Nature and Properties of Electrostatic Solitary Waves in the Earth's Magnetosheath

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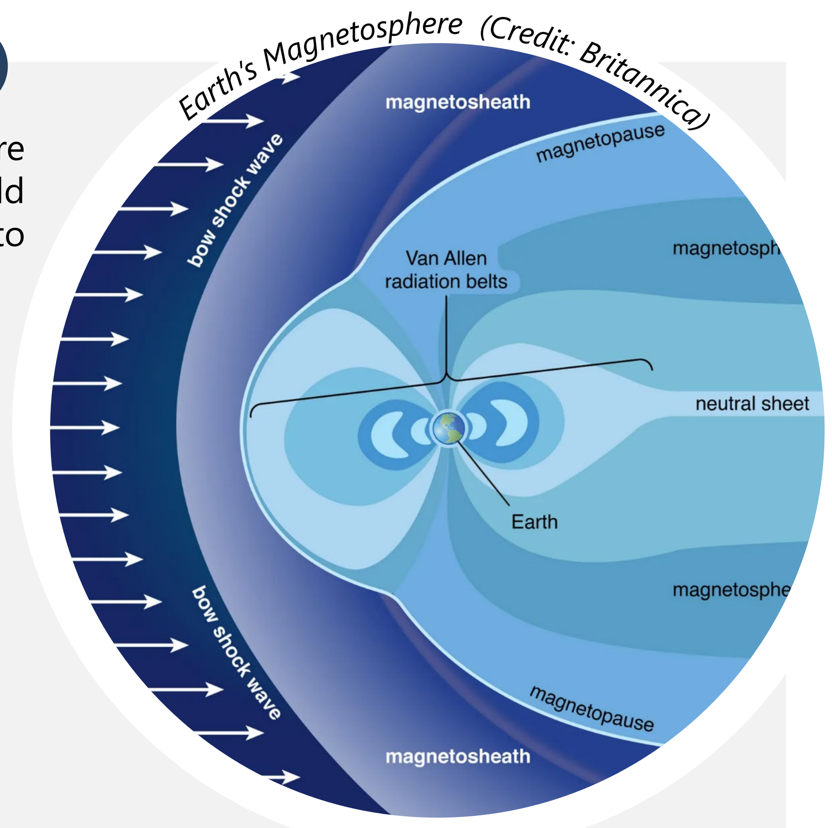
Background and Motivation

- **Electrostatic solitary waves (ESWs)** are nonlinear, localized, bipolar electric field structures propagating parallel/anti-parallel to the background magnetic field [1-15].
- ESWs are categorised into:
  - **Solitons:** Electron/Ion solitons,
  - **Phase-space holes:** Electron/Ion holes
- ESWs plays an important role in plasma transport, particle scattering, and energy exchange processes[1,2,15].



ESWs in Earth's Magnetosheath

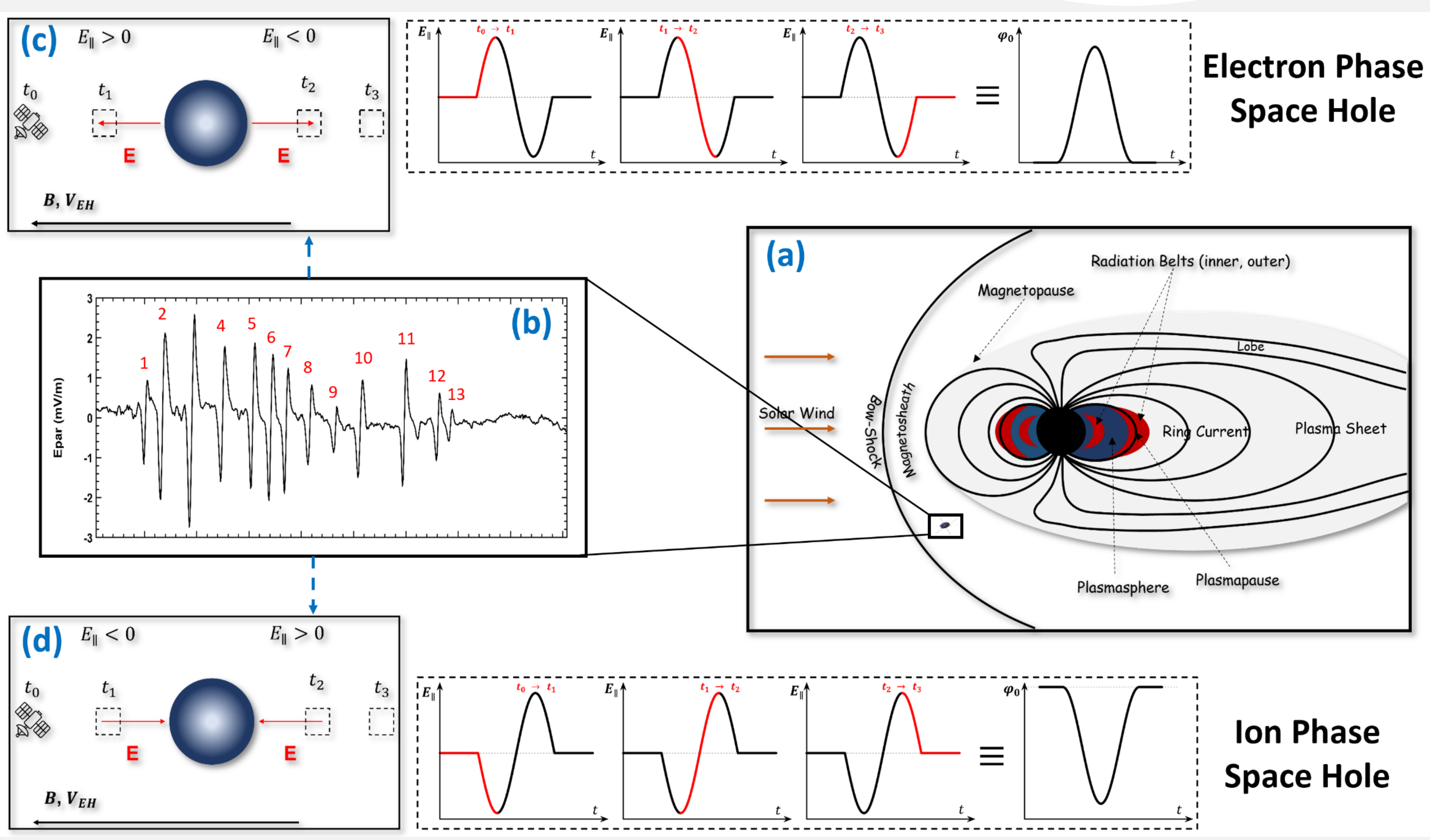


Figure 1: Schematics of (a) Solar wind - Earth's magnetosphere interaction; (b) electrostatic solitary waves within the Earth's Magnetosheath; (c) Electron hole; and (d) Ion hole.

- ESWs were observed Magnetosheath…*Kojima+1997; Pickett+(2003, 2005).* — **Characteristic were unknown**
- *Graham+2016* observed ESWs with positive polarity (**electron holes**).
- *Holmes+2017* observed ESWs with positive polarity (**Ion holes**).
- *Shaikh+2024* observed ESWs with positive polarity (**slow electron holes**).

Inconsistent between these studies motivated the present study

Science objectives

- **Which Solitary waves are often present within the Magnetosheath?**
- **What are the properties and generation mechanism of solitary waves?**
- **How does turbulence level affects characteristics and occurrence of ESWs?**

Data and Methodology

- **MMS S/C:** FPI (Ions:150ms, electrons:30ms), FGM (128Hz), EDP (8192 Hz), and SCM (8192 Hz).
- **Methodology**[13,15-16]**:**
  - Minimum Variance Analysis (MVA)
  - Voltage Interferometry Analysis
- **Assuming locally planar and one dimensional solitary wave** [13-18]
  - Solitary wave speed; $V_s = \frac{\hat{E}_{ij}\, l_{ij}}{\Delta t_{ij}}$ here, $\hat{E}_{ij}$ is polarization direction
  - Electrostatic potential; $\varphi = \int E_L V_s\, dt$
  - Spatial scale of solitary structure; $x = \int V_s\, dt$; with $x = 0$, corresponding to $E_L = 0$.

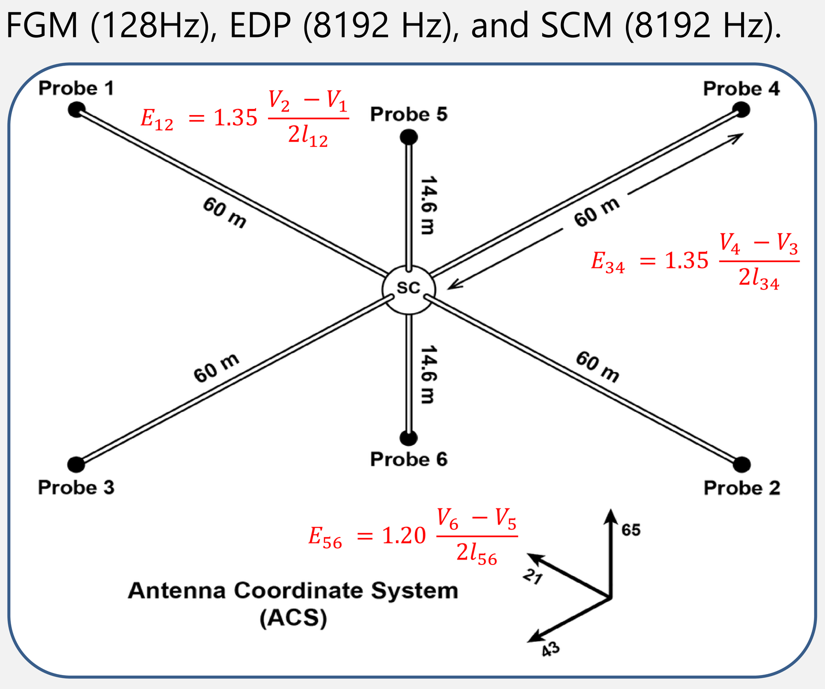


Figure 2: The schematics of the double probe instrument aboard on each MMS spacecraft[2]

Overview plot of Magnetosheath

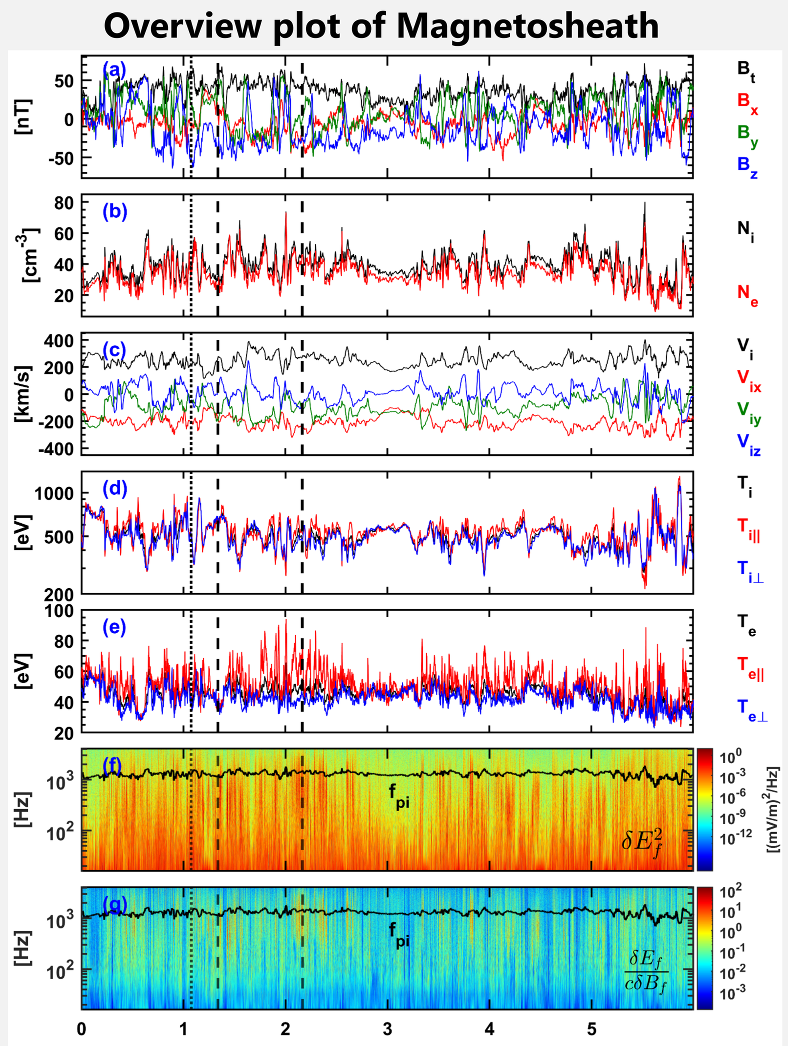


Figure 3: Magnetosheath overview on January 28, 2017.

Interferometry Analysis

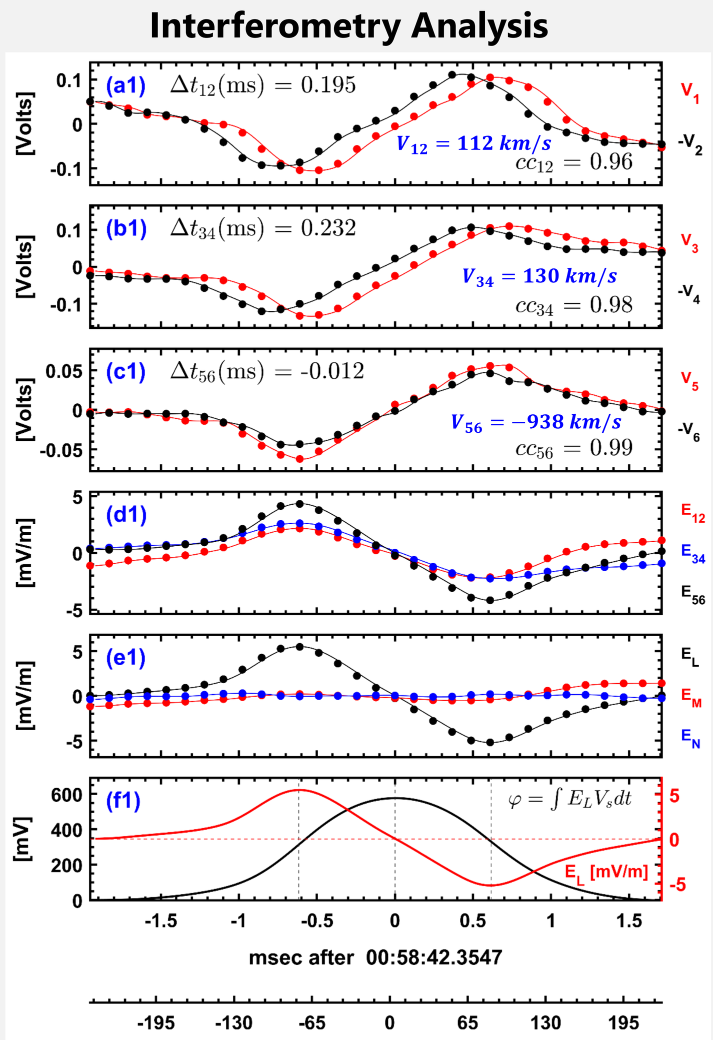


Figure 4: An example of ESW with positive potential.

Selection Criteria

1. At least **one pair of voltage probe** must show:
   - $cc \geq 0.85$
   - $\delta t \geq 0.06\, msec$
2. $E_L \gg E_M, E_N$ which is equivalent to $\frac{\lambda_{max}}{\sqrt{\lambda_{int}^2 + \lambda_{min}^2}} > 5$

Table 1. *List of Magnetosheath, duration, turbulent level, number of observed IHs/EHs by MMS1 & MMS2.*

Magnetosheath Interval	Duration	Turbulence	#IHs		#EHs	
Date and Time	ΔT (min)	$\delta B_{rms}/B_0$	MMS1	MMS2	MMS1	MMS2
Oct 31, 2015; 10:22:27 to 10:27:00	04.55	0.64	134	194	54	91
Jan 27, 2017; 00:55:03 to 00:56:58	01.92	1.05	105	122	277	269
Jan 27, 2017; 00:57:23 to 01:03:13	05.83	2.46	191	362	103	241
Total			430	678	434	601

IHs = 1108 EHs = 1035

Analysis and Results

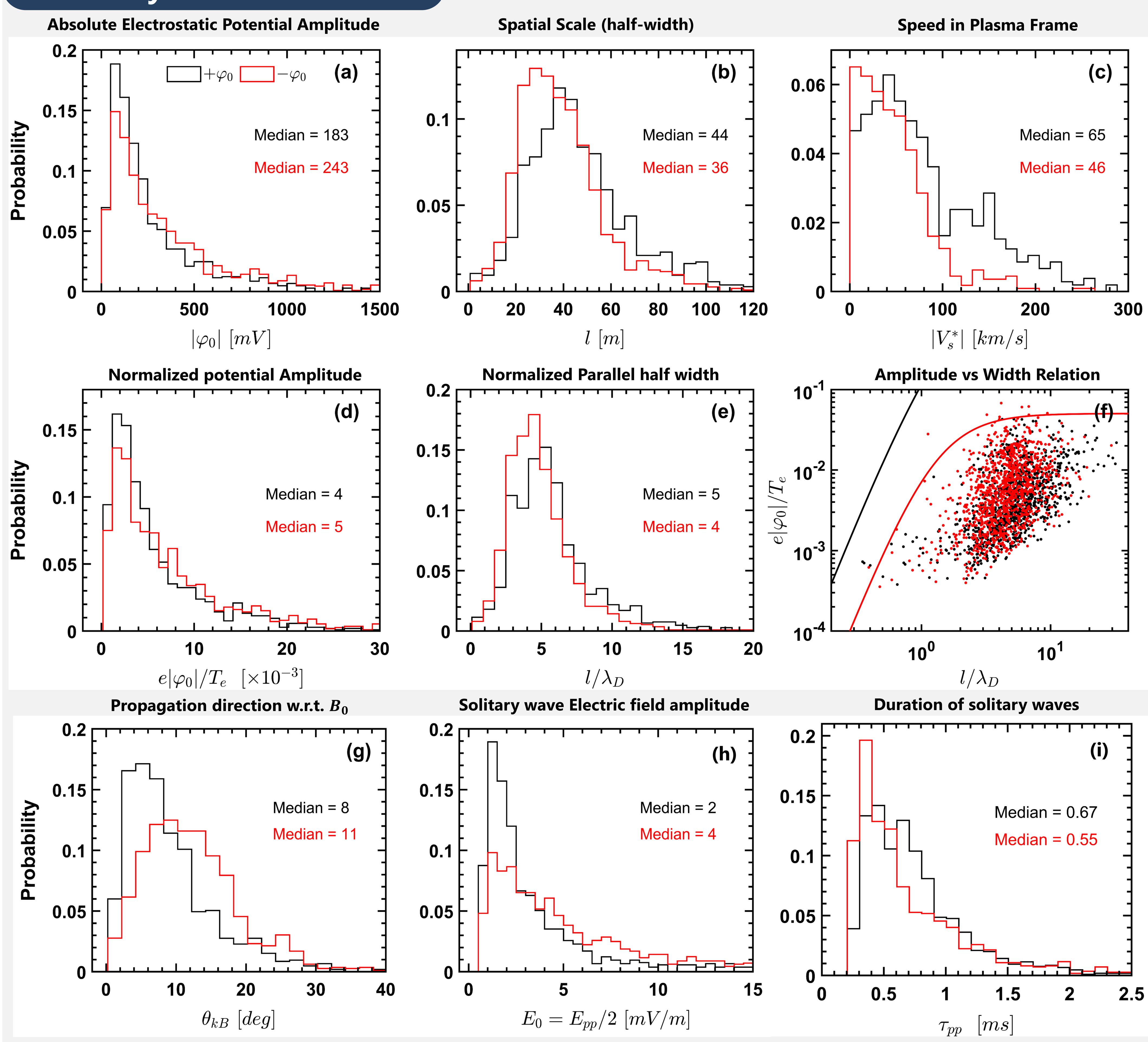


*Figure 5: Distributions of solitary waves properties (**black**: **positive potential structures**, red: negative potential structures).*

Ion velocity distribution functions (IVDFs)

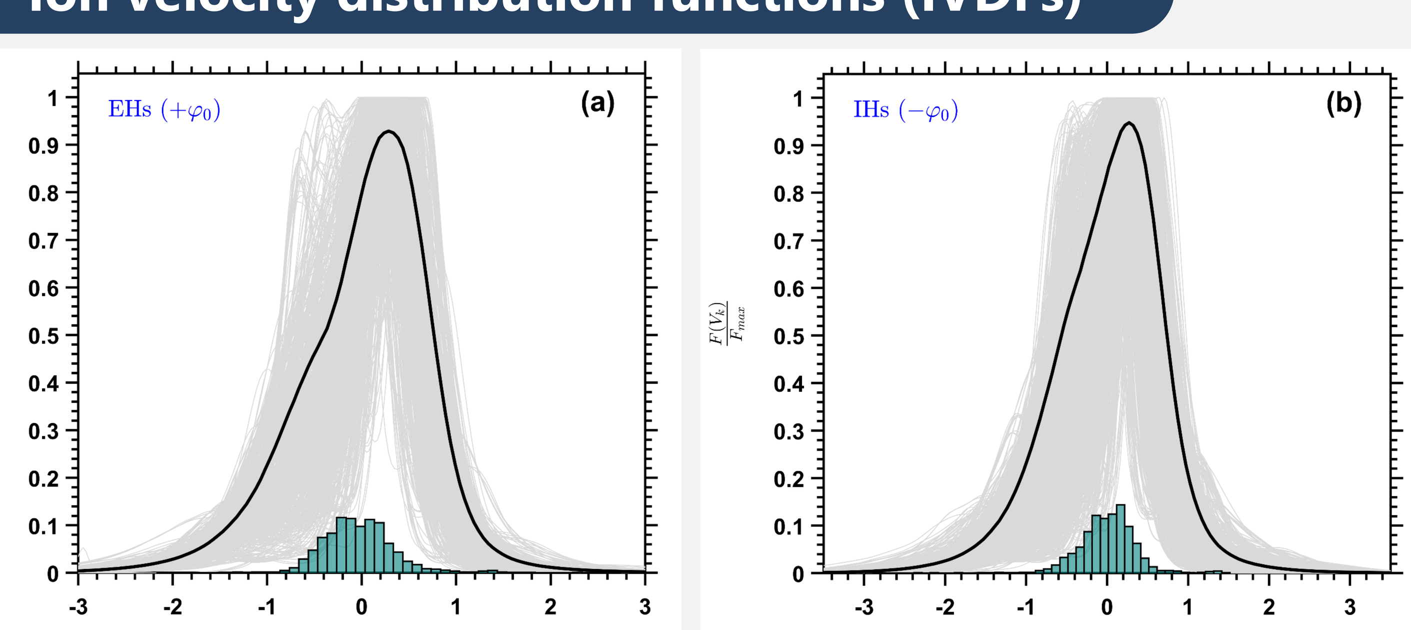


Figure 6: 1D reduced IVDFs $F(V_k)$ in the plasma frame collected over 150 ms around the solitary waves. The grey color distribution is for individual solitary waves, whereas the overplotted black curves present average distributions. Each $F(V_k)$ is normalized with peak value F_{max} and translated into the plasma frame and normalized to ion thermal speed V_{Ti}. The histograms present normalized probability distributions of solitary wave speed in the plasma frame.

Time intervals between EHs/IHs

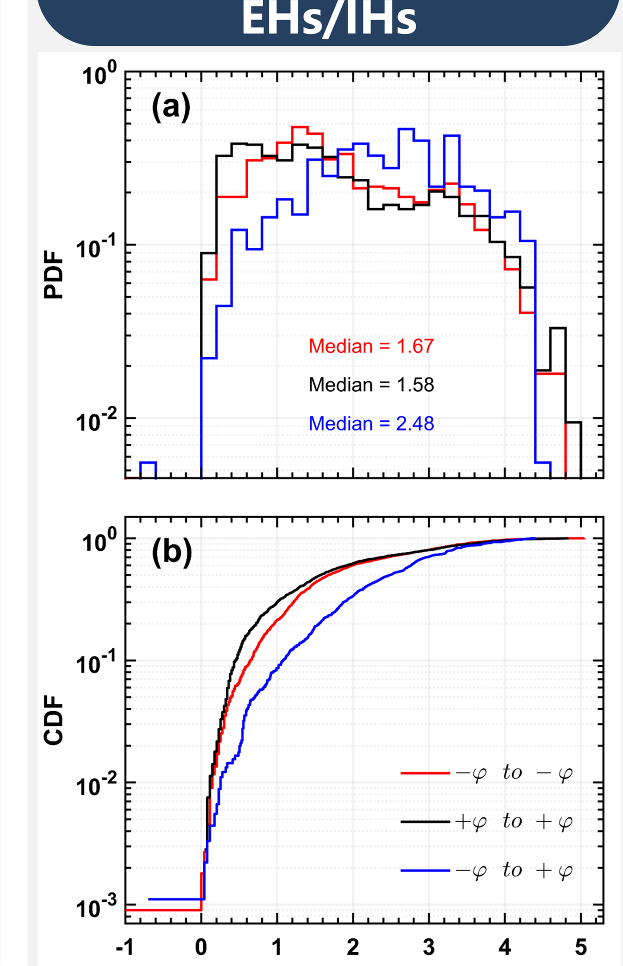


Figure 7: *The probability and Cumulative distribution functions of time intervals between sequentially observed EHs and IHs.*

Summary and Conclusions

Statistically analysis >2,100 ESWs within the three Earth's Magnetosheath crossings having different turbulence amplitude:

- About **48%** of the ESWs are **electron holes (EHs),** whereas **52%** are **ion holes (IHs).**
- **EHs and IHs have similar properties** such as; spatial scales of a few Debye lengths, plasma frame velocities within about 200 km/s, and potential amplitudes < 2 V.
- **EHs and IHs are slow**, their plasma frame speeds are much smaller than local electron thermal speed, but comparable with local ion thermal speed.
- **The cluster of EHs are statistically well-separated from clusters of IHs**, strongly indicates that the solitary waves of different polarities are highly likely produced by instabilities operating separately in time or space.
- Characteristics & occurrence of EHs/IHs are **insensitive to local turbulence intensity**.

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