Simulation Study of Solitary Waves in the Martian Magnetosphere

ISSS-15+IPELS-16

Sahil Pandey, Amar Kakad, Bharati Kakad

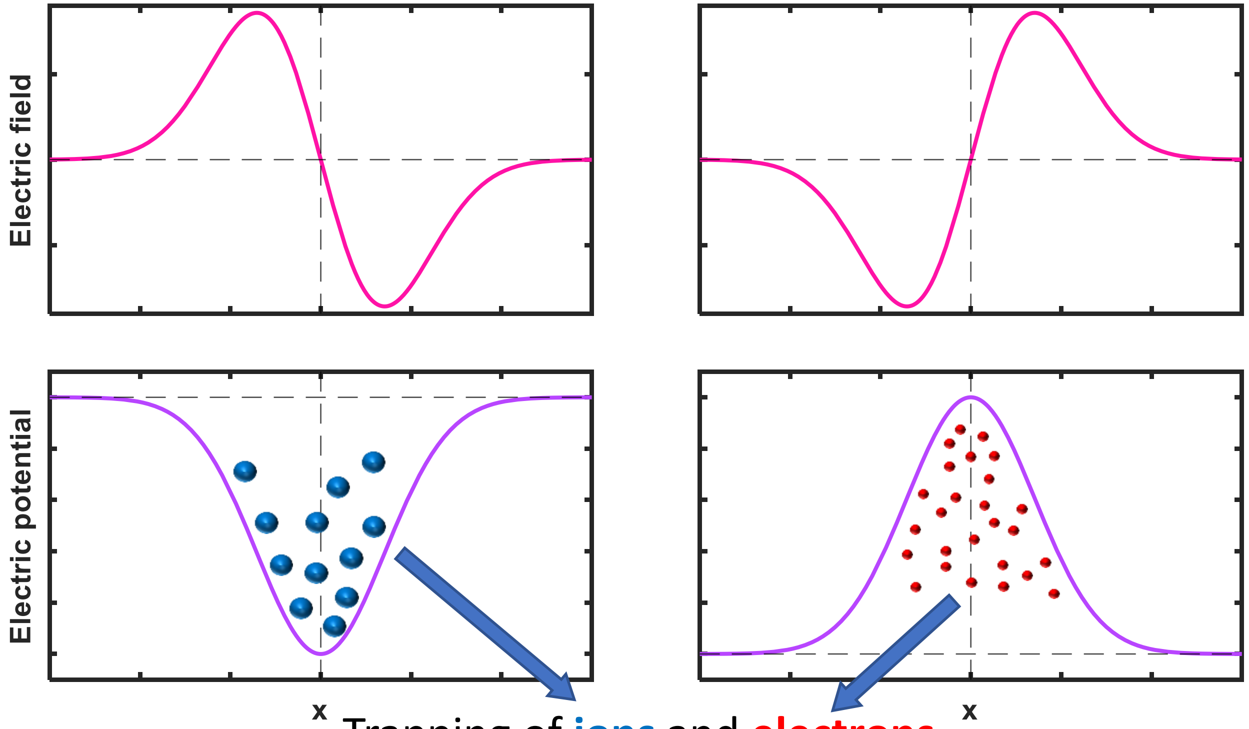
Indian Institute of Geomagnetism, Navi Mumbai, India

Contents

Solitary waves and their roles

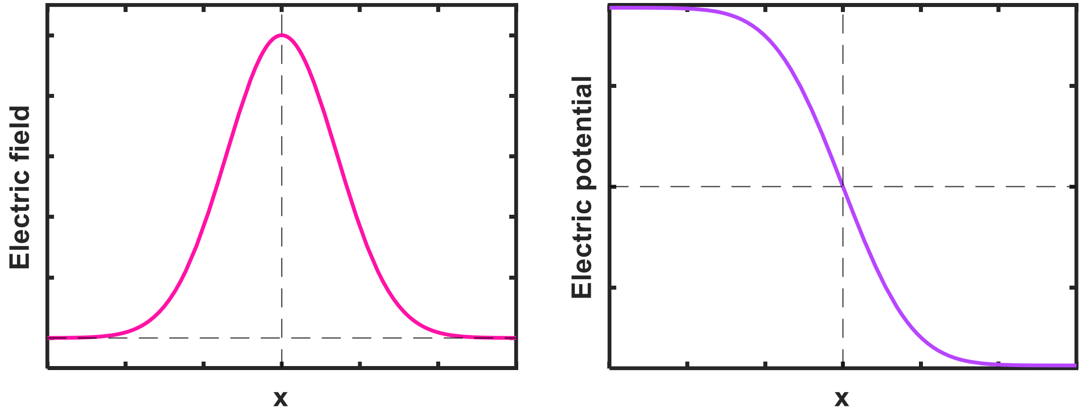
- Isolated electric field pulses which maintain their shape as they propagate.
- Propagate along the magnetic field lines.
- Have been observed in different regions of Earth's magnetosphere (Omura et. al, 1999; Pickett et. al, 2013; Mozer et. al, 2013).

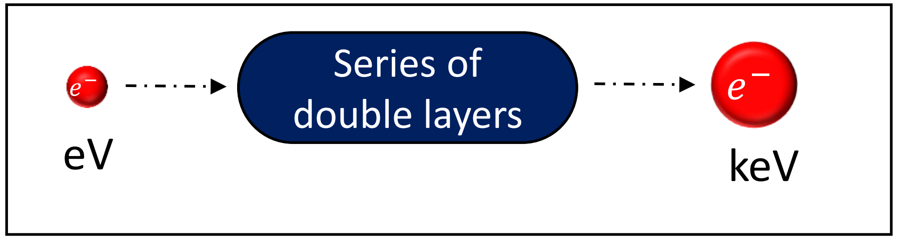
Bipolar solitary wave



Trapping of **ions** and **electrons**

Monoplar solitary wave (DL)

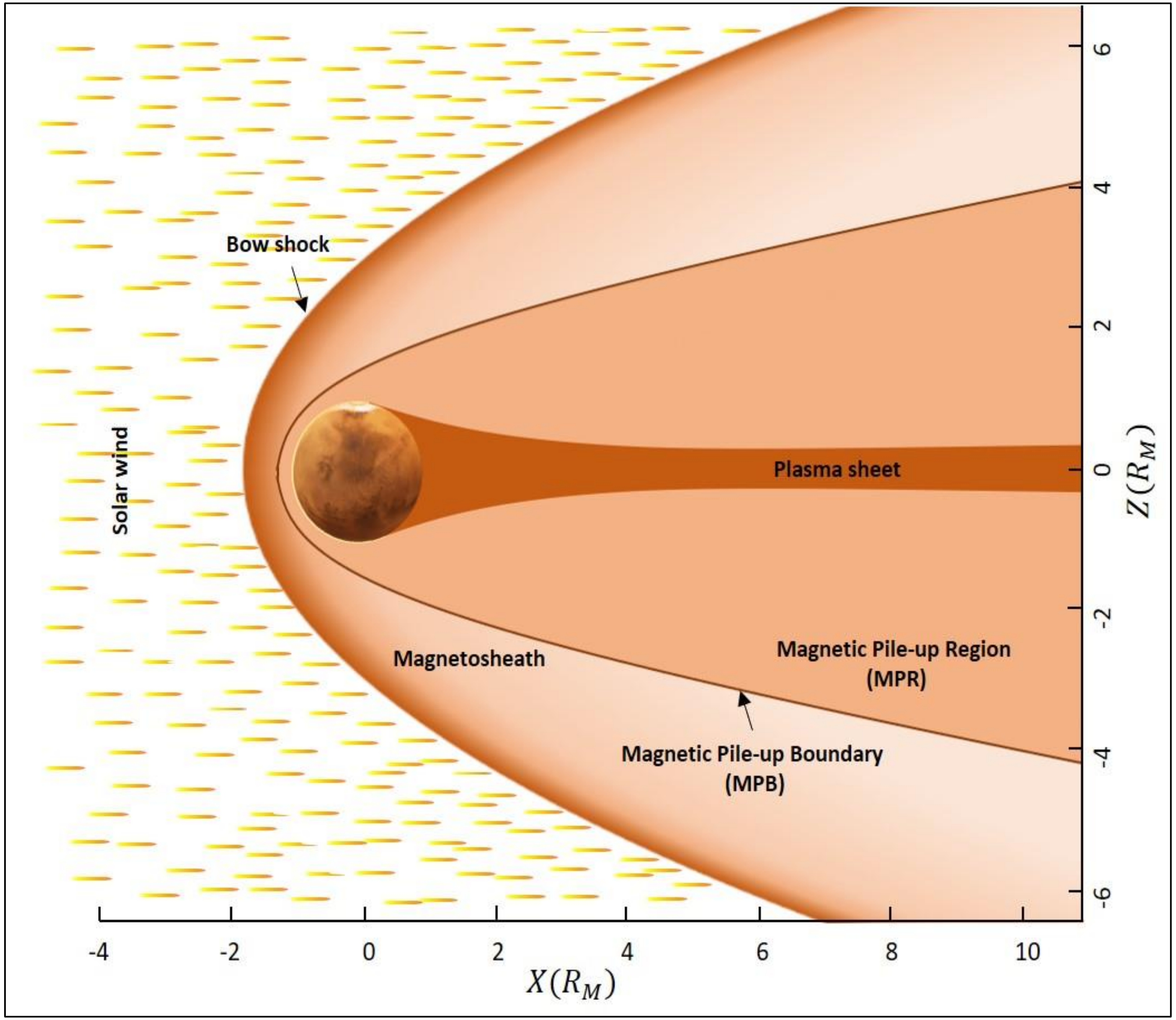




Acceleration of charged particles through series of double layers

Martian plasma environment

- Solar wind directly interacts with the Martian atmosphere.
- Formation of bow shock, Magnetosheath and Magnetic Pile-up region.
- Magnetic field drapes around the Mars.
- Bowshock distance and MPB are situated at 1.63 R_M and 1.25 R_M respectively.
- Thickness of Magnetosheath is of the order of proton gyroradius.



Schematic of Martian induced magnetosphere

Motivation

- Mars has a very thin atmosphere which is constantly being stripped by solar wind.
- Despite its small-scale magnetosphere, various plasma wave activities have been reported.
- Recently, the presence of electrostatic solitary waves has been reported in the Martian plasma environment, but detailed investigations are yet to be carried out (Kakad et al., 2022; Thaller et al., 2022).
- It would be interesting to investigate the role of such waves in an unmagnetized planet like Mars, which is constantly losing its atmosphere.

Data used

Mars Atmosphere and Volatile EvolutioN (MAVEN) mission overview

- Designed to study upper atmosphere of Mars
- Launched by Atlas V rocket on Nov 18, 2013 and Arrived at Mars on Sept 21, 2014
- Perigee: At 150 km ; Apogee: At 6200 km

Instrument: Langmuir Probe and Waves (LPW)

Data: Medium Frequency Burst Mode Calibrated Electric-Field Data

Range: $\pm 1\ V/m$	Resolution: $0.3\ mV/m$	
Data	**Sampling rate (s^{-1})**	**Frequency**
E_{MF}	$65536(2^{16})$	$\sim 100Hz\ to\ 32kHz$

- It measures E_y component of electric field in the spacecraft/payload coordinate system.

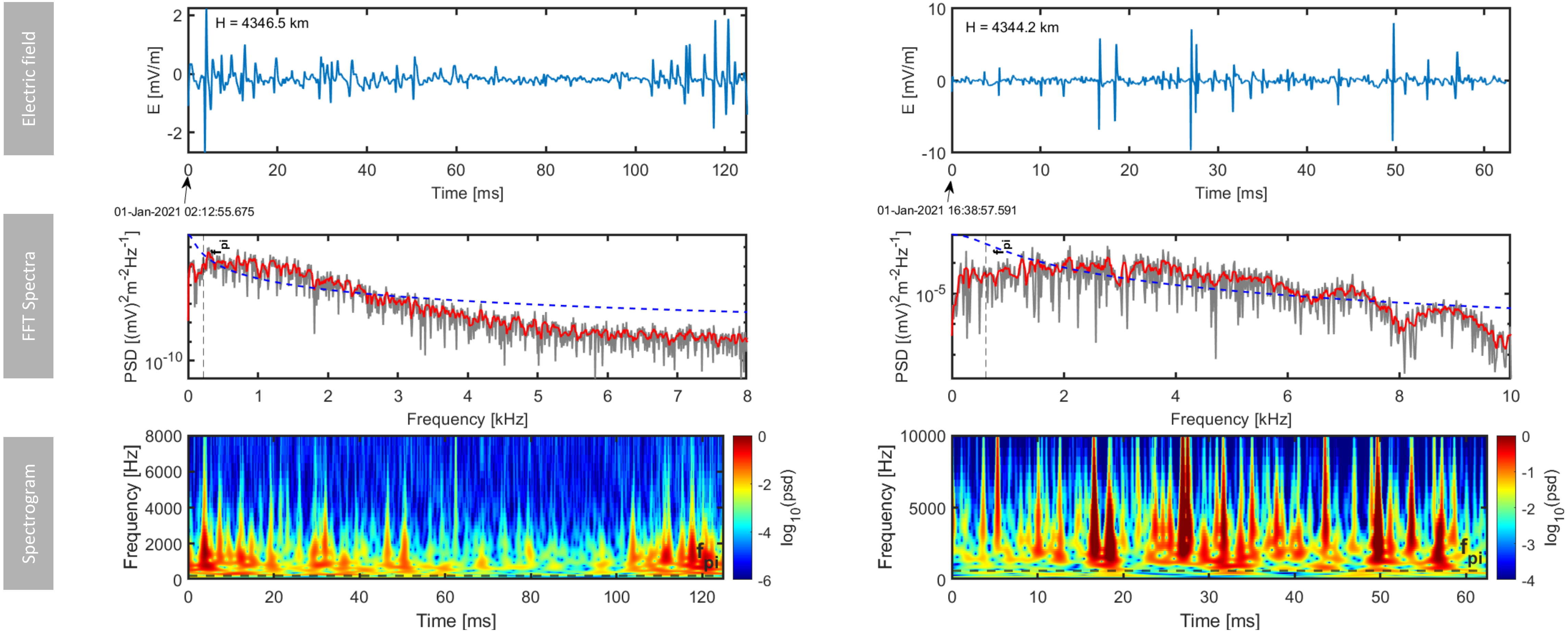
Data link: https://search-pdsppi.igpp.ucla.edu/search/?sc=MAVEN&t=Mars&i=LPW

Observation

Date	1-Jan-2021	No. of Passes	6	No. of burst modes	40

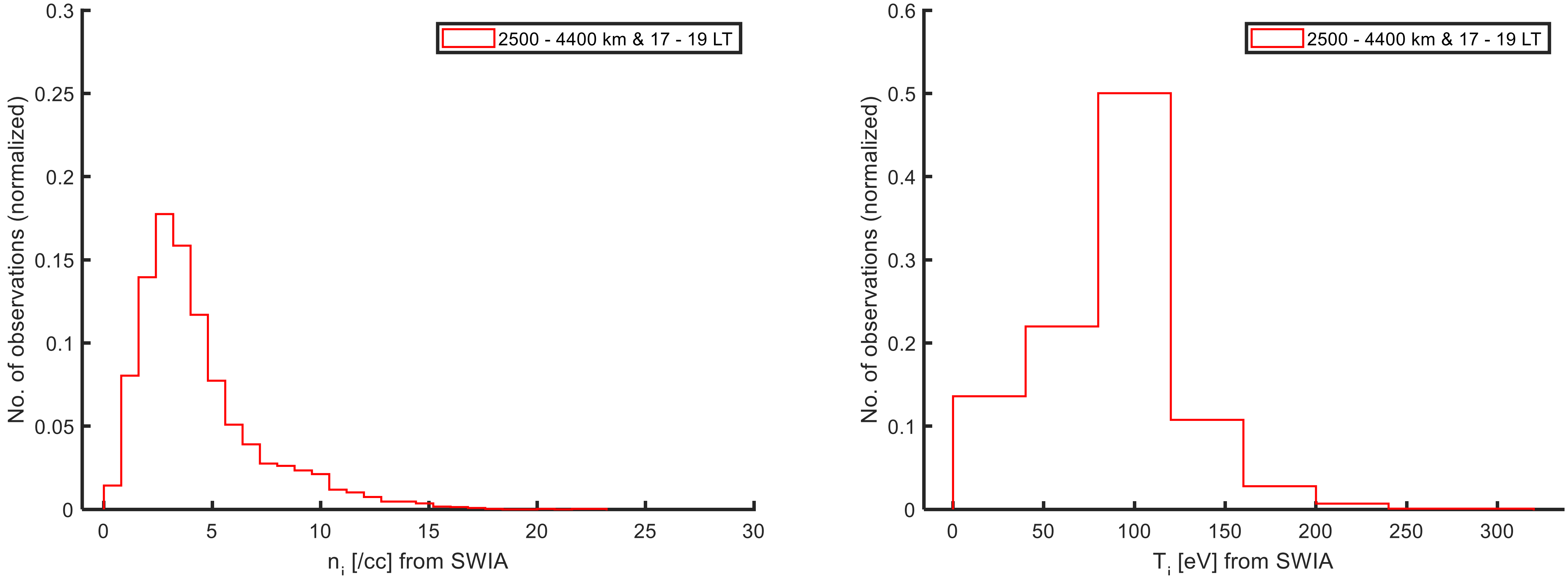
ESW Characteristics	Amplitude	$0.5 - 15.9\ mV/m$	Width (Δt)	$0.09 - 0.52\ ms$	f_{peak}/f_{pi}	> 1 (Mostly)

Examples of of solitary waves observation by LPW instrument



Background parameters

Parameters	Values	Parameters	Values
LT	17-19 LT	n_i	$3-5\ cm^{-3}$
Altitude	2500 – 4400 km	T_i	$70-100\ eV$
B	$2-5\ nT$	f_{pi}	$360-470\ Hz$



Theory

Fluid approach

Three-component model: Ion (n_0, T_i), hot electron (n_{he}, T_{he}) & cold electron (n_{ce}, T_{ce}).

Eq. of continuity: $$\frac{\partial n_j}{\partial t} + \frac{\partial (n_j v_j)}{\partial x} = 0$$

Eq. of motion: $$\frac{\partial v_j}{\partial t} + v_j \frac{\partial v_j}{\partial x} + \frac{q_j}{m_j}\frac{\partial \phi}{\partial x} + \frac{1}{m_j n_j}\frac{\partial P_j}{\partial x} = 0$$

Equation of state: $$\frac{\partial P_j}{\partial t} + v_j \frac{\partial P_j}{\partial x} + 3P_j \frac{\partial v_j}{\partial x} = 0$$

Poisson's equation: $$\frac{\partial^2 \phi}{\partial x^2} = -\sum_j q_j n_j$$

Where, $j = i, he\ \&\ ce$

Transformation to wave frame

$$\xi = x - Mt, \qquad \frac{\partial}{\partial t} = -M\frac{d}{d\xi}, \qquad \frac{\partial}{\partial x} = \frac{d}{d\xi}$$

Where, M is normalized wave speed.

$$\frac{d^2\phi}{d\xi^2} = -\sum_j^{i,he,ce} q_j n_j$$

$$\frac{d^2\phi}{d\xi^2} = -\frac{dS}{d\phi}$$

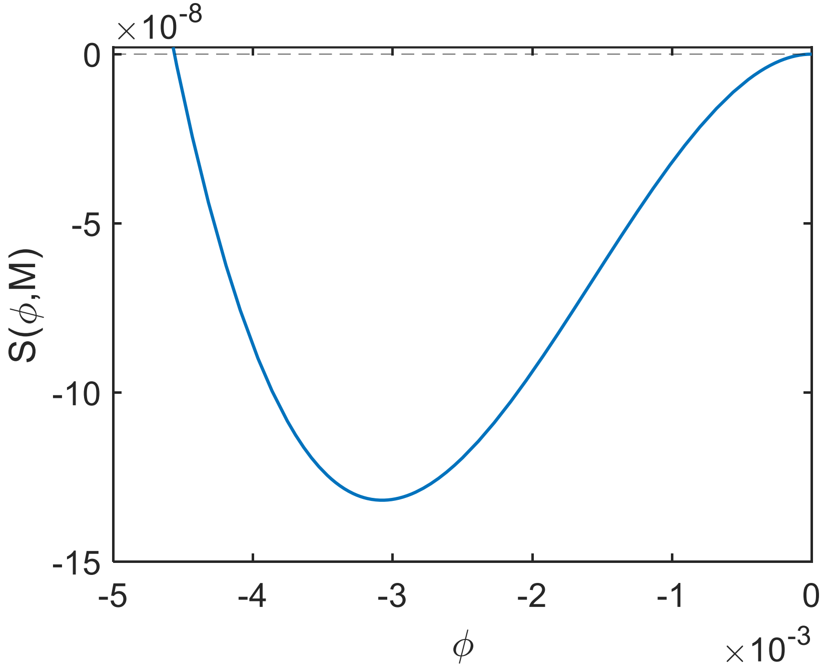
$$\frac{1}{2}\left(\frac{d\phi}{d\xi}\right)^2 + S(\phi, M) = 0$$

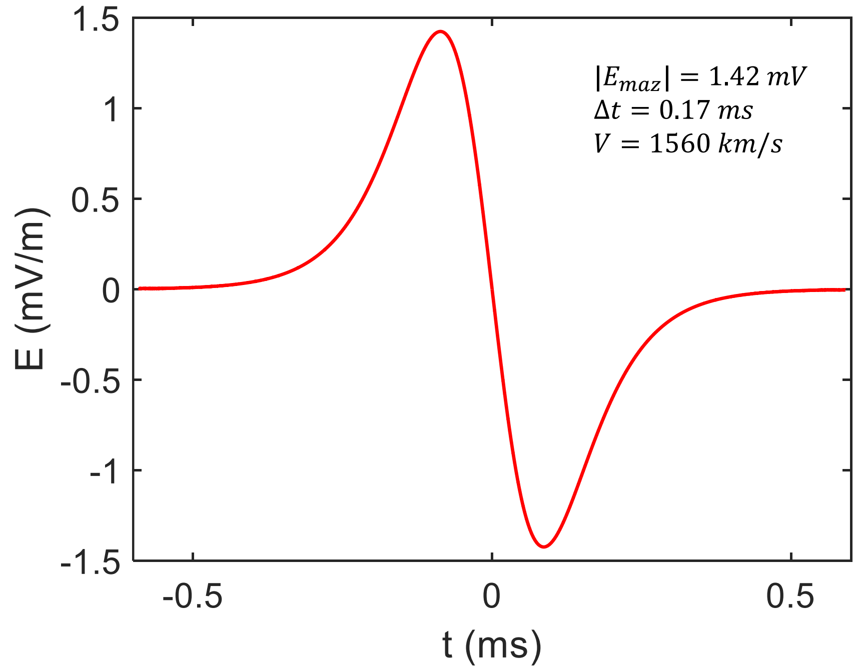
$$S(\phi, M) = \int_0^{\phi} \sum_j^{i,he,ce} q_j n_j \, d\phi$$

$$S(\phi, M) = \sum_{j}^{i,he,ce} \left[\frac{m_j n_{0j} A_{j+}^3}{6B_j} \left[1 - \left(1 - \frac{2q_j\phi}{m_j A_{j+}^2} \right)^{\frac{3}{2}} \right] - \frac{m_j n_{0j} A_{j-}^3}{6B_j} \left[1 - \left(1 - \frac{2q_j\phi}{m_j A_{j-}^2} \right)^{\frac{3}{2}} \right] \right]$$

Where $A_{j\pm} = M - v_{0j} \pm B_j$ and $B_j = \sqrt{3} v_{thj}$

Solution range, $M = 17.09626 - 18.62732$





Parameters: $n_{ce}/n_0 = 0.25$, $n_0 = 5\ cm^{-3}$, $T_i = 85\ eV$, $T_{he} = 15\ eV$, $T_{ce} = 1\ eV$, $M = 17.29626$

Condition for Solitary wave solution

1. $S(\phi, M) = 0\ at\ \phi = 0$
2. $\frac{dS}{d\phi} = 0\ at\ \phi = 0$
3. $\frac{d^2 S(\phi,M)}{d\phi^2} < 0\ at\ \phi = 0$
4. $S(\phi_0, M) = 0\ for\ 0 < |\phi| < |\phi_0|$
5. $S(\phi_0, M) < 0\ for\ 0 < |\phi| < |\phi_0|$

Simulation

Numerical scheme: Finite difference method

Accuracy: 4th order in space & 2nd order in time (Kakad et al., JGR, 2014)

Model: Ion (n_0, T_i), hot electron (n_{he}, T_{he}) & cold electron (n_{ce}, T_{ce})

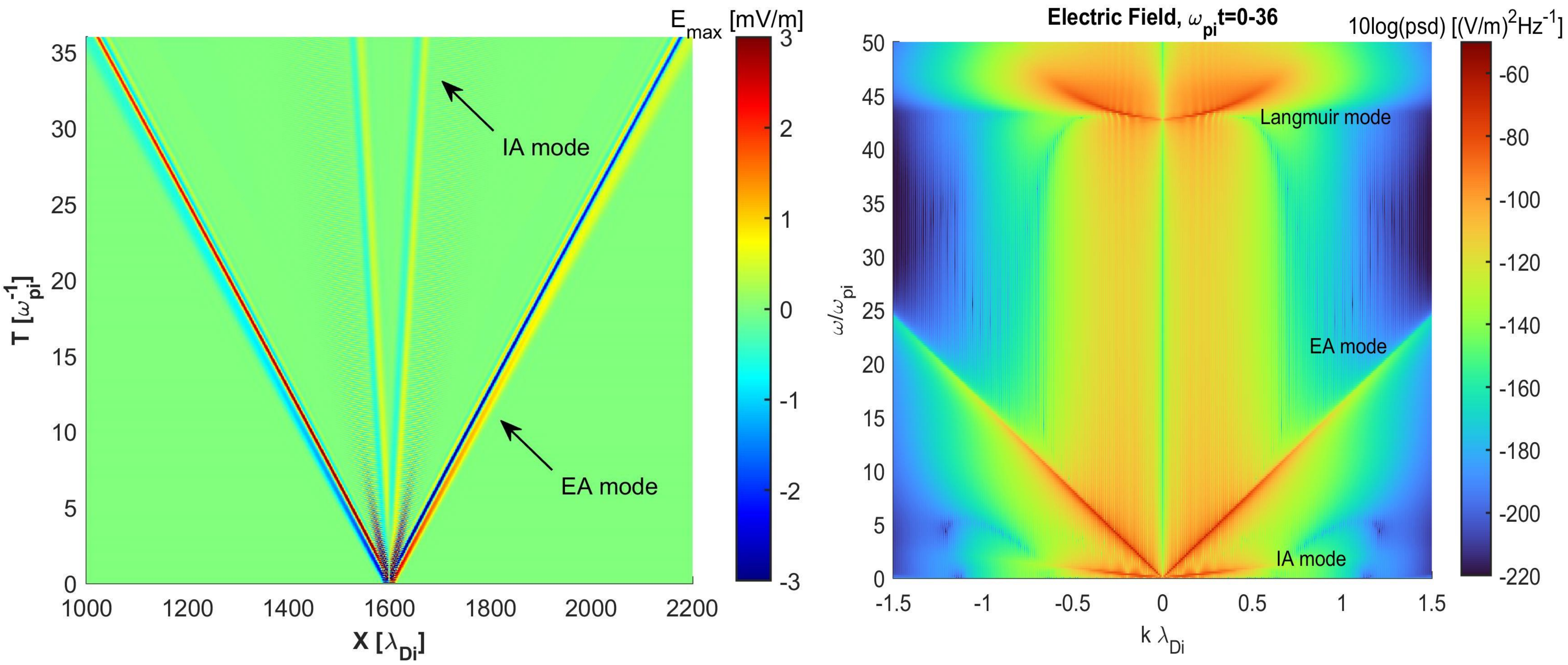
Simulation parameters:

Parameters	Values	Parameters	Values
T_i	$85\ eV$	v_{Ti}	$90\ km/s$
T_{he}	$15\ eV$	v_{The}	$1624\ km/s$
T_{ce} (assumed)	$1\ eV$	v_{Tce}	$419\ km/s$
n_0	$5\ cm^{-3}$	λ_{Di}	$30.6\ m$
n_{ce} (free parameter)	$1.25\ cm^{-3}$ (25%)	Temporal grid size (Δt)	$2 \times 10^{-5}\ \omega_{pi}^{-1}$
Spatial grid size (Δx)	$0.2\ \lambda_{Di}$	l_0	$6.4\ \lambda_{Di}$
Length scale (L_x)	$3200\ \lambda_{Di}$	Δn	$15\%\ n_0$

Density: $n_j(x) = n_{0j}(x) + \delta n$

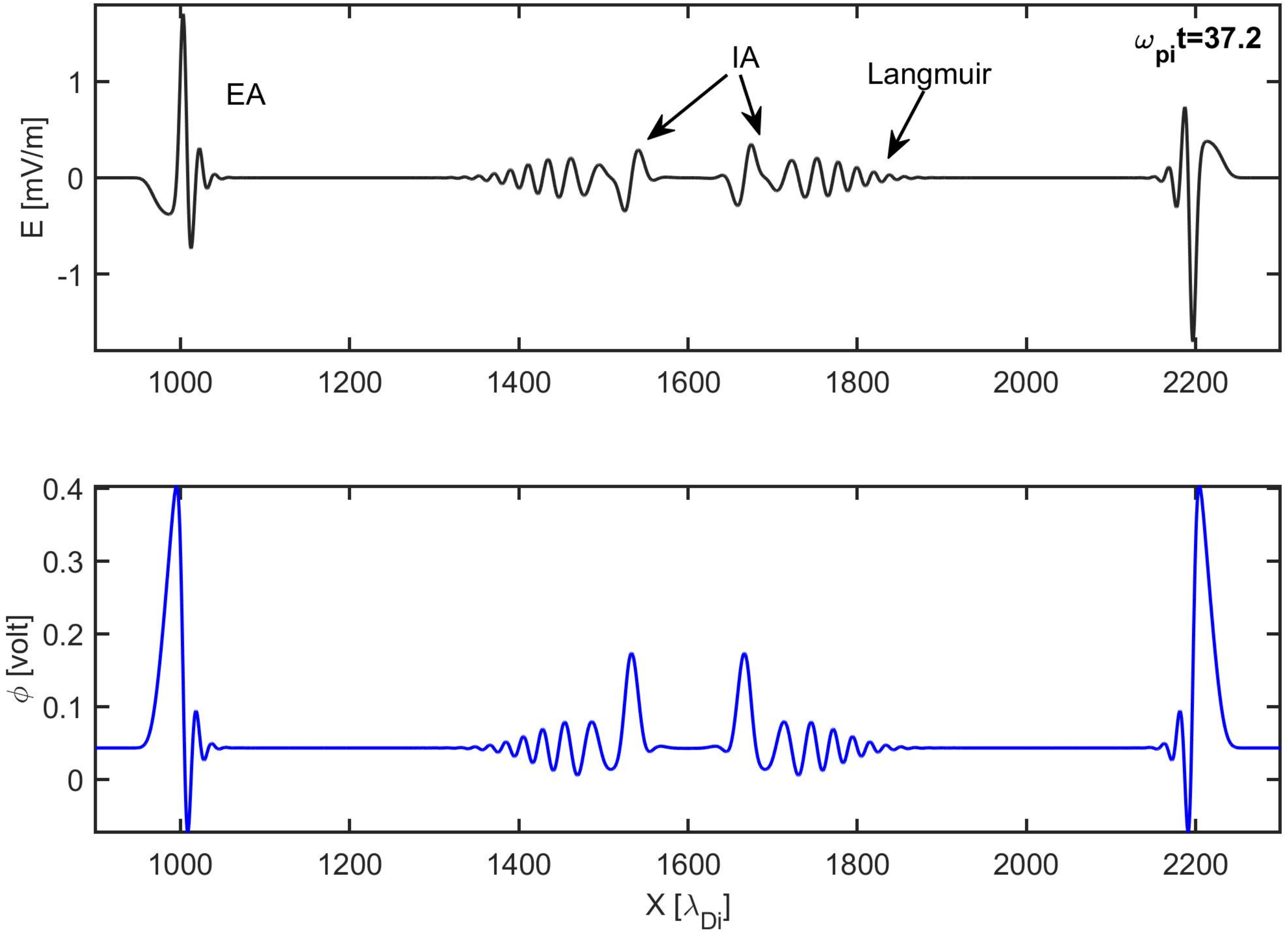
Density perturbation: $\delta n = \Delta n \exp\left(-\frac{(x-x_c)^2}{l_0^2}\right)$

Simulation result: $\boldsymbol{X}-\boldsymbol{T}$ and $\boldsymbol{\omega}-\boldsymbol{k}$ plot



Electron Acoustic mode is driven by cold and hot electrons. Speed is 16.6 v_{Thi}.

Example of Formation of Solitary Waves in Simulations



ESW characteristics	
Amplitude (E_{max})	$1 - 1.15\ mV/m$
Width (Δt)	$0.2\ ms$
Speed (V)	$1494\ km/s$

Conclusion

- We present observations of solitary waves using the LPW instrument from Jan 1, 2021.
- These waves are observed at altitudes ranging from 2500 km to 4400 km around 17-19 LT.
- The frequencies associated with the solitary waves are greater than the ion plasma frequency f_{pi} , suggesting that they could be associated with electron dynamics..
- We modeled the observations using a nonlinear fluid approach and simulations.
- Both theory and simulation suggest that the observed solitary waves are Electron Acoustic Solitary Waves (EASWs).
- The characteristics of Electron Acoustic Solitary Waves are in agreement with the observations.

Thank you