Particle Transport Driving Nonlinear Plasma Waves at Injection Fronts in the Inner Magnetosphere

David Malaspina\textsuperscript{1}, Aleksandr Ukhorskiy\textsuperscript{2}, Xiangning Chu\textsuperscript{1}, John Wygant\textsuperscript{3}

\textsuperscript{1} U. Colorado / LASP Boulder, CO
\textsuperscript{2} APL Laurel, MD
\textsuperscript{3} University of Minnesota Minneapolis, MN

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Magnetotail reconnection drives narrow (1 Re) Earthward injection flow channels: Bring particles Earthward And drive waves!
Injections and plasma wave activity (~2011)

Flow breaking

MHD modes

Injection

Betatron acceleration (μ conservation)

Velocity Space Instabilities

Whistler-mode, EMIC, magnetosonic waves...

Relativistic electron acceleration, ion/electron losses

After a figure by: Chris Chaston
Injections and plasma wave activity (~2018)

Flow breaking

MHD modes

Cascades, phase mixing, filamentation

Kinetic Alfvén Waves

Field-aligned electron acceleration, ion heating, ionospheric ion outflows

Time Domain Structures (phase space holes, double layers, solitons)

Electron acceleration, electron scattering

Whistler-mode, EMIC, magnetosonic waves...

Nonlinear whistler-mode waves

Relativistic electron acceleration, ion/electron scattering

Betatron acceleration (μ conservation)

Velocity Space Instabilities

After a figure by: Chris Chaston
Waves at Plasma Boundaries (burst mode data)

Phase space holes

e- solitary structures

double layers

Kinetic Alfven waves

Nonlinear whistlers

Kinetic waves + structures confined near plasma boundaries (injections, plasma sheet edge, plasmapause)

[Malaspina+ 2015]
Waves at Plasma Boundaries (burst mode data)

Kinetic waves + structures in CRESS data
Nearly all boundaries have kinetic structures AND nearly all kinetic structures appear at boundaries (Injections, plasma sheet inner edge, plasmapause)
Impacts


[Artemyev+ 2015] Electron trapping and acceleration by kinetic Alfvén waves in the inner magnetosphere (JGR)

[Osmane+ 2016] On the connection between microbursts and nonlinear electronic structures in planetary radiation belts (APJ)

[Chaston+ 2016] Driving ionospheric outflows and magnetospheric O\(^+\) energy density with Alfvén waves

[Vasko+ 2017] Diffusive scattering of electrons by electron holes around injection fronts

[Mozer+ 2017] Pulsating auroras produced by interactions of electrons and time domain Structures (JGR)

[Chaston+ 2017] Radial transport of radiation belt electrons in kinetic field-line resonances

Kinetic Structures and Waves:
Scatter, Transport, and Accelerate the ~few keV and Seed (10 keV – 100 keV) populations

Quantifying how these waves / structures impact the plasma requires a census:

- Which waves/structures are most prevalent?
- What are their properties (amplitudes, spatial scales)?
- Where are their preferred growth regions?

A census requires:

- lots of time-domain fields burst data (non-unique spectral signatures)
- automated identification algorithms

In this work, we:

- Identify periods of unbroken burst data
- Develop and apply ID algorithms
- Reveal the zoo of waves/structures and their properties, statistically
Electron injection
- MeV flux ~steady
- Dispersionless e- increase

Fields burst systems:
- EFW B1
  - 6V, 3 SCM @ 16.4 k sample/s
  - scientist-selected interval
- EFW B2
  - 6V, 3E, 3 SCM @ 16.4 k sample/s
  - s/c selected 6 s bursts
- EMFISIS Trig.
  - 3E, 3 SCM @ 35 k sample/s
  - s/c selected 6 s bursts
- EMFISIS Continuous
  - 3E, 3 SCM @ 35 k sample/s
  - timed 0.5 s bursts (each 15 min)

This event:
- 45 min of unbroken B1 coverage!
Particle Injection

“Dispersionless” injection shows dispersion of anisotropy

Consistent with: Injection far Earthward of plasma sheet inner boundary (Assume conservation of μ)

Perpendicular electrons: 300 keV e- near front traveled at least 6 Re

Parallel electrons: 10 keV e- near front local e- caught in flow (accelerated locally?)

Flux || 8.18°, 24.5°, 155.45°, 171.8°
--------- = ------------------------------------
Flux prp. 90°
Particle Injection

Behind the front:
- 300 keV e- are local (closed drift paths) did not travel with the front

Behind the front:
- 10 keV e- traveled with front (but not very far)
Injection as wave driver

Four distinct $B_z$ enhancements

Each drives a full spectrum of waves
- ECH
- whistler-mode
- KAW
- phase space holes
Each Bz enhancement drives full spectrum of waves

- $f > 2 \text{f}_{ce}$ (ECH)
- $f_{ce} < f < 2 f_{ce}$ (ECH)
- $0.5 f_{ce} < f < f_{ce}$ (UB Whistler-mode)
- $0.1 f_{ce} < f < 0.5 f_{ce}$ (LB Whistler-mode)
- $f < 0.1 f_{ce}$ (Kinetic Alfven)

Electron Flux ($\sim 30$ keV)

$|B|$ and Bz

Injection as wave driver
A Zoo of waves

Kinetic Alfvén waves
(Chaston+ 2014, 2016)

Nonlinear whistler-mode waves
(Mozer+ 2013)

Phase space holes
(Mozer+ 2013
Osmane + 2017
Artemyev+ 2014)

Phase space holes with $|B|$ spikes
(Malaspina+ 2014
Vasko+ 2015)
Electron Holes

Compare hole properties
- Burst 1 (this work) $\sim 4,200$ EH
- Burst 2 [Vasko+ 2017] $\sim 100$ EH

[Vasko+ 2017] EH Diffusion coeff (lead factor):

$$D_0 = \left( \frac{2\pi}{m_e^2 \omega_0^3} \right) \left( \frac{1}{L_L L_L} \right) \left( \frac{d_{||}}{d_{||}} \right)^2 1 \phi_0^2$$

Burst 1 holes:
- shallower ‘typical’ potential
- Implies 10x to 100x weaker diffusion than estimated using triggered bursts

What about event-to-event variation?
Nonlinear Whistler-Mode Waves

Lower-band whistler-mode waves
- Both E and B show harmonics
  - signals at 2f for waves at f
- Harmonics above f only
- Distorted waveforms indicate strong harmonics
- Harmonics more electrostatic than primary waves
- not strong enough to be noticed in SCM time-series, but often exist
Nonlinear Whistler-Mode Waves

Harmonic vs. Primary signals

3,192 of the 5,400 intervals (0.5 s each) are dominated by whistler-mode waves

E-field harmonics:
- $E_{2f}$ increases with $E_f$
- $E_{2f}$ as large as 14% of $E_f$
- $E_{2f}$ observable for waves $> 1 \text{ mV/m}$

B-field harmonics:
- $B_{2f}$ increases with $B_f$
- $B_{2f}$ as large as 3% of $B_f$
- $B_{2f}$ observable for waves $> 0.1 \text{ nT}$

Nonlinear behavior is common, not exceptional, for lower band whistler-mode waves

(амplitudes from sum of spectral data, bandpass of +/- 100 Hz about $f$ or $2f$)
Conclusions

[1] The studied injection transported e- at least 6 $R_E$ from plasma sheet into inner magnetosphere

[2] This injection had four separate magnetic compressions
    Each compression drove waves across the observed spectrum

[3] A zoo of nonlinear waves and kinetic structures are observed
    (though not all previously identified were found)

[4] ‘Typical’ phase space holes are weaker than estimated using triggered burst data
degree of event-to-event variation?

[5] Lower band whistler-mode waves show amplitude-dependent nonlinearities (harmonics)
    These harmonics are common over a range of amplitudes

[6] Statistical study under way
    Are there ‘typical’ wave / structure properties at these boundaries?
    How is injection energy partitioned into various wave types?

[7] How important are these structures/waves for the inner magnetosphere?
Fin
**Instrumental Harmonics?**

**Black:** $E_{2f}$ vs. $E_f$ (from earlier figure)

**Green:** $E_{2f}$ vs. $E_f$ (assuming -40 dB of instrumental harmonic distortion)

**Red:** $B_{2f}$ vs. $B_f$ (for upper band whistler-mode waves, when upper band is stronger than lower band)
Instrumental Harmonics?

Harmonics in the electronics?

- THD = total harmonic distortion = \(2f + 3f + 4f\) ...

- EFW receiver board verified ~ -70 dB THD
- EFW preamps, bias board verified ~ -40 dB THD

- SCM sensor (?)
  - No strong \(B_{2f}\) for upper band waves

Harmonics in the plasma sheath?

- SCM has no plasma sheath effect

- \(E_{2f}\) envelope does not follow \(E_f\) envelope
  (expected for sheath harmonic [Boehm+ 1994])

Eliminated electronics, sheath, left with:
Harmonics are real!
- $E_{2f}$ envelope does not follow $E_f$ envelope