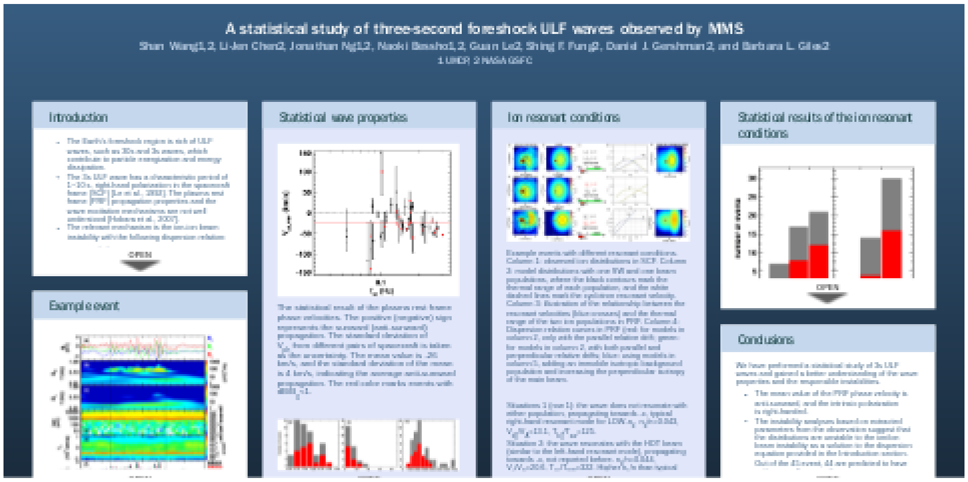
A statistical study of three-second foreshock ULF waves observed by MMS



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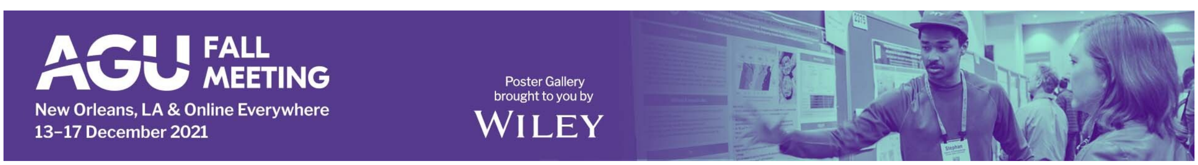


INTRODUCTION

- The Earth's foreshock region is rich of ULF waves, such as 30s and 3s waves, which contribute to particle energization and energy dissipation.
- The 3s ULF wave has a characteristic period of 1~10 s, right-hand polarization in the spacecraft frame (SCF) [Le et al., 1992]. The plasma rest frame (PRF) propagation properties and the wave excitation mechanisms are not well understood [Hobara et al., 2007].
- The relevant mechanism is the ion-ion beam instability with the following dispersion relation:

$$1 - \frac{k^2c^2}{\omega^2} + \sum_j K_j^-(k,\omega) = 0$$

where $K_j^-(k,\omega) = \frac{\omega_j^2}{\omega^2}[\xi_j Z(\xi_j^-) + (1 - \frac{T_{\perp j}}{T_{\parallel j}})\frac{Z'(\xi_j^-)}{2}], \xi_j = (\omega - \mathbf{k}\cdot\mathbf{v_{0j}})/kv_j$,
$\xi_j^- = (\omega - \mathbf{k}\cdot\mathbf{v_{0j}} - \omega_{cj})/kv_j$

The subscript j represents the population (incoming solar wind (SW), beam (b) and electron (e)), and each population follows a drift-Maxwelldian distribution with a drift velocity of v_{0j} and thermal speed of $v_j=\sqrt{(2T_{\parallel j}/m_j)}$, Z and Z' are the plasma dispersion function and its derivative, $\omega_{cj}=q_jB/m_j$ is the cyclotron frequency.

Let x be along the background B_0 with the positive direction same with the beam motion; SW moves towards -x. Consider $k=k_x>0$, and the sign of ω_r indicates the propagation towards + or - x direction.

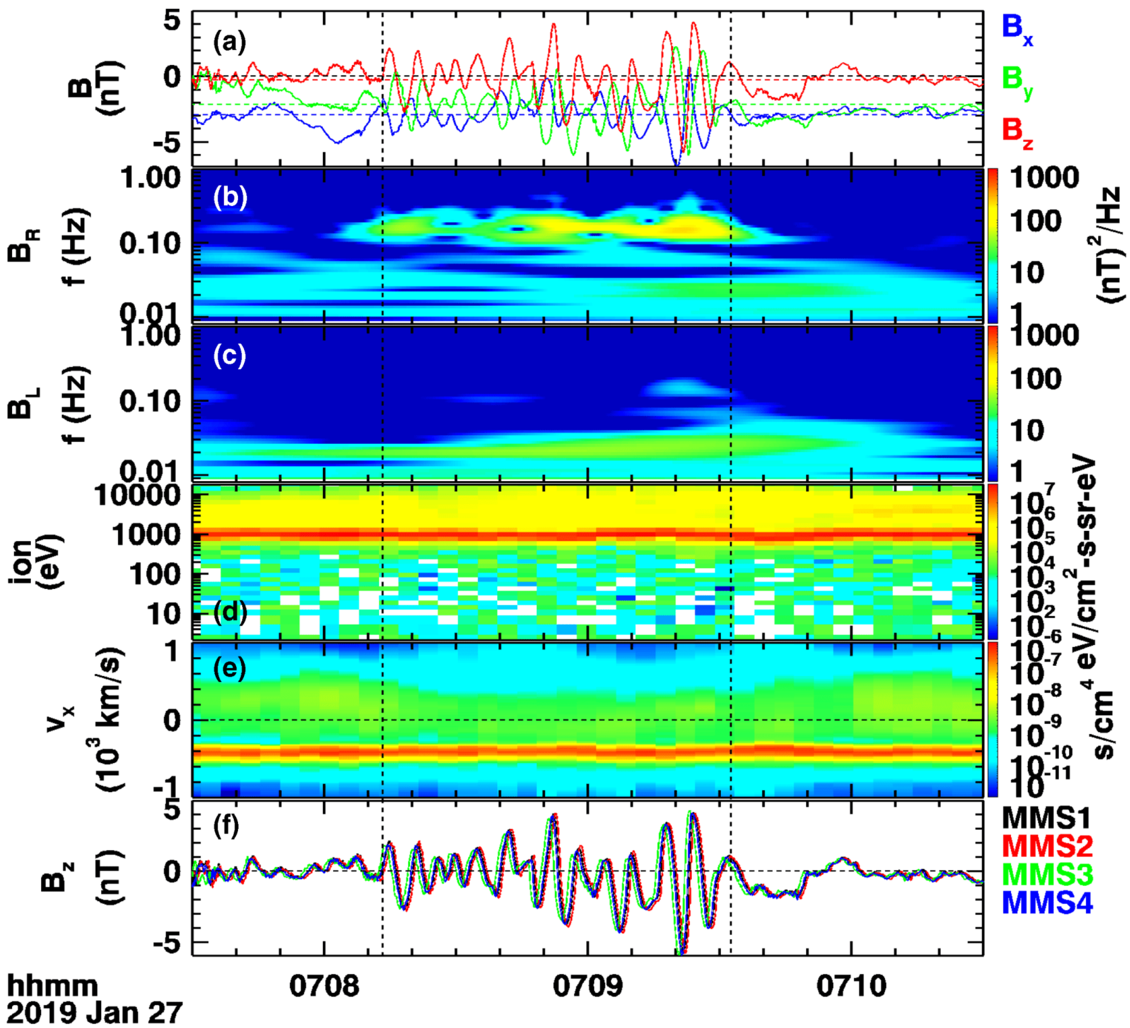
Resonant condition: $|\xi_j^-|<\sim1$

Candidate instabilities:

- right-hand non-resonant instability: propagate toward -x in PRF, not resonant with either ion population or resonant with SW when n_b and/or dV/V_A is large [Gary et al., 1984; Akimoto et al., 1993].
- left-hand resonant instability: propagate toward +x, resonant with the beam, requring a hot beam distribution with many particles moving with vx<0 [Gary et al., 1984].

We will discuss the wave properties of 45 3s ULF events observed by MMS, and discuss the responding instability and ion resonant conditions using the linear instability analysis with extracted parameters from the observations.

EXAMPLE EVENT



An example 3s ULF wave event. (a) magnetic field in GSE with the horizontal lines marking the background B_0 level. (b)-(c) wavelet power spectra of the magnetic field separated into the right-hand and left-hand modes in SCF. The 3s wave has right-hand polarization, co-existing with the left-hand 30s wave. (d) and (e) Ion energy spectrogram and phase-space spectrogram along vx showing the SW and beam populations. (f) B_z from four spacecraft with similar waveforms and clear time delays, used for determining $V_{ph.}$

Propagation direction: [-0.818, -0.517, 0.073] GSE.

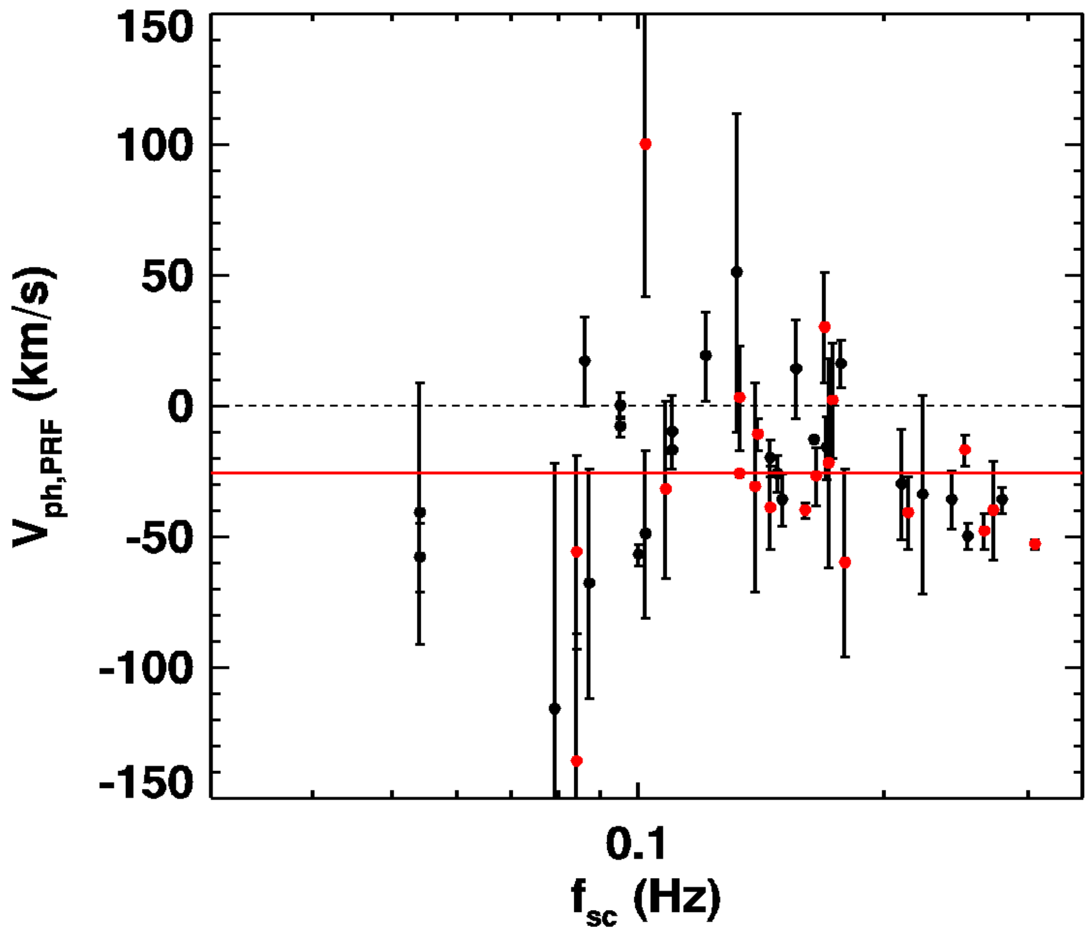
V_{ph} in SCF based on timing between MMS 2-1, 2-4, and 2-3: 299.6, 297.6, and 300.0 km/s.

$<V_{ph}>$ in PRF: -13 km/s=-0.31 V_A (anti-sunward)

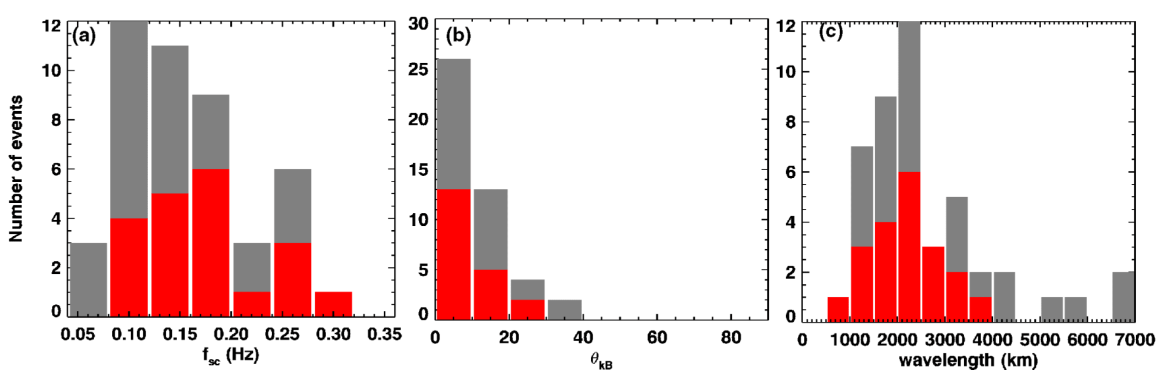
f_{PRF}=0.13 f_{ci}, kd_i=0.40.

Extracting partial moments for the SW and beam: n_b/n=0.04, $V_{d||}/V_A$=13.1, $V_{d\perp}/V_A$=2.9, β_{SW}=0.9, $T_{b||}/T_{SW}$=125, $T_{b\perp}/T_{b||}$=1.8. The linear instability analysis predicts the maximum growth for the right-hand resonant mode with kd_i=0.23. The wave is not resonant with either SW or beam.

STATISTICAL WAVE PROPERTIES

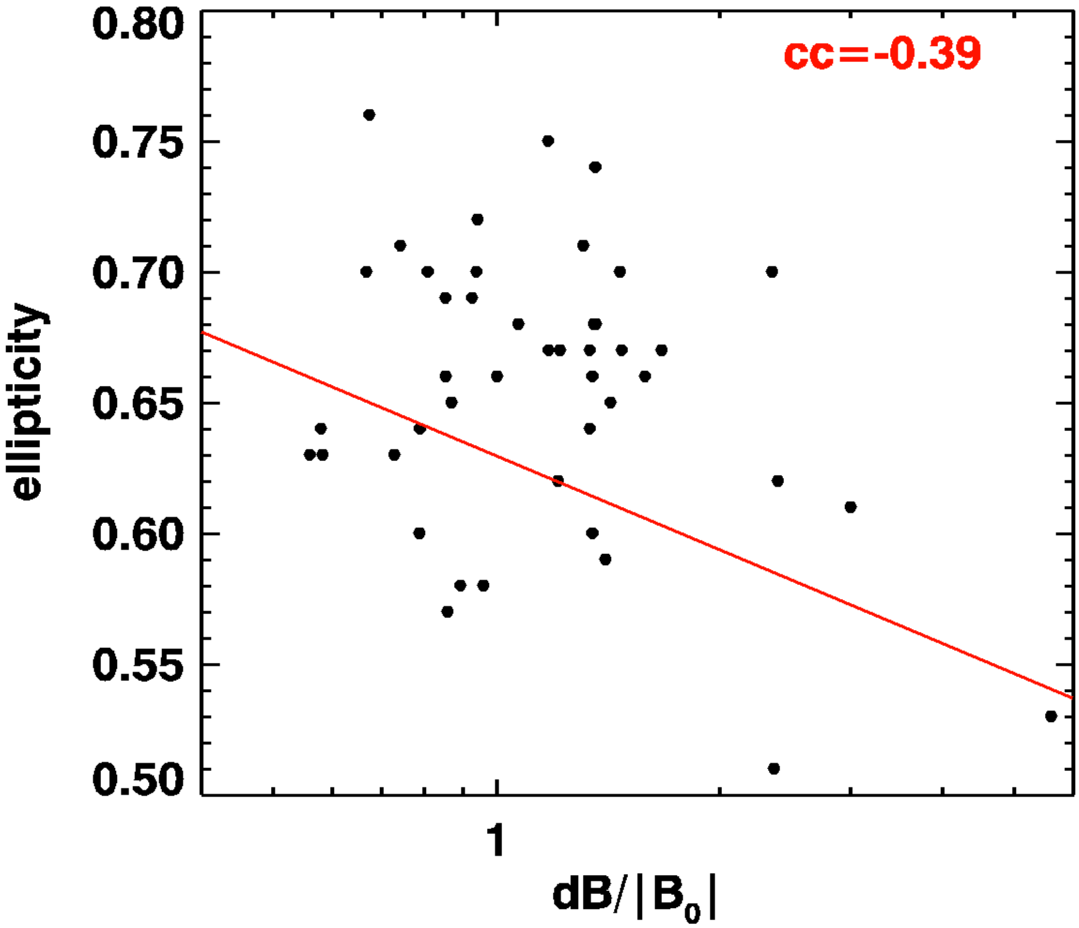


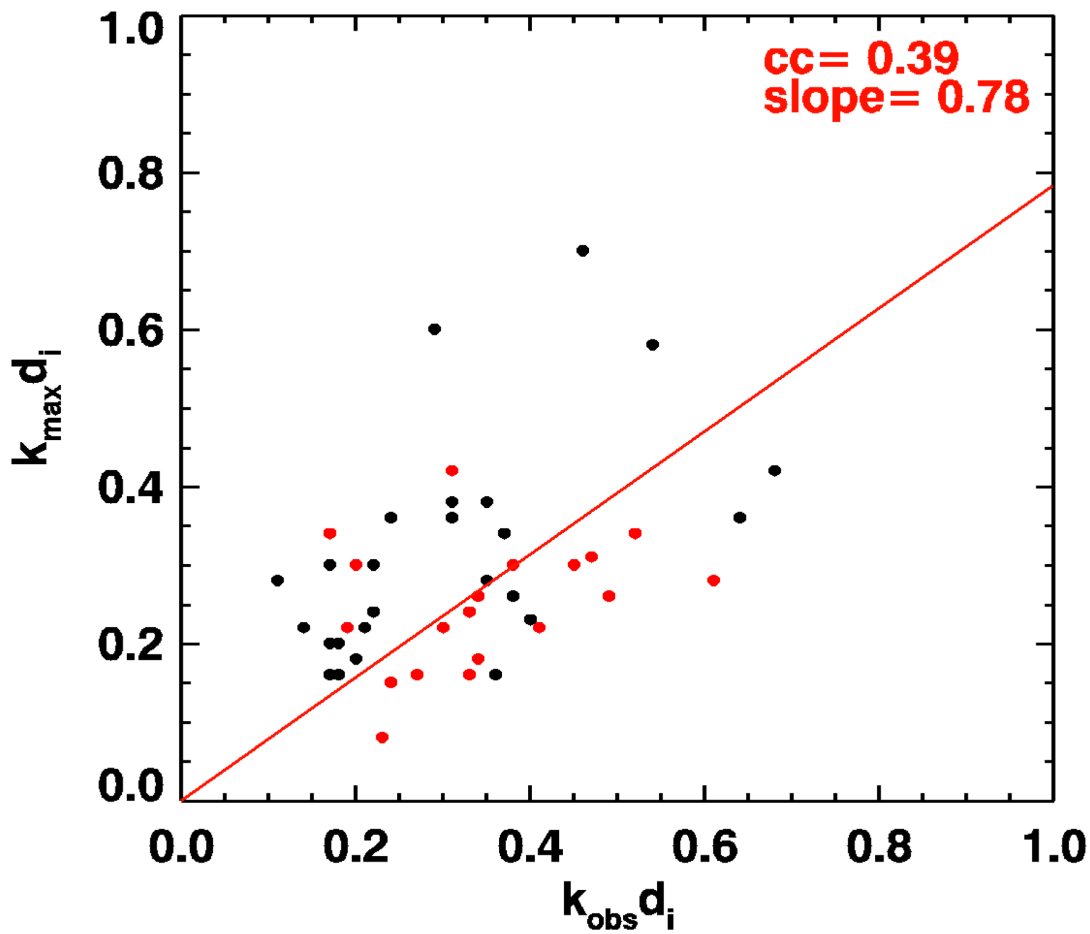
The statistical result of the plasma rest frame phase velocities. The positive (negative) sign represents the sunward (anti-sunward) propagation. The standard deviation of V_{ph} from different pairs of spacecraft is taken as the uncertainty. The mean value is -26 km/s, and the standard deviation of the mean is 4 km/s, indicating the average anti-sunward propagation. The red color marks events with $dB/B_0<1$.



Statistics of the SCF frequency, angle between the propagation and B_0, and the wavelength of the 3s ULF wave.

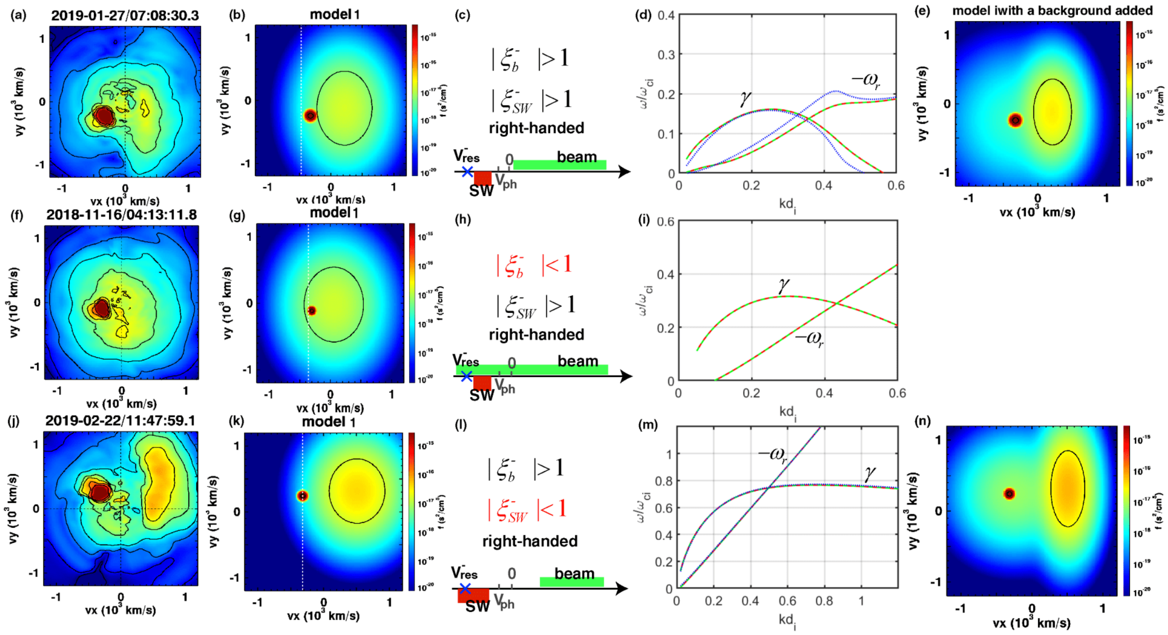
The ellipticity and the wave amplitude exhibit a weak negative correlation, indicating that the wave becomes less well circularly polarized as it grows.


cc=-0.39
0.80
0.75
0.70
0.65
0.60
0.55
0.50
ellipticity
1
dB/|B0|



The wave number at the maximum growth rate (k_{max}) from the linear instability analysis shows reasonable consistency with the observed wave number (k_{obs}).

ION RESONANT CONDITIONS



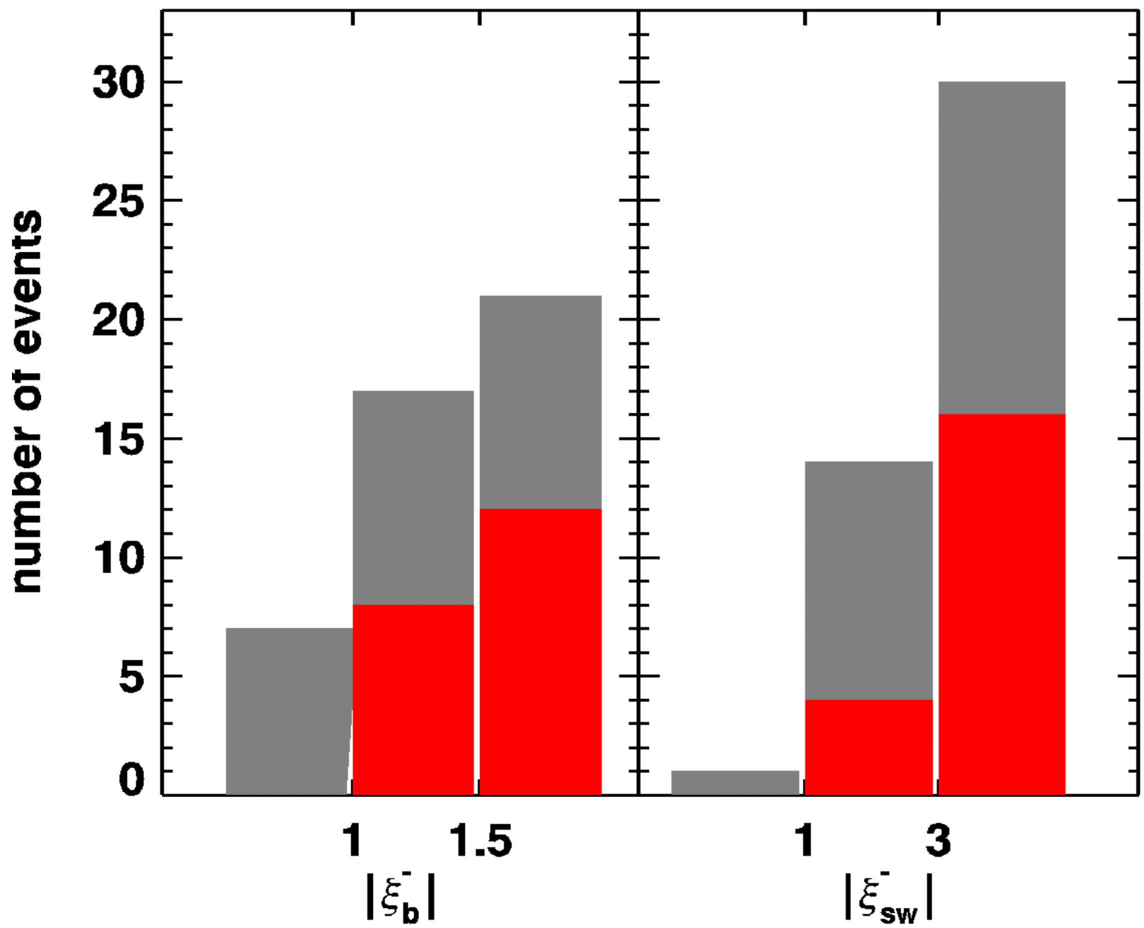
Example events with different resonant conditions. Column 1: observed ion distributions in SCF. Column 2: model distributions with one SW and one beam populations, where the black contours mark the thermal range of each population, and the white dashed lines mark the cyclotron resonant velocity. Column 3: illustration of the relationship between the resonant velocities (blue crosses) and the thermal range of the two ion populations in PRF. Column 4: Dispersion relation curves in PRF (red: for models in column 2, only with the parallel relative drift; green: for models in column 2, with both parallel and perpendicular relative drifts; blue: using models in column 5, adding an immobile isotropic background population and increasing the perpendicular isotropy of the main beam.

Situations 1 (row 1): the wave does not resonate with either population, propagating towards -x, typical right-hand resonant mode for LOW-n_b. $n_b/n=0.043$, $V_{d||}/V_A=13.1$, $T_{b||}/T_{sw}=125$.

Situation 2: the wave resonates with the HOT beam (similar to the left-hand resonant mode), propagating towards -x, not reported before. $n_b/n=0.044$, $V_d/V_A=20.6$, $T_{b||}/T_{SW}=322$. Higher n_b/n than typical left-hand resonant mode studied in Gary et al. (1984).

Situation 3: the wave resonates with SW, propagating towards -x, right-hand resonant mode for HIGH n_b, HIGH V_d. $n_b/n=0.084$, $V_{d||}/V_A=32.7$, $T_{b||}/T_{SW}=195$.

STATISTICAL RESULTS OF THE ION RESONANT CONDITIONS



Statistics of the event numbers that satisfy the cyclotron resonant conditions $|\xi_j^-|<1$, close to resonance ($1<|\xi_b^-|<1.5$ or $1<|\xi_{SW}^-|<3$), and not in resonance ($|\xi_j^-|>1.5$ or 3), for beam (left) and SW (right) populations. The red color marks events with $dB/B_0<1$.

About half of the events have the beam close to the resonant condition. SW typically is not in resonance, but cases exist when its resonant condition is approximately satisfied.

CONCLUSIONS

We have performed a statistical study of 3s ULF waves and gained a better understanding of the wave properties and the responsible instabilities.

- The mean value of the PRF phase velocity is anti-sunward, and the intrinsic polarization is right-handed.
- The instability analyses based on extracted parameters from the observation suggest that the distributions are unstable to the ion/ion beam instability as a solution to the dispersion equation provided in the Introduction section. Out of the 45 event, 44 are predicted to have anti-sunward propagation.
- In terms of the ion resonant condition, the wave can be (1) not resonant with either ion population, (2) resonant with SW, (3) resonant with the beam with sunward propagation, (4) resonant with the beam with anti-sunward propagation. Situations (1) and (2) correspond to the right-hand non-resonant mode, (3) corresponds to the left-hand resonant mode, and (4) is a new discovery, which exits for hot beams while the beam density is higher than that for the typical left-hand resonant mode.

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AUTHOR INFORMATION

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ABSTRACT

We perform a statistical study of 3-s ultra-low frequency (ULF) waves using MMS observations in the Earth's foreshock region. The average phase velocity in the plasma rest frame is determined to be anti-sunward, and the intrinsic polarization is right-handed. We further examine the linear instability conditions based on drift-bi-Maxwellian distribution functions according to observed plasma conditions. The resulting instability is a solution to the common dispersion equation of the ion/ion right-hand non-resonant and left-hand resonant instabilities. The predicted wave propagation is also predominantly anti-sunward. The cyclotron resonant conditions of the solar wind and backstreaming beam ions are evaluated, and we find that in some cases, the anti-sunward propagating waves can be resonant with beam ions, which was overlooked in previous studies. The result suggests that the dispersion equation provides the 3-s ULF waves a fundamental explanation that unifies a rich variety of resonant conditions. In the later stage, the 3s ULF waves could further develop into Short Large Amplitude Magnetic Structures, contributing to the turbulence in the foreshock region.

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