Observation and Numerical Simulation of Propagation of ULF Waves From the Ion Foreshock Into the Magnetosphere

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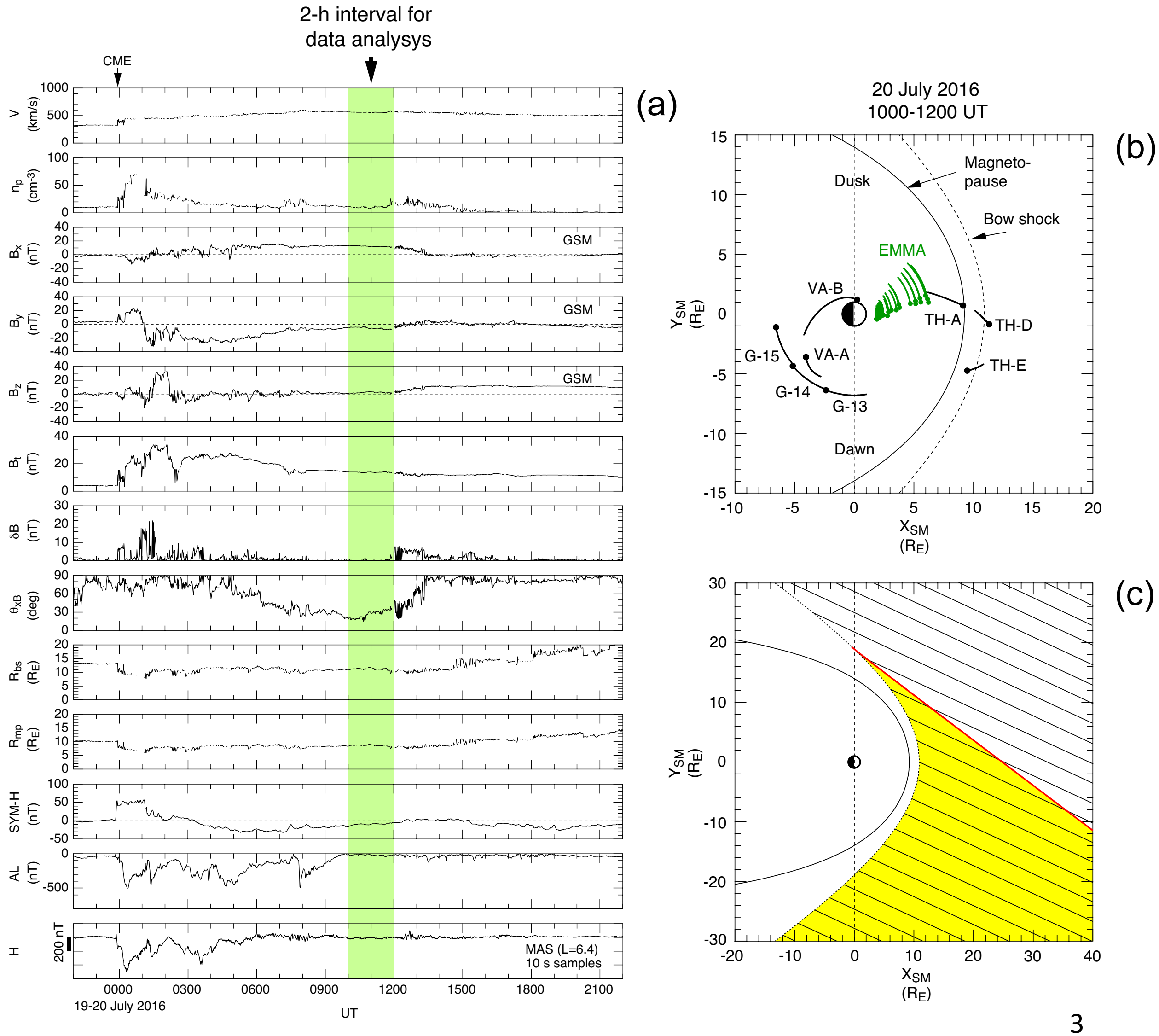
Abstract

Observational studies have demonstrated that ULF waves excited in the ion foreshock are a main source of Pc3-4 ULF waves detected in the magnetosphere. However, quantitative understanding of the propagation of the waves is not easy, because the waves are generated through a kinetic process in the foreshock, pass through the turbulent magnetosheath, and propagate as fast mode waves and couple to shear Alfven waves within the magnetosphere. Recent advancement of hybrid numerical simulations of foreshock dynamics motivated us to analyze observational data from multiple sources and compare the results with simulation results. We have selected the time interval 1000-1200 UT on 20 July 2016, when the THEMIS, GOES, and Van Allen Probe spacecraft covered the solar wind, foreshock, magnetosheath, and magnetosphere. The EMMA magnetometers (L=1.6-6.5) were located near noon. We found that the spectrum of the magnetic field magnitude (Bt) in the foreshock exhibits a peak near 90 mHz, which agrees with the theoretical prediction assuming an ion beam instability in the foreshock. A similar Bt spectrum is found in the dayside outer magnetosphere but not in the magnetosheath or in the nightside magnetosphere. On the ground, a 90 mHz spectral peak was detected in the H component only at L=2-3. The numerical simulation using the VLASIATOR code shows that the foreshock is formed on the prenoon sector but that the effect of the upstream waves in the magnetosphere is most pronounced at noon. The Bt spectrum of the simulated waves in the outer magnetosphere exhibits a peak at 90 mHz, which is consistent with the observation..

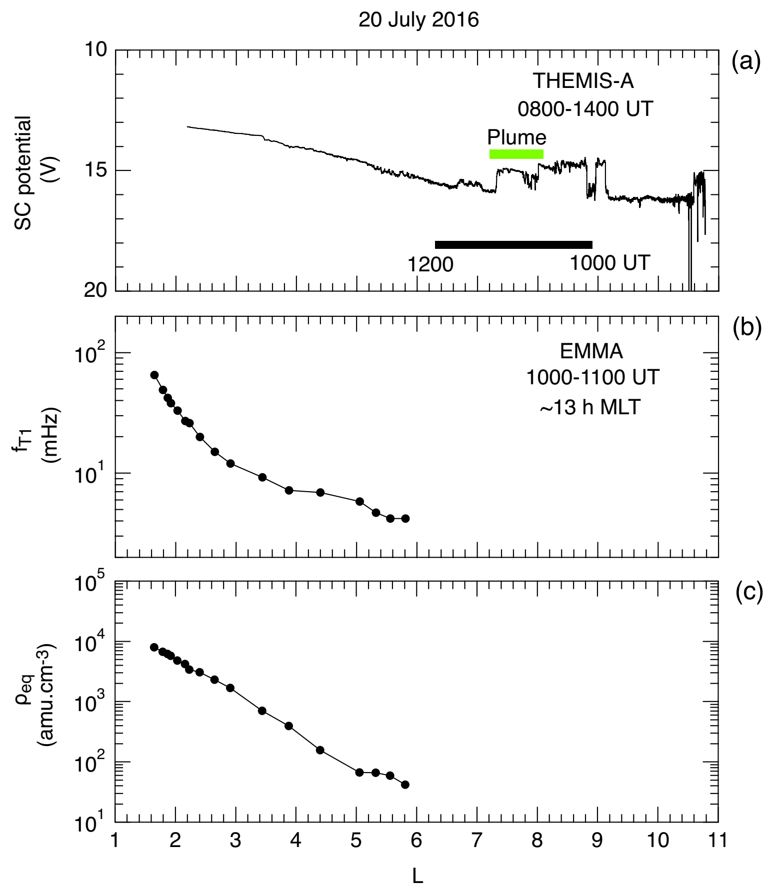
Magnetic cloud on 20 July 2016

- Steady IMF
  - Magnitude ~15 nT
  - Cone angle < 30°
- Multiple spacecraft
  - THEMIS, GOES, and Van Allen Probes
- Ground magnetometers
  - EMMA
  - N = 23
  - L = 1.6–6.5



Density radial profile

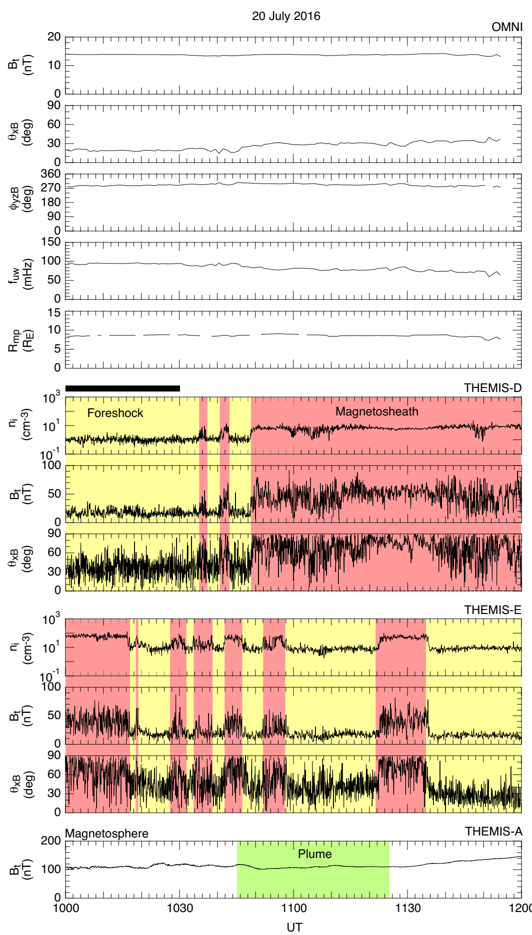
- THEMIS-A spacecraft potential
  - Plume in the outer magnetosphere
- Magnetoseismic analysis of EMMA data
  - Smooth plasmaspheric mass density profile at L < 6



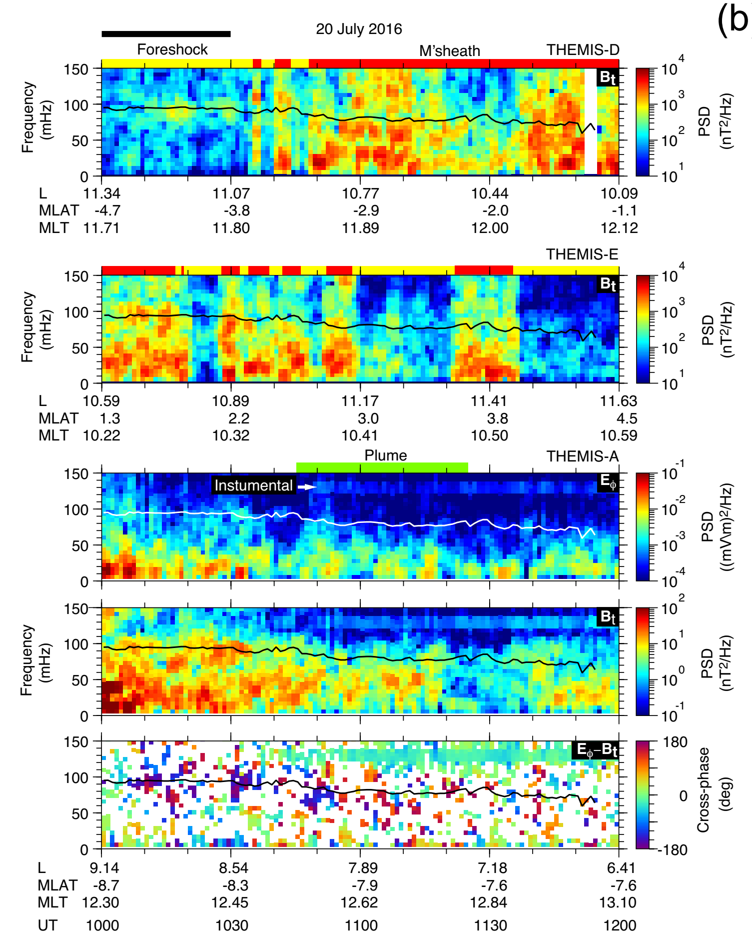
Dayside spacecraft observations

- Foreshock/sheath
  - Broadband
  - No strong peak at theoretical frequency f_{uw}
- Magnetosphere
  - Broadband
  - Cross-phase indicates instances of tailward propagation

$$f_{\text{uw}}(\text{mHz}) = 7.6 B_{\text{t}}(\text{nT})\cos^2\theta_{xB}$$



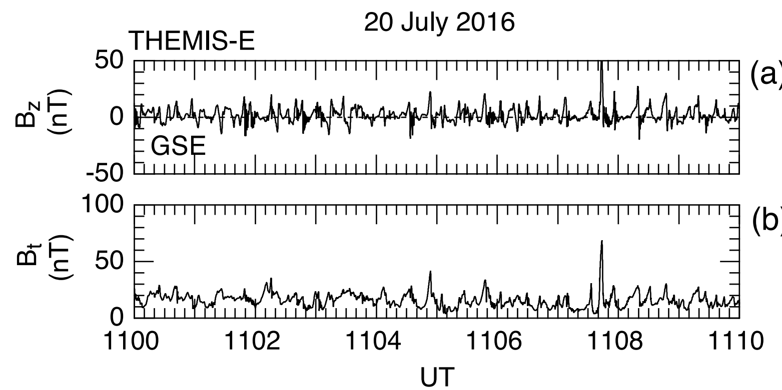
(a)

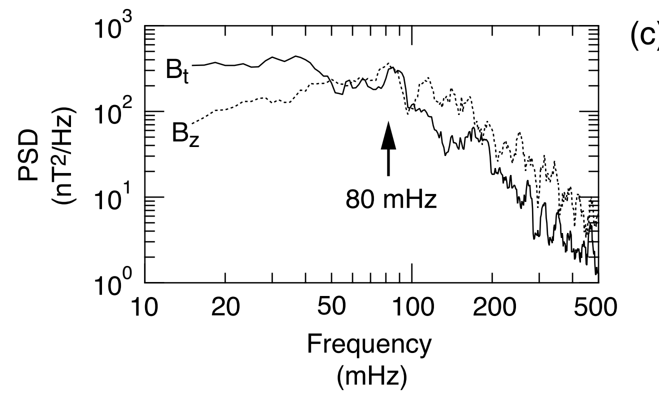


(b)

Foreshock waves just outside the magnetosheath

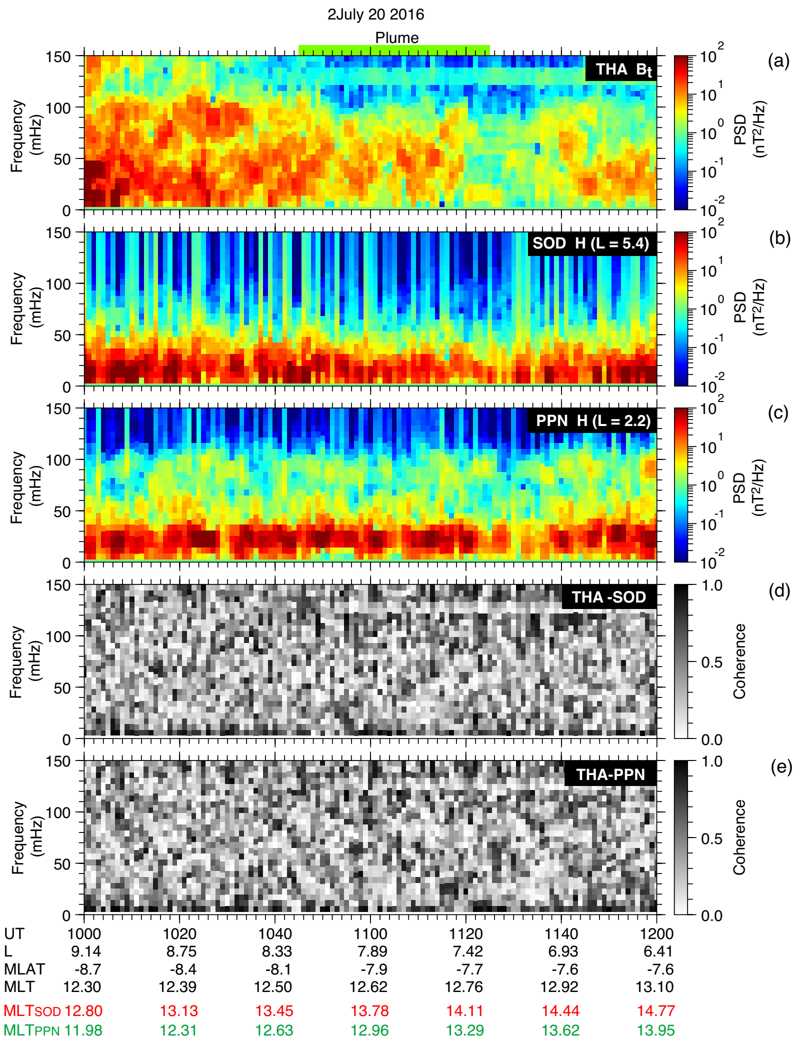
- Large amplitude
- Transverse component (B_z)
  Broad peak at 80 mHz ($\sim f_{uw}$)
- Compressional component (B_t)
  – Strong power at 30-40 mHz





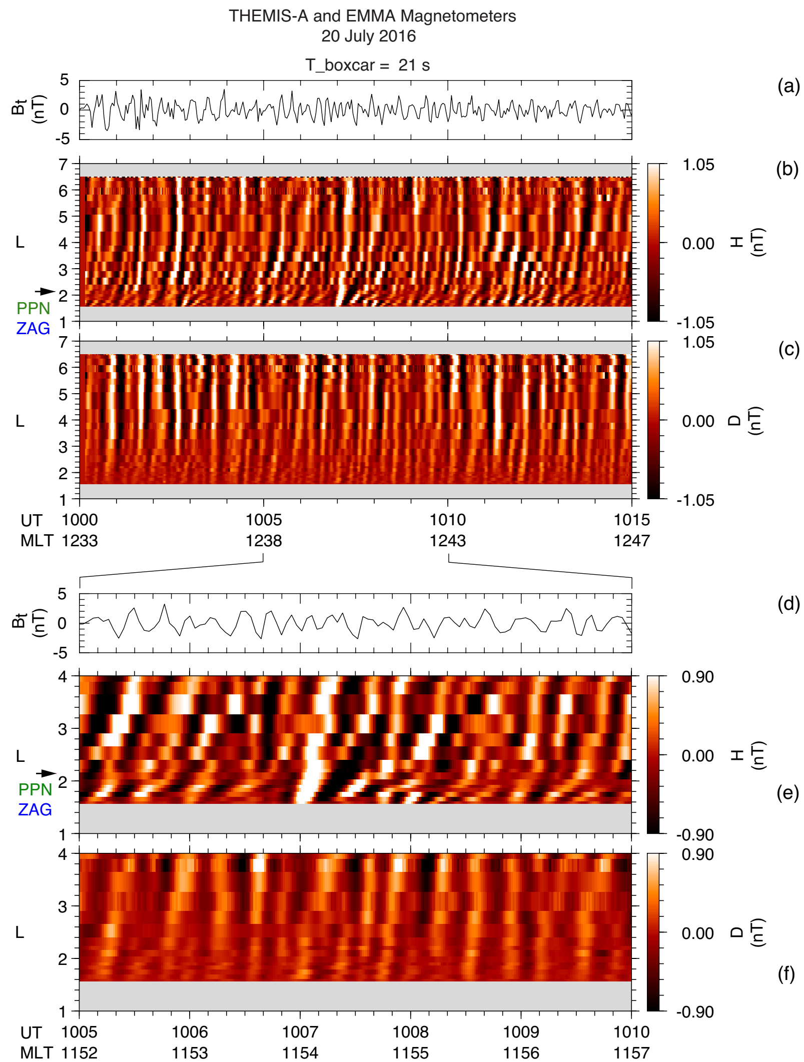
Comparison of waves between space and ground

- Power spectra
  - not similar between space and ground
- Coherence
  - Low at all frequencies



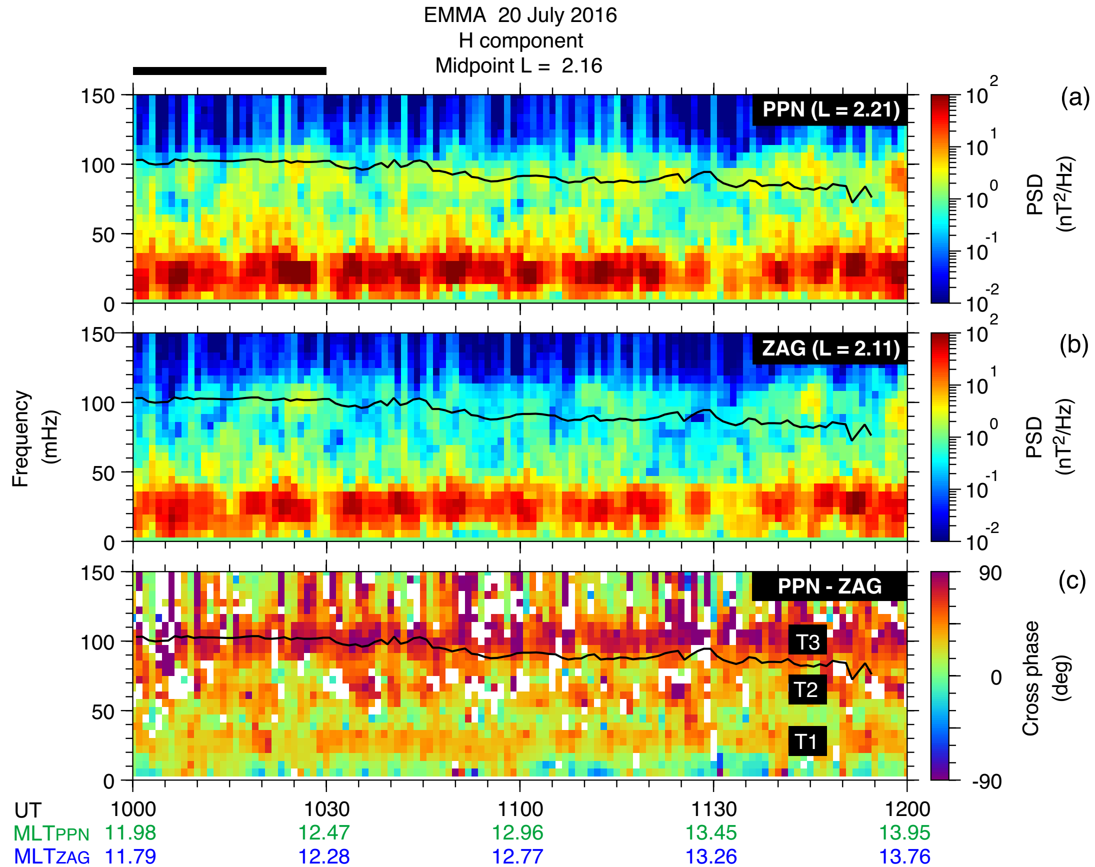
EMMAgram

- H component
  - Poleward phase propagation
  - Transient pulsations at low L
- D component
  - Weaker poleward propagation
  - No transient pulsations

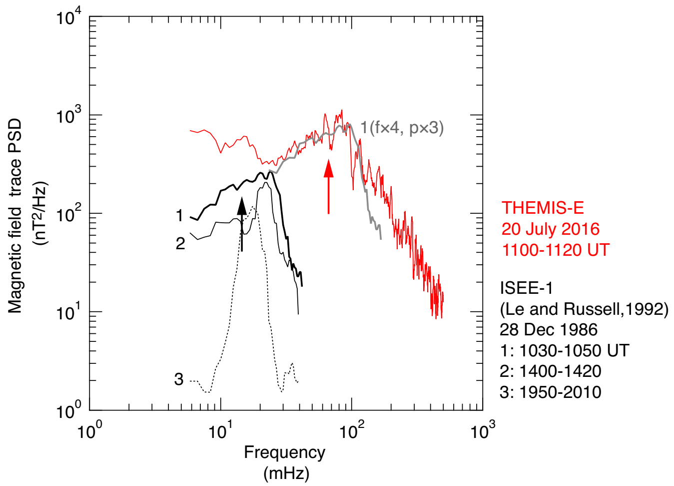


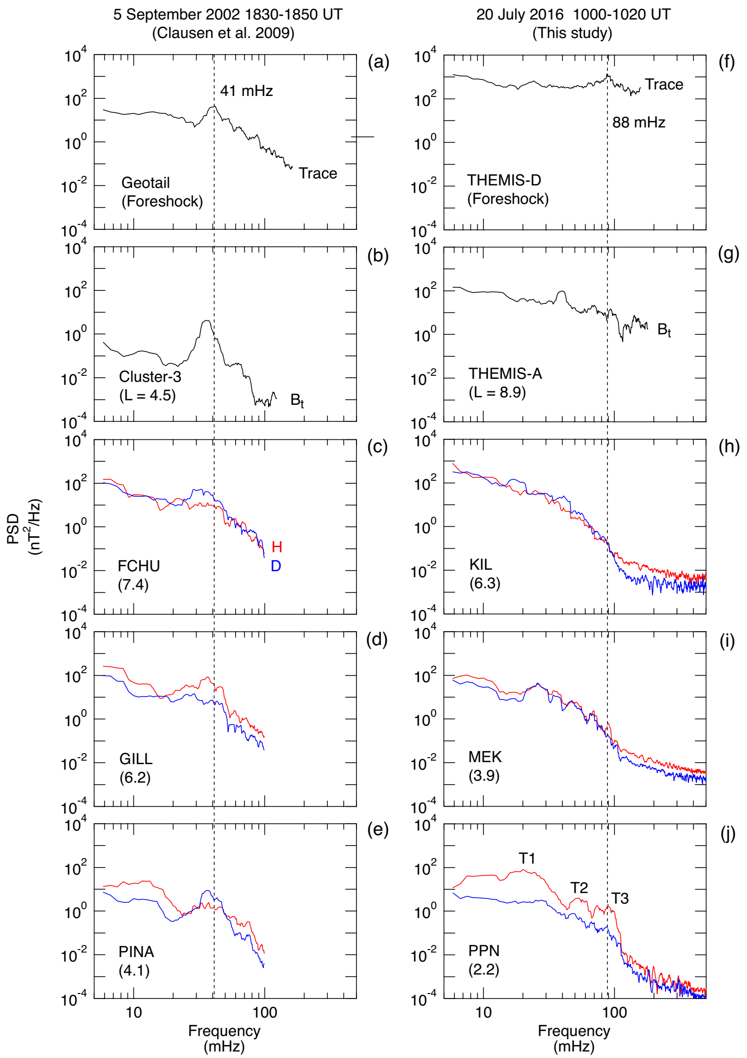
Cross-phase analysis

- Power spectra
  - Peaks at ~30 and ~90 mHz
  - The higher frequency matches f_{uw}
- Cross spectra
  - T1, T2, and T3 waves detected



Comparison with previous studies

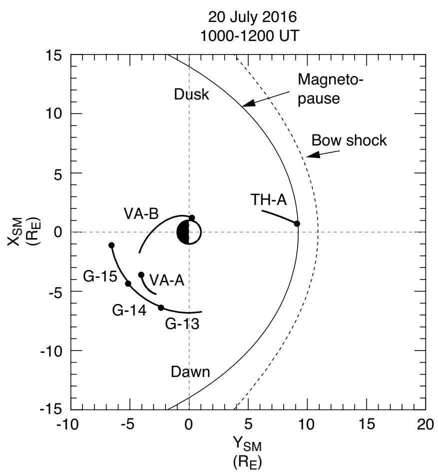


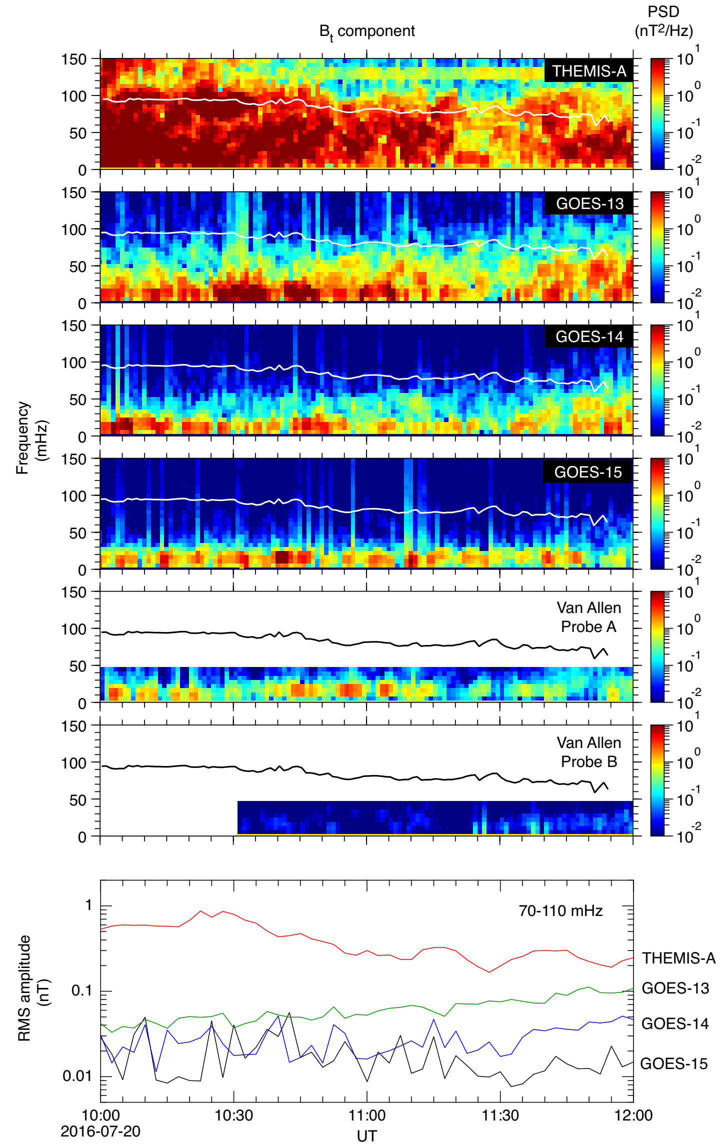


- Comparison with ISEE study
  - Higher frequency
  - Higher power
  - Broader spectral peak

- Comparison with Cluster study
  - No single outstanding spectral peak

Local time dependence of wave power

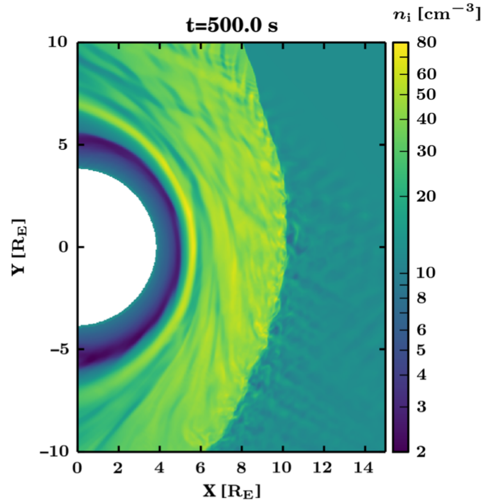




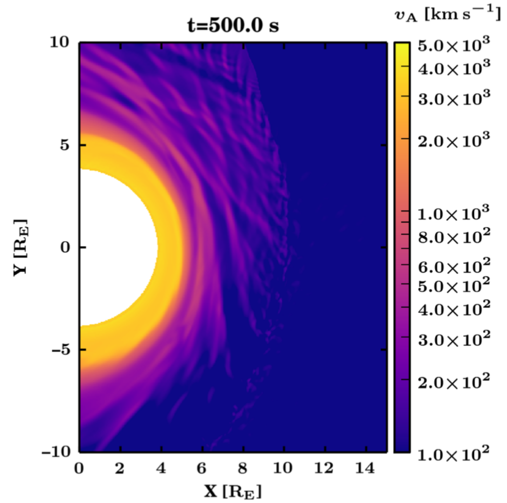
- Nightside waves
  - Much weaker than dayside waves
  - No indication of upstream wave propagation

Vlasiator simulation

- Magnetosphere is included
  - Magnetopause at 5 Re
  - Realistic Alfven velocity



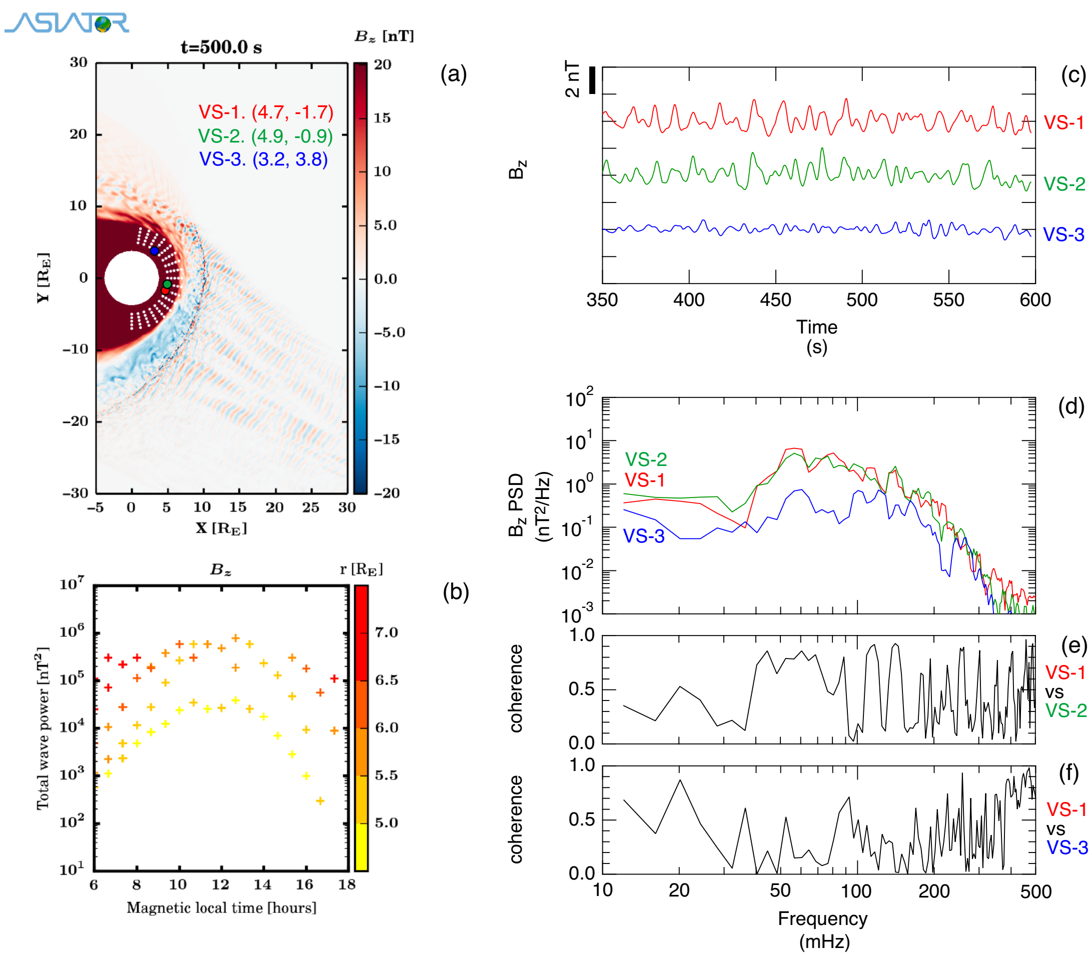
Proton density



Alfven velocity

Simulated waves

- Foreshock
  - Short coherence length
  - Multiple wave packets
- Magnetosphere
  - Wave power peaks at noon
  - Low coherence between noon and dusk
  - Rapid power decrease toward dawn/dusk



Summary

- A magnetic cloud in the solar wind produces an ion foreshock populated with ULF waves with higher-than-usual frequencies and complex spectra.
- In the magnetosphere and on the ground, there are only weak signatures of oscillations directly driven by the foreshock waves.
- Numerical simulation indicates short spatial scales and a multiple frequencies of the foreshock waves.