Identification of the Nature of Electromagnetic Waves near the Proton-cyclotron Frequency in Solar-terrestrial Plasmas

Jinsong Zhao\textsuperscript{1} \textsuperscript{©}, Tiyan Wang\textsuperscript{2}, Daniel B. Graham\textsuperscript{3} \textsuperscript{©}, Jiansen He\textsuperscript{4}, Wen Liu\textsuperscript{1}, Malcolm W. Dunlop\textsuperscript{2,5}, and Dejin Wu\textsuperscript{1}

\textsuperscript{1}Key Laboratory of Planetary Sciences, Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008, People’s Republic of China
\textsuperscript{2}RAL Space, STFC, Oxfordshire OX11 0QX, UK
\textsuperscript{3}Swedish Institute of Space Physics, Uppsala, Sweden
\textsuperscript{4}School of Earth and Space Sciences, Peking University, Beijing 100871, People’s Republic of China
\textsuperscript{5}School of Space and Environment, Beihang University, Beijing 100191, People’s Republic of China

Received 2019 October 18; revised 2019 December 30; accepted 2020 January 1; published 2020 February 7

Abstract

Low-frequency (quasi-)monochromatic electromagnetic waves near the ion-cyclotron frequency always exhibit both left-hand (LH) and right-hand (RH) polarization in solar-terrestrial spacecraft observations. However, due to the Doppler frequency shift resulting from the bulk flow of charged particles, the nature of these waves in the plasma frame is still unclear. This paper proposes a useful method to directly identify the nature of the observed waves. Using three wave parameters including polarization, direction of the parallel Poynting flux, and correlation between perpendicular magnetic field and perpendicular ion/electron velocity, we could discriminate the wave mode (Alfvén/ion-cyclotron wave or fast-magnetosonic/whistler wave) and its propagation direction (along or against the magnetic field) in the plasma frame. Using \textit{Magnetospheric Multiscale} spacecraft measurements, we analyze two wave events containing both LH- and RH-polarized low-frequency electromagnetic waves in the Earth’s magnetosheath, and find that these waves correspond to counter-propagating Alfvén/ion-cyclotron waves in the plasma frame. Our method is helpful for studying low-frequency electromagnetic waves detected by satellites that have particle measurements with an adequate temporal resolution.

\textit{Unified Astronomy Thesaurus} concepts: \textit{Planetary magnetosphere} (997); \textit{Solar wind} (1534); \textit{Space plasmas} (1544); \textit{Plasma physics} (2089)

1. Introduction

The Alfvén/ion-cyclotron wave is a left-hand (LH) polarized wave in a motionless plasma, and this mode is specially named the electromagnetic ion-cyclotron wave as the wave frequency $\omega$ approximates the ion-cyclotron frequency $\omega_{ci}$. Electromagnetic ion-cyclotron waves can play important roles in energizing and scattering the charged particles in solar-terrestrial environments (e.g., Cranmer 2001; Hollweg & Isenberg 2002; Summers & Thorne 2003; Gary et al. 2006; Kasper et al. 2008; He et al. 2015; Roberts & Li 2015; Kitamura et al. 2018). For example, the cyclotron resonant interaction of electromagnetic ion-cyclotron waves with ions can contribute to the acceleration of the fast solar wind (e.g., Cranmer 2001; Hollweg & Isenberg 2002; Ofman et al. 2002). Another low-frequency electromagnetic wave mode is the right-hand (RH) polarized fast-magnetosonic/whistler wave (Gary 1993; Huang et al. 2019). Different from the Alfvén/ion-cyclotron wave defined by $\omega < \omega_{ci}$ the fast-magnetosonic/whistler wave can extend to frequencies larger than $\omega_{ci}$ in the plasma frame (Huang et al. 2019).

Using in situ spacecraft measurements, the low-frequency electromagnetic waves near the proton-cyclotron frequency are usually observed in the solar wind (e.g., Jian et al. 2009, 2010, 2014; Boardsen et al. 2015; Siu-Tapia et al. 2015; Wicks et al. 2016; Ala-Lahí et al. 2019; Li et al. 2019; Zhao et al. 2019a) and in the planetary space environments (e.g., Leisner et al. 2006; Delva et al. 2011; Wei et al. 2011, 2014; Remya et al. 2014; Romanelli et al. 2016; Zhao et al. 2018, 2019b). These waves usually exhibit both LH and RH polarization (e.g., Jian et al. 2010, 2014). However, the observed LH- and RH-polarized electromagnetic waves in the spacecraft frame cannot be directly related to LH-polarized Alfvén/ion-cyclotron and RH-polarized fast-magnetosonic/whistler waves in the plasma frame, respectively. When the charged particles have a bulk flow propagating along the ambient magnetic field at a velocity larger than the wave phase speed, the observed LH-polarized electromagnetic wave can be the forward (along the magnetic field) Alfvén/ion-cyclotron wave or the backward (against the magnetic field) fast-magnetosonic/whistler wave in the plasma frame (Gary et al. 2016). The observed RH-polarized electromagnetic wave can be the forward fast-magnetosonic/whistler wave or the backward Alfvén/ion-cyclotron wave in the plasma frame (Gary et al. 2016). Therefore, the nature of the observed LH- and RH-polarized electromagnetic waves is a controversial question.

To identify the nature of the observed electromagnetic waves, one promising method is to explore the plasma instability based on the local plasma parameters (Gary et al. 2016; Jian et al. 2016; Zhao et al. 2019b). The theoretical instability analysis can provide a direct clue on the occurrence of the Alfvén/ion-cyclotron instability or the fast-magnetosonic/whistler instability in the plasma frame. The theoretical results show that the Alfvén/ion-cyclotron wave (or fast-magnetosonic/whistler wave) could be excited by the instability resulted from the ion temperature anisotropy with $T_{i\parallel} > T_{i\perp}$ (or $T_{i\perp} < T_{i\parallel}$; e.g., Gary 1993). Moreover, the differential flows among different ion components could result in both Alfvén/
ion-cyclotron and fast-magnetoacoustic/whistler waves (e.g., Liu et al. 2019). However, if the observed waves are far away from their source region, this theoretical instability method may be inapplicable to identify the nature of the observed LH and RH electromagnetic waves.

In this study, we provide a new method to discriminate the nature of the LH- and RH-polarized electromagnetic waves in the spacecraft frame. We compare low-frequency electromagnetic waves in the spacecraft frame to those in the plasma frame in Section 2, and propose that three parameters (polarization, direction of the parallel Poynting flux, and correlation coefficient between perpendicular velocity and magnetic field perturbations) are helpful for identifying the nature of the wave in the plasma frame. Furthermore, this paper presents two applications on analyses of the observed LH- and RH-polarized electromagnetic waves in Section 3, illustrating the validation of our method.

2. Theoretical Predictions: Effects of the Bulk Flow Velocity on Wave Properties

To clearly show the distinctness of low-frequency electromagnetic waves in the plasma frame and in the spacecraft frame, we consider the parallel and antiparallel waves in an electron–proton plasma, where the wave dynamics are controlled by the following momentum equation and Maxwell’s equations:

\[
\partial_t V_{\perp} + V_{\parallel} \cdot \nabla V_{\perp} = \frac{q_j}{m_j} (E_\parallel + V_{\perp} \times B_0 + V_{\parallel} \times B_0),
\]

\[
\nabla \times B = \mu_0 J,
\]

\[
\nabla \times E = -\partial_t B,
\]

where \( q_j \) is the particle charge, \( m_j \) is the particle mass, \( V_{\perp}, J_{\perp}, B_{\perp} \), and \( E_\parallel \) are the perpendicular components of velocity, current density, magnetic and electric fields, respectively. \( V_0 = V_0 e_i \) and \( B_0 = B_0 e_i \) denote the bulk flow velocity and the ambient magnetic field, respectively. The subscript ‘j’ represents electrons “e” and protons “p.”

We assume a plane wave solution, and perform the transformations \( \partial_t \to -i\omega \) and \( \nabla \to i\text{ke}_i \) in Equations (1)–(3). From Equations (1) and (3), we have

\[
[\omega - V_0 k^2 - \omega_{ij}^2]V_{\perp} = i(\omega - V_0 k^2)\frac{q_j}{m_j\omega}E_\parallel - \frac{q_j\omega e_i}{\omega} - k \times \frac{q_j e_i}{\omega} = \frac{q_j}{m_j \omega}E_\parallel \times e_i.
\]

Using \( J_{\parallel} = n_0 e_i (V_{\parallel} - V_{\perp}) \), and combining Equations (2)–(4), we have

\[
\left[ \lambda_e^2 k^2 + \frac{Q}{(\omega - V_0 k)^2 - \omega_{cp}^2} \right]E_\parallel - \frac{Q(\omega - V_0 k)}{(\omega - V_0 k)^2 - \omega_{cp}^2} \frac{1}{\omega} - \frac{Q(\omega - V_0 k)}{(\omega - V_0 k)^2 - \omega_{ce}^2} \frac{1}{\omega} = 0,
\]

where \( V_{\parallel} = V_0, Q = m_e / m_i, \omega_{cp} = q_i B_0 / m_i, \) and \( \lambda_e \) is the electron inertial length. From Equation (5), we can obtain the following dispersion relation:

\[
\omega = V_0 k + V_A k^2 + \left[ \frac{\pm(1 - Q)\lambda_p k^2/2 + \sqrt{1 + Q + \lambda_e^2 k^2}^2 + (1 - Q)^2 \lambda_p^2 k^2/4}{1 + Q + \lambda_e^2 k^2} \right],
\]

which describes two Alfvén/proton-cyclotron mode waves and two fast-magnetoacoustic/whistler mode waves. Here \( \lambda_p \) is the proton inertial length. From Equations (3)–(5), we have the relations between \( V_{\perp} \) and \( B_{\perp} \):

\[
(1 - Q^2) V_{\perp \perp} = -\frac{1}{k(\omega - V_0 k)} \times [V_A^2 k^2 - Q(1 + Q + \lambda_e^2 k^2)(\omega - V_0 k^2)] B_{\perp},
\]

\[
(1 - Q^2) V_{\perp \parallel} = \frac{1}{k(\omega - V_0 k)} \times [QV_A^2 k^2 - (1 + Q + \lambda_e^2 k^2)(\omega - V_0 k^2)] B_{\parallel}. \]

Based on Equations (3) and (5)–(8), Figure 1 presents the dispersion relations and linear responses of four wave modes in the plasma frame where \( V_0 = 0 \) and in the spacecraft frame where \( V_0 = \pm 2V_A \). As shown in the left panels in Figure 1, \( \omega_{R1} \) (thick solid lines) and \( \omega_{R2} \) (thin solid lines) are fast-magnetoacoustic/whistler waves, and \( \omega_{L1} \) (thick dashed lines) and \( \omega_{L2} \) (thin dashed lines) are Alfvén/proton-cyclotron waves. Since the electromagnetic polarization is defined in the case of \( \omega > 0 \), the polarization \( P \) is given as \( P = \text{sign}(\omega)(iB_\parallel / B_\perp) \), where \( B_1 \) and \( B_2 \) are two magnetic component perpendicular to \( B_\perp \), and the orthogonal coordinates are defined as \( e_i = e_i \times e_i \), and \( e_i \). The wave polarization is independent of the wave direction, that is, the fast-magnetoacoustic/whistler (Alfvén/proton-cyclotron) wave is RH (LH) circularly polarized. From the ratio between \( V_{\perp \perp} / V_{\parallel \perp} \) and \( B_{\perp} / B_\parallel \), we find that for the forward (backward) fast-magnetoacoustic/whistler mode, \( -1 < V_{\perp \perp} / V_{\parallel \perp} < 0 \) and \( \omega_{R1} / \omega_{R2} \leq -1 \) (\( 0 < V_{\perp \perp} / V_{\parallel \perp} < 1 \) and \( \omega_{R1} / \omega_{R2} \geq 1 \)), and for the forward (backward) Alfvén/proton-cyclotron mode, \( V_{\perp \perp} / V_{\parallel \perp} \leq -1 \) and \( -1 < V_{\perp \perp} / V_{\parallel \perp} < 0 \) (\( \omega_{R1} / \omega_{R2} \geq 1 \) and \( 0 < V_{\perp \perp} / V_{\parallel \perp} \leq 1 \)). In Figure 1, we also show the distributions of the Poynting flux, \( S = E \times B / \mu_0 \), where \( E \) and \( B \) indicate wave electric and magnetic fields. Considering the parallel and antiparallel wave and using Equation (3), the Poynting flux has only the parallel component, and it can be written as \( S_\parallel = 2\omega k \), which gives the dependence of \( S_\parallel \) on the phase velocity \( \omega / k \). The positive (black lines) and negative (red lines) phase speeds \( \omega / k \) correspond to the wave propagating along (against) \( B_\perp \).

In the spacecraft frame where \( V_0 = 2V_A \) (Figure 1(b)), due to Doppler frequency shift \( V_k \), the backward Alfvén/proton-cyclotron wave at \( V_0 = 0 \) becomes forward propagation, and it also becomes RH-polarized. Also, a part of the backward RH-polarized fast-magnetoacoustic/whistler wave at \( V_0 = 0 \) becomes forward LH-polarized mode. As \( \lambda_p > 1 \), there still exists a backward RH-polarized fast-magnetoacoustic/whistler wave. On the other hand, when \( V_0 = -2V_A \) (Figure 1(c)), the forward LH-polarized Alfvén/proton-cyclotron wave at \( V_0 = 0 \) becomes backward RH-polarized mode.
and the forward RH-polarized fast-magnetosonic/whistler wave with $\lambda pk = 1$ at $V_0 = 0$ turns to the backward LH-polarized mode. For the forward fast-magnetosonic/whistler wave with $\lambda pk > 1$, its polarization remains the same as that at $V_0 = 0$.

Comparing the ratio of $V_{\perp}/V_A$ to $B_i/B_0$ in the plasma frame to that in the spacecraft frame, we find that this ratio is independent of $V_0$. Note that this conclusion can be confirmed by the expressions (6)–(8). Therefore, the correlation coefficient between $B_1$ and $V_{\perp}$ ($CC_{B_1,V_{\perp}}$) is a useful parameter to identify the direction of the observed wave in the plasma frame, e.g., $CC_{B_1,V_{\perp}} > 0$ corresponding to the backward wave and $CC_{B_1,V_{\perp}} < 0$ for the forward wave. Then, by combining the information of the polarization and the direction of $S_{||}$, we can clearly identify the nature of the electromagnetic wave in the spacecraft frame. As shown in

Table 1. Alfvén/proton-cyclotron and fast-magnetosonic/whistler waves have different behaviors in the parameter space of $CC_{B_1,V_{\perp}}$, $S_{||}$, and polarization.

| Mode in the Plasma Frame ($V_0 > V_A$) | Polarization | $CC_{B_1,V_{\perp}}$ | $S_{||}$ |
|----------------------------------------|--------------|---------------------|--------|
| Forward A/PC wave                      | −1 (1)       | >0 (<0)             | 1 (−1) |
| Backward A/PC wave                     | 1 (−1)       | >0 (>0)             | 1 (−1) |
| Forward F/W wave with small $k$        | 1 (−1)       | <0 (<0)             | 1 (−1) |
| Forward F/W wave with large $k$        | 1 (1)        | <0 (<0)             | 1 (1)  |
| Backward F/W wave with small $k$       | −1 (1)       | >0 (>0)             | 1 (−1) |
| Backward F/W wave with large $k$       | 1 (1)        | >0 (>0)             | −1 (−1) |
3. Application: Two Observation Events

Figure 2 shows two events containing both LH- and RH-polarized low-frequency electromagnetic waves observed by MMS: (I) Event 1 occurred in the time interval of 12:27:00 UT–12:37:00 UT on 2018 October 7, and (II) Event 2 during 08:30:00 UT–09:00:00 UT on 2018 November 10. (Top panels) Power spectrum of the magnetic field; (second panels) wave normal angle ($\theta_f$); (third panels) ellipticity; (fourth panels) degree of polarization; (fifth panels) the normalized parallel Poynting flux ($S_i/|S|$); (sixth panels) electron number density ($n_e$); (seventh panels) ion bulk flow velocity in GSE coordinates and total ion bulk flow velocity $|V|$; (eighth panels) perpendicular and parallel ion temperatures ($T_{i\perp}$ and $T_i$); (ninth panels) perpendicular and parallel electron temperature ($T_{e\perp}$ and $T_e$); and (bottom panels) the magnetic field in GSE coordinates and total magnetic field $|B|$.

These two events have the same distribution, that is, the magnetic field data in Figure 2, we find $V_{i\perp} = V_i \cdot B / |B| \sim 1.7V_A$ in Event 1 and $V_{e\perp} = V_e \cdot B / |B| \sim -2.5V_A$ in Event 2.

Figure 3 shows the magnetic field and velocity power spectral densities (PSDs) and the correlation between the magnetic field and the velocity in Event 1, where the particle bulk flow is streaming along the ambient magnetic field at a velocity $\sim 200 \text{ km s}^{-1}$, and this bulk flow velocity is larger than the local Alfvén speed $\sim 100 \text{ km s}^{-1}$. For Event 1, the $MMS$ spacecraft provides the high-resolution plasma measurements, e.g., 0.15 s per sample for ions, and 0.03 s per sample for electrons. Using particle and magnetic field data, Figure 3(a) presents PSDs of $B$, $V_i$, and $V_e$ by use of Welch’s method (Welch 1967). From PSDs of $B$ and $V_i$, we see that transverse magnetic field and ion velocity fluctuations dominate the parallel component. $B_i$ and $V_{i\perp}$ PSDs have two distinct peaks in the range of $0.04 \text{ Hz} < f < 0.2 \text{ Hz}$ (lower-frequency band) and in $0.3 \text{ Hz} < f < 1 \text{ Hz}$ range (upper-frequency band). Two band
wave features also arise in PSDs of $V_e$, where we removed the effects of the spacecraft spin tone at 0.05 Hz. Figure 3(b) further gives the correlation coefficient between perpendicular magnetic fluctuations ($B_\perp$) and velocity fluctuations ($V_{i\perp}$ and $V_{e\perp}$). Here the correlation coefficient is defined as $CC_{ij} \equiv R_{ij}^2 \cos(\phi_{ij})$ that can clearly give the positive and negative correlation between these two variables, where $R_{ij}^2$ and $\phi_{ij}$ denote the coherency and phase difference angle of two signals “$i$” and “$j$” (Grinsted et al. 2004). The distributions of $CC_{B_i,V_{i\perp}}$ and $CC_{B_i,V_{e\perp}}$ in Figure 3(b) show the positive correlation $CC_{B_i,V_{i\perp}} \sim 1$ in the lower-frequency band and the negative correlation $CC_{B_i,V_{e\perp}} \sim -1$ in the upper-frequency band. Figures 3(c) and (d) also illustrate the positive and negative correlation between $B_\perp$ and $V_{i\perp}$ filtered in the lower- and upper-frequency bands during the period of 12:30:00 UT–12:32:00 UT.

Based on features of $CC_{B_i,V_i}$, $S_i/|S|$ and polarization in Event 1, we could discriminate the nature of the observed LH- and RH-polarized electromagnetic waves in the plasma frame. First, due to $CC_{B_i,V_i} < 0$ in the upper-frequency band, we conclude that the observed LH-polarized electromagnetic waves are propagating along $B_0$ in the plasma frame, and due to $CC_{B_i,V_i} > 0$ in the lower-frequency band, the observed RH-polarized waves propagate reversely to $B_0$ in the plasma frame. Since $S_i/|S| \approx 1$ for all observed waves, the upper-band LH-polarized waves correspond to the forward Alfvén/proton-cyclotron waves, and the lower-band RH-polarized waves correspond to the backward Alfvén/proton-cyclotron waves.
In Event 2, MMS records the high-resolution plasma data during 08:48:04 UT–08:51:10 UT, when the particle bulk flow (∼300 km s⁻¹) streams against to the ambient magnetic field where \( V_A \sim 100 \) km s⁻¹. Therefore, it can yield to the analysis of the correlation between \( \mathbf{B}_0 \) and \( V_A \), shown in Figure 4. It gives \( CC_{B_0, V_A} > 0 \) for the upper-band LH-polarized waves and \( CC_{B_0, V_A} < 0 \) for the lower-band RH-polarized waves. Therefore, the upper-band (lower-band) waves propagate reversely to (along) \( \mathbf{B}_0 \). From \( S_f / |S| \approx -1 \) for all observed waves, we conclude that the observed LH- and RH-polarized waves correspond to the backward and forward Alfvén/proton-cyclotron waves in the plasma frame, respectively.

To show the excitation mechanism for the observed forward and backward Alfvén/proton-cyclotron waves, we analyze the wave instability based on the plasma kinetic model (Xie & Xiao 2016). The physical parameters are obtained by averaging the plasma and magnetic field data during 12:29:00 UT–12:30:00 UT for Event 1 and during 08:31:00 UT–08:33:00 UT for Event 2. The theoretical results are presented in Figure 5, which shows the strongest Alfvén/proton-cyclotron instability. The positive and negative wave frequencies \( f \) represent the wave propagating along and against \( \mathbf{B}_0 \), respectively. The blue and red solid lines in Figure 5 denote the theoretical predictions in the spacecraft frame. Moreover, in order to compare the waves between the spacecraft frame and the plasma frame, we assume a motionless plasma condition, and give wave dispersion relations in the plasma frame, indicated by the blue and red dashed lines in Figures 5(a) and (Ia). The blue and red solid lines in the spacecraft frame correspond to their counterparts (blue and red dashed lines) in the plasma frame.

For Event 1, due to the bulk flow streaming along \( \mathbf{B}_0 \), the antiparallel Alfvén/proton-cyclotron wave (red dashed line in Figure 5(a)) in the plasma frame becomes parallel propagation (red solid line in Figure 5(a)) in the spacecraft frame. Two unstable Alfvén/proton-cyclotron waves (blue and red solid lines) have the same distributions of growth rate in the wavenumber space (Figure 5(b)). These two waves have different frequency bands, i.e., \( f / f_p \approx 0.2–0.5 \) and 0.7–1.3 (Figure 5(c)), in the spacecraft frame. This result is nearly consistent with the two frequency bands in Event 1. On the other hand, for Event 2, since the bulk flow streams against to \( \mathbf{B}_0 \), the parallel Alfvén/proton-cyclotron wave (blue dashed line in Figure 5(Ia)) in the plasma frame becomes antiparallel propagation (blue solid line in Figure 5(Ia)) in the spacecraft frame. Furthermore, from Figure 5(Ic), we see that two antiparallel Alfvén/proton-cyclotron waves have frequencies similar to the observed values in Event 2.

Therefore, we find that the source of the observed Alfvén/proton-cyclotron waves is the ion temperature anisotropy instability. Also, we conclude that the ion temperature anisotropy instability can produce both parallel and antiparallel Alfvén/proton-cyclotron waves in the plasma frame, but two parallel (or antiparallel) Alfvén/proton-cyclotron waves in the spacecraft frame.

### 4. Summary and Discussion

This study provides a useful method to identify the nature of the nearly parallel and antiparallel LH- and RH-polarized low-frequency electromagnetic waves in the spacecraft frame. This method does not need to perform a coordinate transformation from the spacecraft frame into the plasma frame.

This paper gives the theoretical results of low-frequency electromagnetic waves in the plasma frame and in the spacecraft frame. Since the flow velocity can be larger than the local Alfvén speed in the solar wind and in the planetary magnetosheath, we present the theoretical predictions of the wave properties in the cases of \( V_0 = \pm 2 V_A \), as shown in Figure 1. These results show different behaviors for different kinds of electromagnetic waves in the parameter space of \( CC_{B_0, V_A} \), \( S_f / |S| \), and polarization. When the charged particles flow along \( \mathbf{B}_0 \) at a speed larger than \( V_A \), each electromagnetic wave exhibits:

1. \( CC_{B_0, V_A} < 0 \), \( S_f / |S| = 1 \), and LH polarization for the forward Alfvén/proton-cyclotron wave in the plasma frame;
2. \( CC_{B_0, V_A} > 0 \), \( S_f / |S| = 1 \), and RH polarization for the forward Alfvén/proton-cyclotron wave in the spacecraft frame;
3. \( CC_{B_0, V_A} < 0 \), \( S_f / |S| = 1 \), and RH polarization for the forward fast-magnetosonic/whistler wave in the plasma frame;
4. \( CC_{B_0, V_A} > 0 \), \( S_f / |S| = 1 \), and LH polarization for the backward fast-magnetosonic/whistler wave having a long wavelength in the plasma frame;
5. \( CC_{B_0, V_A} > 0 \), \( S_f / |S| = -1 \), and RH polarization for the backward fast-magnetosonic/whistler wave having a small wavelength in the plasma frame.

On the other hand, when the particles stream against \( \mathbf{B}_0 \) at a speed larger than \( V_A \), we find:
Plasma kinetic instability analyses based on local plasma parameters in Event 1 and Event 2. (I) Plasma parameters averaged during 12:29:00 UT –12:30:00 UT on 2018 October 7 by MMS: $n_p = n_e \approx 56.6 \text{ cm}^{-3}$, $T_{p\parallel} \approx 121.2 \text{ eV}$, $T_{p\perp} \approx 74.4 \text{ eV}$, $T_{e\parallel} \approx 40.8 \text{ eV}$, $T_{e\perp} \approx 44.7 \text{ eV}$, $V_0 = 228.7 \text{ km s}^{-1}$, and $B \approx 43.5 \text{ nT}$. (II) Plasma parameters averaged during 08:31:00 UT–08:33:00 UT on 2018 November 10 by MMS: $n_p = n_e \approx 35.4 \text{ cm}^{-3}$, $T_{p\parallel} \approx 343.8 \text{ eV}$, $T_{p\perp} \approx 249.0 \text{ eV}$, $T_{e\parallel} \approx 52.1 \text{ eV}$, $T_{e\perp} \approx 58.5 \text{ eV}$, $V_0 = -340.8 \text{ km s}^{-1}$, and $B \approx 33.8 \text{ nT}$. (Top panels) The wave frequency $f$ normalized by the proton-cyclotron frequency $f_{pc}$ (middle panels) the growth rate $\gamma$ normalized by $f_{pc}$; and (bottom panels) the distribution of $\gamma$ as a function of $f$. The blue thick and red thin solid lines represent two unstable Alfvén/proton-cyclotron waves in the spacecraft frame. In panels (Ia) and (Iia), the blue and red dashed lines represent the forward and backward fast-magnetosonic/whistler wave having a small wavelength in the plasma frame.

The most interesting finding is that $CC_{B,V}$ is independent on the direction of the bulk flow velocity with respect to the ambient magnetic field. Therefore, $CC_{B,V}$ can be used to determine the direction of the observed waves in the plasma frame. Moreover, this paper applies a new method to identify the LH- and RH-polarized electromagnetic waves from MMS measurements. As shown in Section 3, we observe the coexistence of LH- and RH-polarized waves in the Earth’s magnetosheath, and identify these waves corresponding to the counter-propagating Alfvén/proton-cyclotron waves in the plasma frame. Furthermore, we propose that the source of Alfvén/proton-cyclotron waves is the ion temperature anisotropy cyclotron instability.

It should be noted that because our method depends on the particle measurement, for the satellites having adequate resolution of the particle measurement, this method is helpful for studying the nature of low-frequency electromagnetic waves in solar-terrestrial environments.

This work was supported by the NNSFC 41531071, 41974203, 11673069, and 11761131007. D.B.G. is supported by Swedish National Space Board, grant 128/17. J.S.H. is supported by NNSFC 41574168 and 41874200. M.W.D. is supported by NNSFC 41874193 and 41574155, NERC Grant NE/H004076/1, and by STFC in-house research grant. We thank the MMS team for data access and support, and the data are available at the LASP-CU Boulder website (https://lasp.colorado.edu/mms/sdc/public/).

**ORCID iDs**

Jinsong Zhao @ https://orcid.org/0000-0002-3859-6394
Daniel B. Graham @ https://orcid.org/0000-0002-1046-746X
References

Ala-Lahti, M., Kilpua, E. K. J., Souček, J., Pulkkinnen, T. I., & Dimmock, A. P. 2019, JGRA, 124, 3893

Boardsen, S. A., Jian, L. K., Raines, J. L., et al. 2015, JGRA, 120, 10207

Burch, J. L., Moore, T. E., Torbert, R. B., & Giles, B. L. 2016, SSRv, 199, 5

Cranmer, S. R. 2001, JGRA, 106, 24937

Delva, M., Mazelle, C., & Bertucci, C. 2011, SSRv, 162, 5

Ergun, R. E., Tucker, S., Westfall, J., et al. 2016, SSRv, 199, 167

Gary, S. P. 1993, Theory of Space Plasma Microinstabilities (Cambridge: Cambridge Univ. Press)

Gary, S. P., Jian, L. K., Broiles, T. W., et al. 2016, JGRA, 121, 30

Grinsted, A., Moore, J. C., & Jevrejeva, S. 2004, NPGeo, 11, 561

He, J., Wang, L., Tu, C., Marsch, E., & Zong, Q. 2015, ApJL, 800, L31

Hollweg, J. V., & Isenberg, P. A. 2002, JGRA, 107, 1147

Huang, C., Zhao, J., Sun, H., et al. 2019, ApJ, 874, 128

Jian, L. K., Moya, P. S., Viñas, A. F., et al. 2016, in AIP Conf. Proc. 1720, Solar Wind 14, ed. K. T. Das, B. Kristiawan, & M. S. Shekhawat (Melville, NY: AIP), 040007

Jian, L. K., Russell, C. T., Luhmann, J. G., et al. 2009, ApJL, 701, L105

Jian, L. K., Russell, C. T., Luhmann, J. G., et al. 2010, JGRA, 115, A12115

Kasper, J. C., Lazarus, A. J., & Gary, S. P. 2008, PhRvL, 101, 261103

Lindqvist, P.-A., Olsson, G., Torbert, R. B., et al. 2016, SSRv, 199, 137

Liu, Z., Zhao, J., Sun, H., et al. 2019, ApJ, 874, 128

Orman, L., Gary, S. P., & Viñas, A. 2002, JGRA, 107, 1461

Pollock, C., Moore, T., Jacques, A., et al. 2016, SSRv, 199, 331

Potemra, B., Tsurutani, B. T., Reddy, R. V., et al. 2014, ApJL, 793, 6

Roberts, O. W., & Li, X. 2015, ApJ, 802, 1

Romanelli, N., Mazelle, C., Chaufray, J. Y., et al. 2016, JGRA, 121, 11113

Russell, C. T., Anderson, B. J., Baumjohann, W., et al. 2016, SSRv, 199, 189

Siu-Tapia, A., Blanco-Cano, X., Kajdic, P., et al. 2015, JGRA, 120, 2363

Summers, D., & Thorne, R. M. 2003, JGRA, 108, 1143

Wei, H. Y., Cowee, M. M., Russell, C. T., & Leinweber, H. K. 2014, JGRA, 119, 5244

Wei, H. Y., Russell, C. T., Zhang, T. L., & Blanco-Cano, X. 2011, P&SS, 59, 1039

Welch, P. D. 1967, IEEE Trans. Audio Electroacoust., 15, 70

Wicks, R. T., Alexander, R. L., Stevens, M., et al. 2016, ApJ, 819, 6

Xie, H., & Xiao, Y. 2016, PIST, 18, 97

Zhao, G. Q., Feng, H. Q., Wu, D. J., Pi, G., & Huang, J. 2019a, ApJ, 871, 175

Zhao, J. S., Wang, T. Y., Dunlop, M. W., et al. 2018, ApJ, 867, 58

Zhao, J. S., Wang, T. Y., Dunlop, M. W., et al. 2019a, GeoRL, 46, 4545