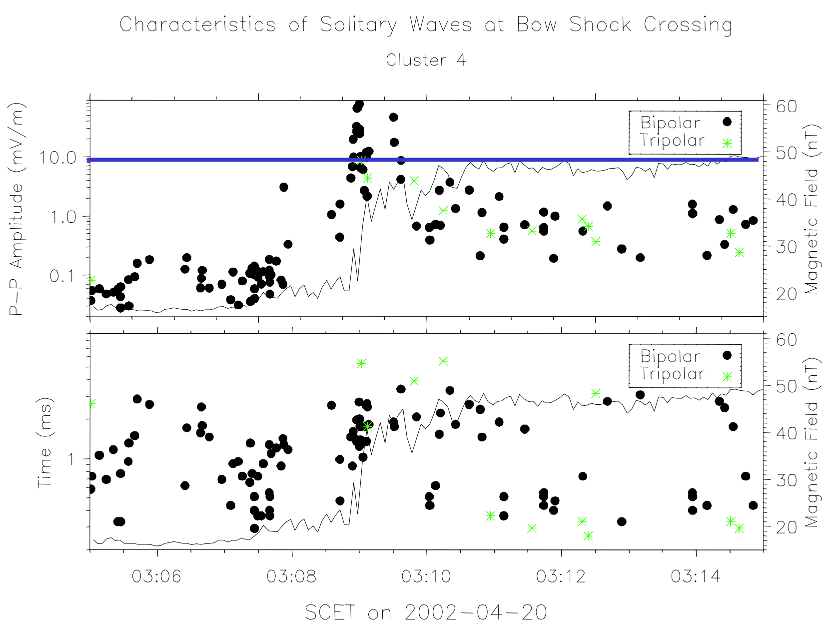
- Quasi-perpendicular, θ_{BN} ~ 85º
- β ~ 0.29
- M_A~ 6.4
- Almost total absence of ESWs in transition region, as well as upstream; numerous downstream but of very short duration



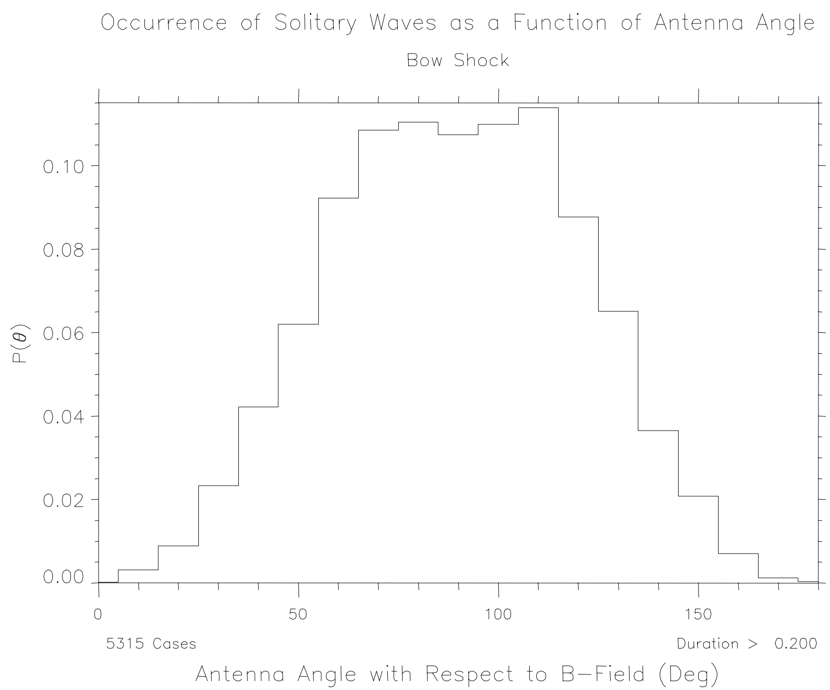
- Quasi-perpendicular, θ_{BN} ~ 52º
- β ~ 2.4
- M_A ~13.5
- Nearly an absence of ESWs upstream, but longer time duration SWs detected in transition region and downstream

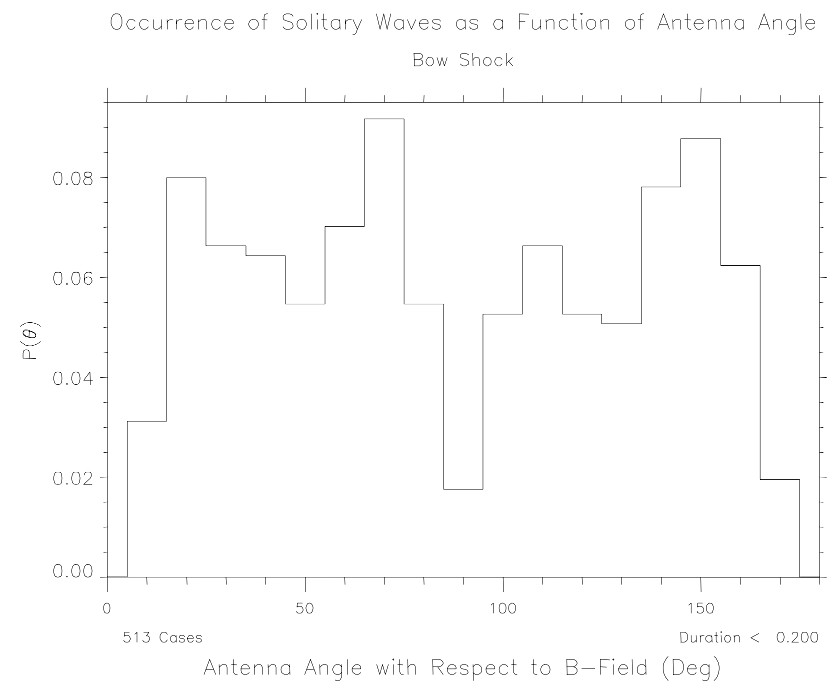


- Quasi-perpendicular, θ_{BN} ~ 73º
- β ~1.4
- M_A ~ 8.2
- Most ESW time durations > 1 ms; amplitude related to magnetic field strength



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





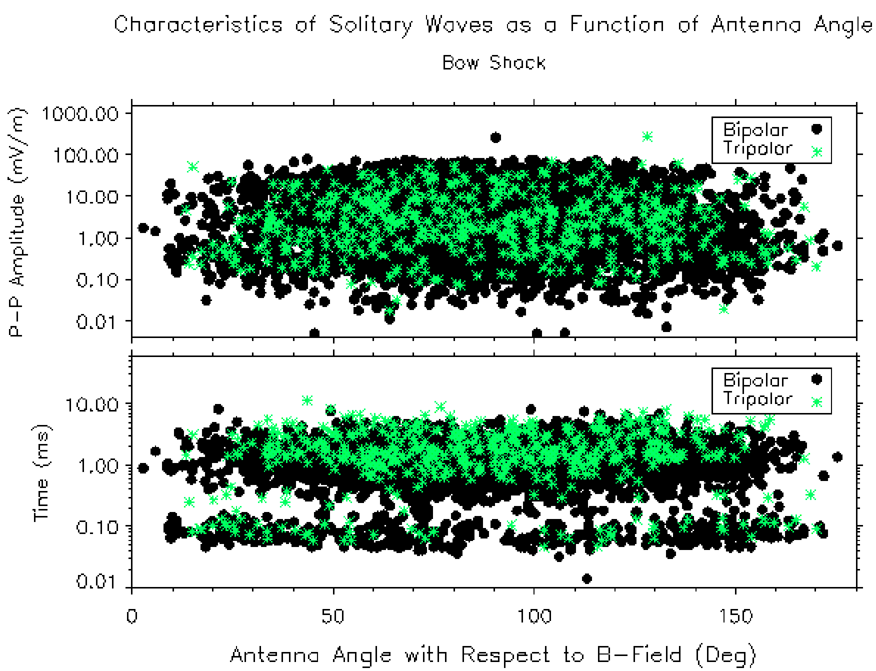
BOW SHOCK

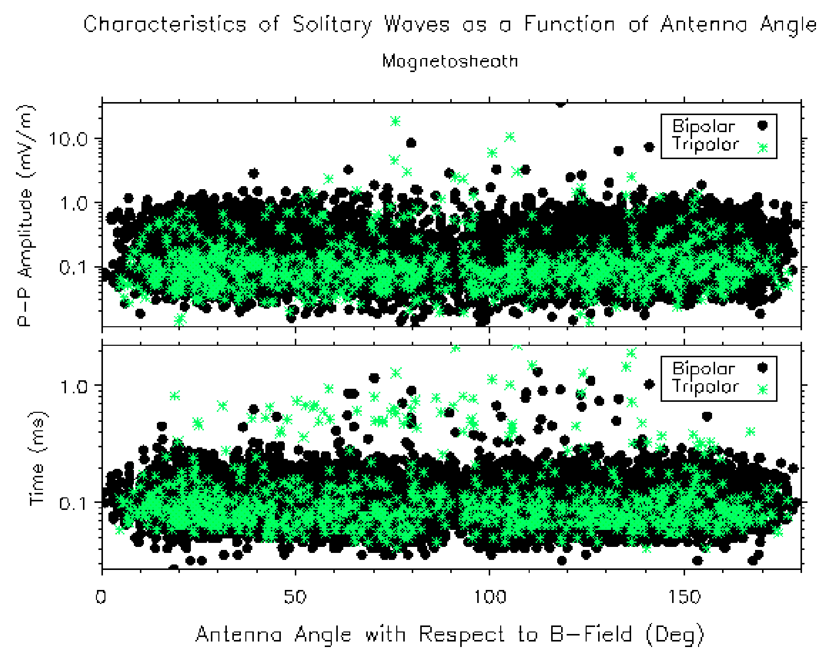
Solitary Wave Time Duration **> 0.2 ms**

- Angle occurrence greatest at 90º +/- 15º
- Suggests that this major population does not propagate along the magnetic field and related to ions.

Solitary Wave Time Duration **< 0.2 ms**

- Nearly total absence of SWs at 90º
- Suggests that this minor population propagates along the magnetic field and may be related to electrons



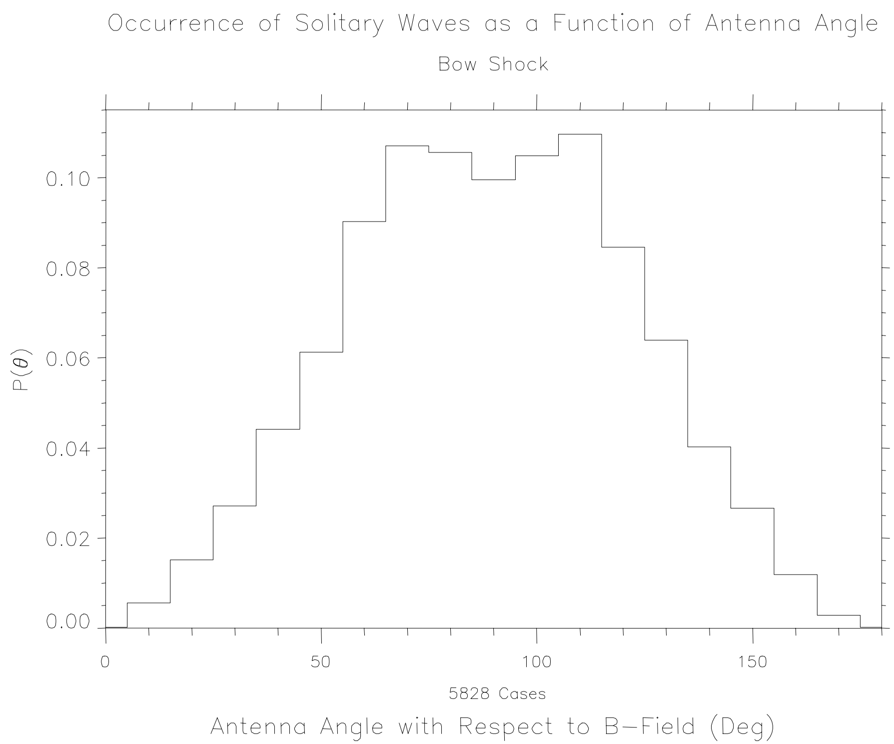


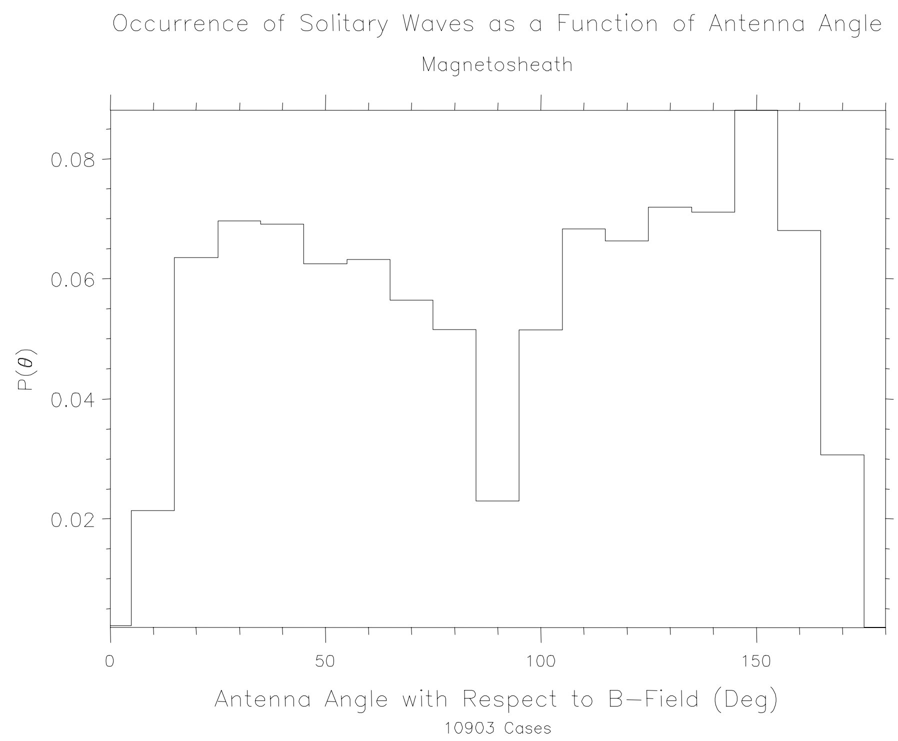
BOW SHOCK

- 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

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



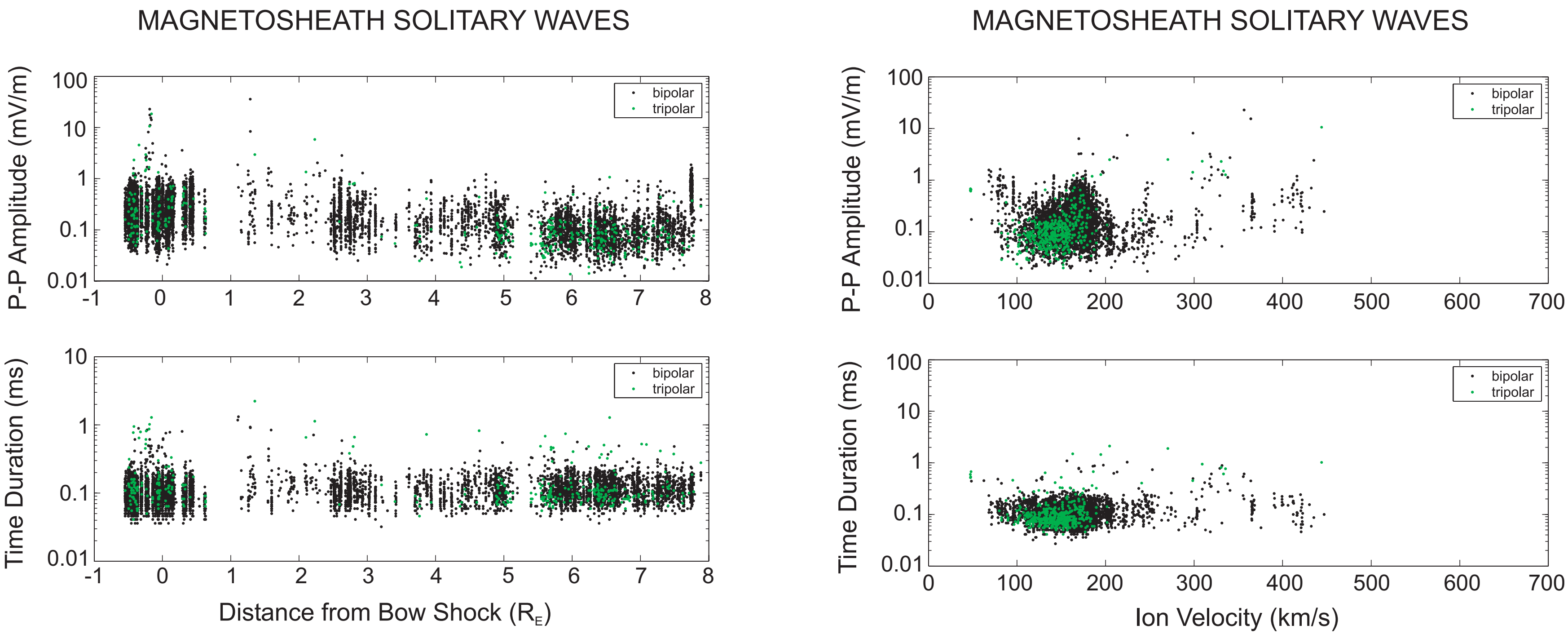


BOW SHOCK

- Angle occurrence peaks around 90º
- Suggests that 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

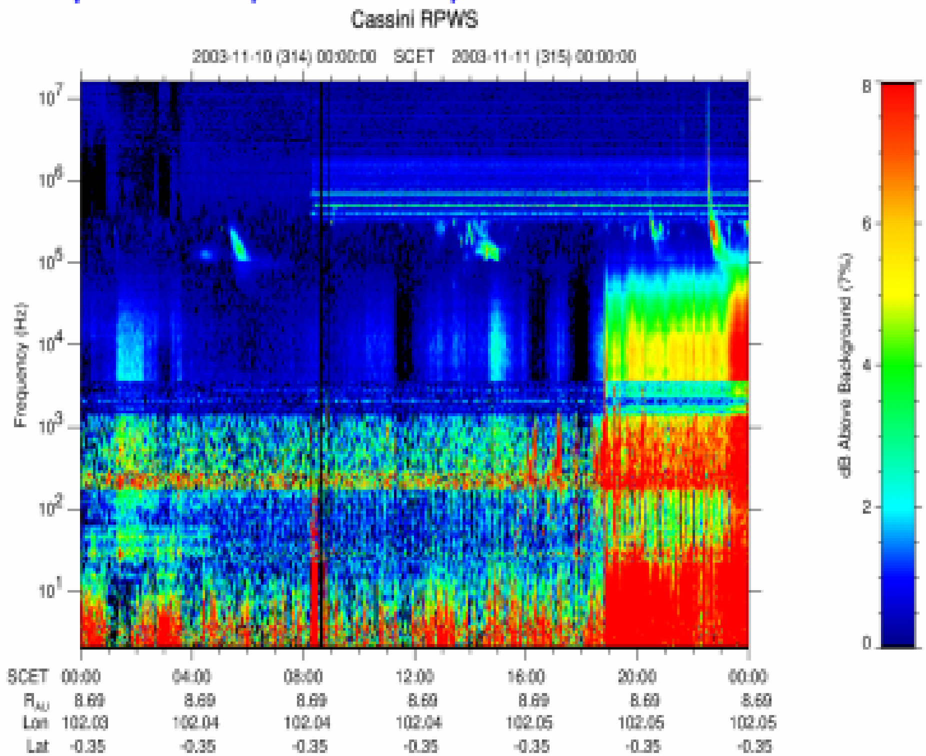
Distance from Bow Shock

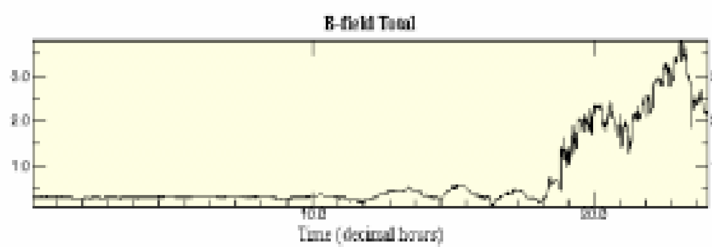
- No dependence for amplitude or time duration
- Suggests local generation at multiple locations in the magnetosheath rather than generation at bow shock

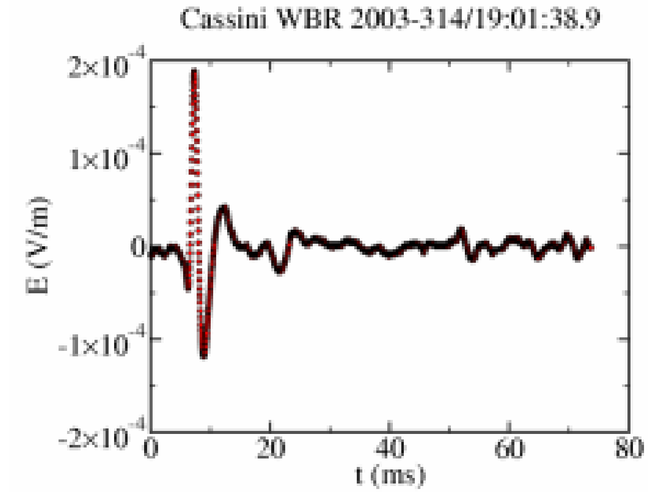
Dependence on Ion Velocity

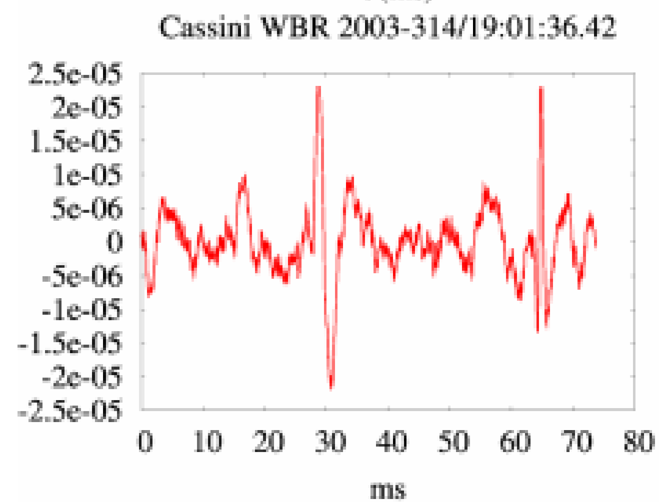
- Slight trend for larger amplitudes at larger velocities, but no dependence for time duration
- Suggests ions not solely responsible for creation

Interplanetary shock by Nov. 4, 2003 solar flare

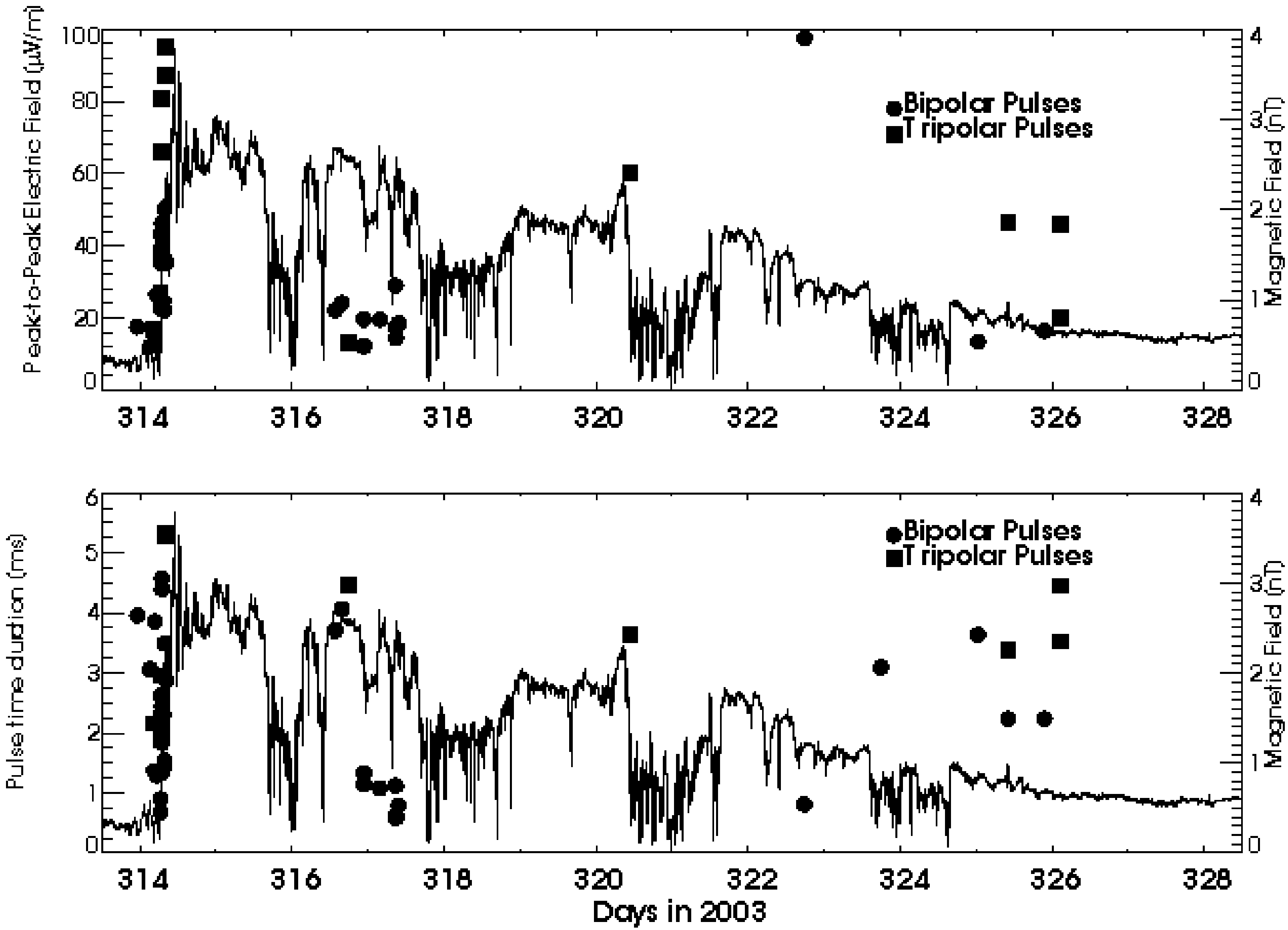






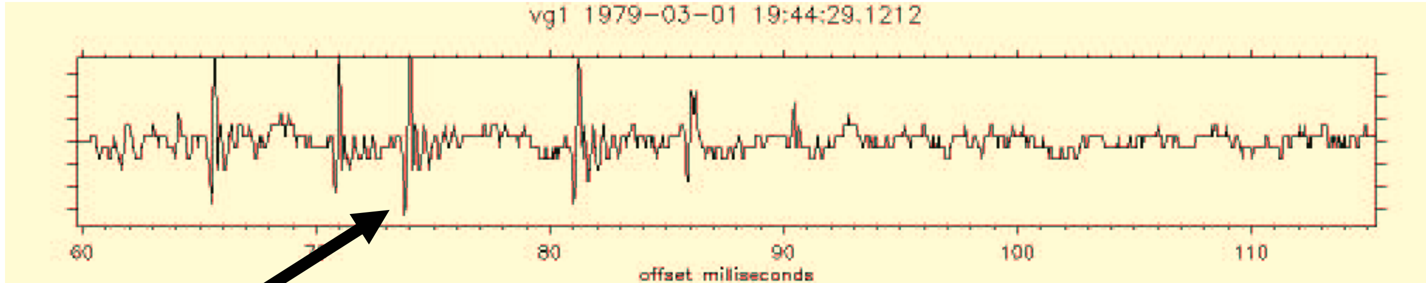


Analysis provided by J. Williams and L.-J. Chen Using Cassini RPWS Data



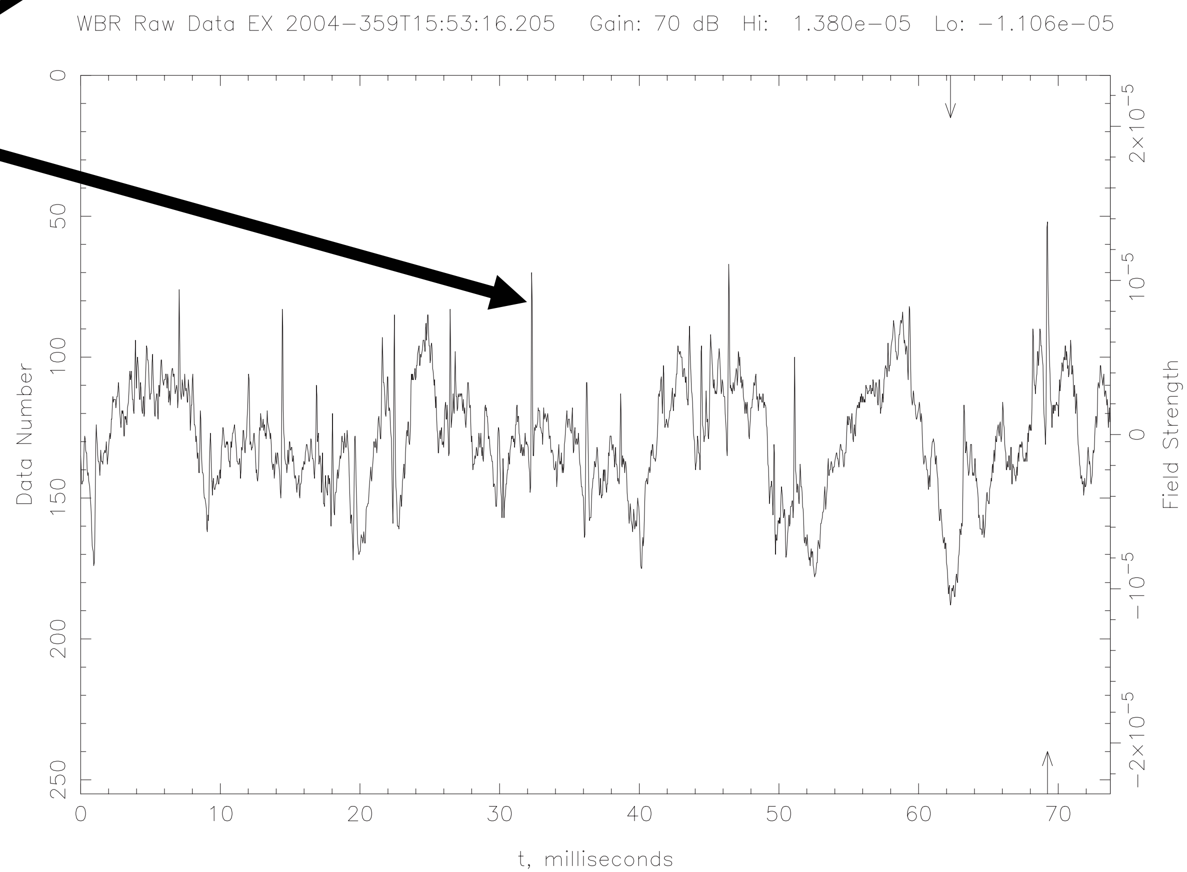
OUTER PLANET MAGNETOSHEATHS

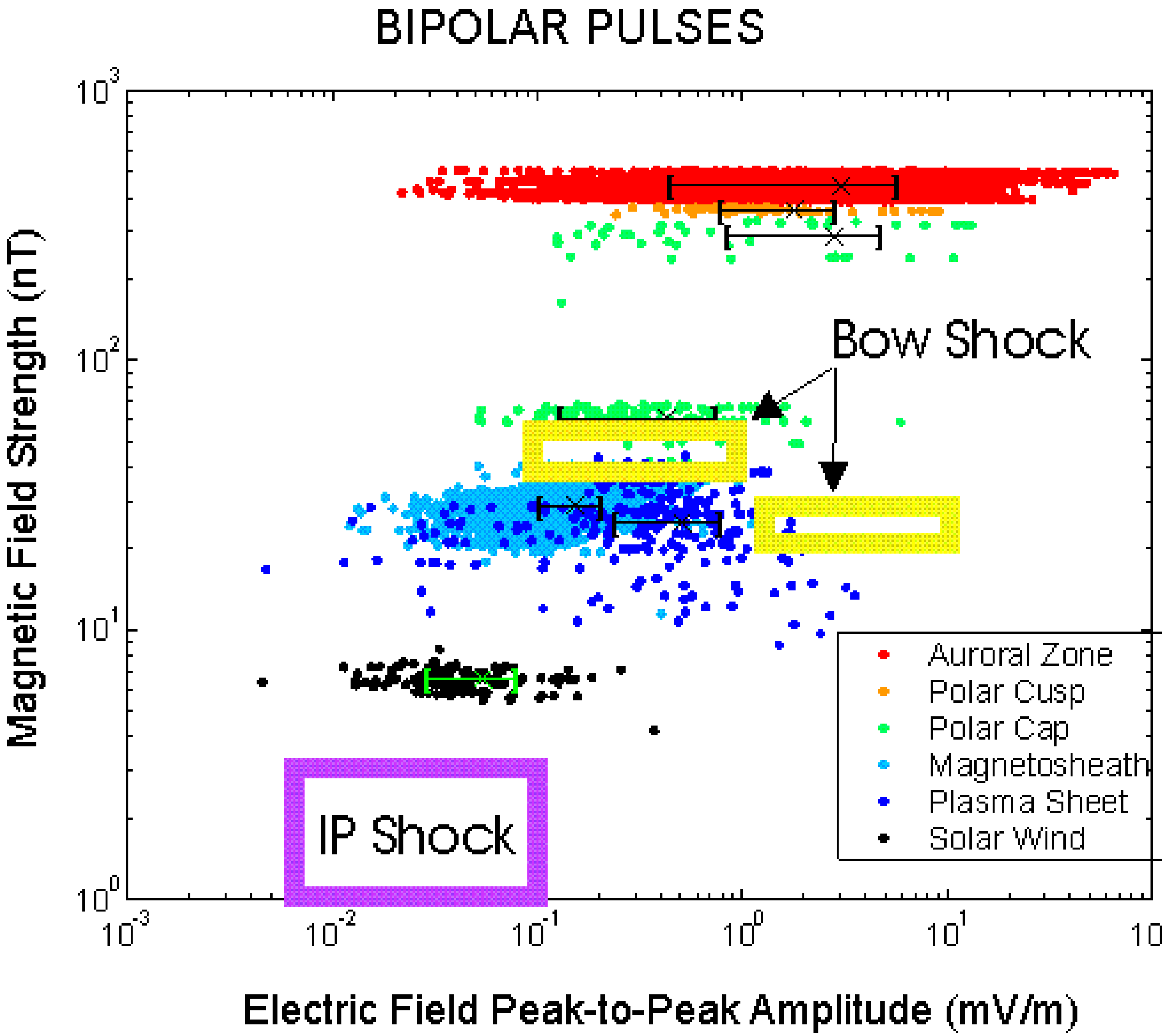
Jupiter



ESW: Time Duration ~ 1 ms or less

Saturn





[Figure Adapted from Pickett et al., *Ann. Geophys*., 2004]

Conclusion: consistent with BGK mode

Effects of finite magnetic field results in larger sizes and/or smaller potential amplitudes for smaller magnetic field.

Governed by inequalities leading to an allowed range of amplitudes at any given field strength

[From Chen et al., *PRE*, 2004]

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 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 might be possible in the magnetosheath and solar wind. These would be fluid solitons.
- We need to look at numerous ESW events across the bow shock and magnetosheath and the particle populations that are observed during them to find statistical correlations and trends.

SUMMARY

- Electrostatic solitary waves (solitary structures) are observed in the solar wind, across the bow shock and in the magnetosheath at Earth, Jupiter, and Saturn and at Interplanetary Shocks.
- These ESW have time durations consistent with electron modes (< 100 microseconds or less) and ion modes (> 200 microseconds) and potential amplitudes which, for the most part, are 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 crossings using the Cluster WBD 77 kHz bandwidth filter in conjunction with EFW snapshots
- Explore the various generation mechanisms from a theoretical perspective using observed particle and field inputs to models.

Acknowledgments:

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