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Waves in Kinetic-Scale Magnetic Dips: MMS Observations in the Magnetosheath

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Abstract Kinetic-scale magnetic dips (KSMDs), with a significant depression in magnetic field strength, and scale length close to and less than one proton gyroradius, were reported in the turbulent plasmas both in recent observation and numerical simulation studies. These KSMDs likely play important roles in energy conversion and dissipation. In this study, we present observations of the KSMDs that are labeled whistler mode waves, electrostatic solitary waves, and electron cyclotron waves in the magnetosheath. The observations suggest that electron temperature anisotropy or beams within KSMD structures provide free energy to generate these waves. In addition, the occurrence rates of the waves are higher in the center of the magnetic dips than at their edges, implying that the KSMDs might be the origin of various kinds of waves. We suggest that the KSMDs could provide favorable conditions for the generation of waves and transfer energy to the waves in turbulent magnetosheath plasmas.

Plain Language Summary The Earth's magnetosheath is a turbulent plasma environment where energy conversion, particle acceleration, and mass and momentum transport take place. Many of these key processes involve kinetic-scale physics. However, in-depth studies from previous missions are limited by their lower spacecraft data resolution. The recent Magnetospheric Multiscale (MMS) mission provides us with a large amount of high-temporal cadence data for studying kinetic-scale physics in the magnetosheath. In this study, we report whistler mode waves, electrostatic solitary waves and electron cyclotron waves within kinetic-scale magnetic dips (KSMDs) that can be generated in the turbulent magnetosheath. These waves could be excited by electron temperature anisotropy or beams. As is well known, plasma waves are important processes in converting energy, accelerating and scattering electrons and ions, and modifying the distributions of charged particles. If plasma instabilities develop within the KSMDs, the resulting waves could absorb free energy from plasma particles and may propagate out of the KSMDs. Thus, our discoveries could significantly advance the understanding of energy conversion and dissipation for kinetic-scale turbulence. This study provides a new reference not only for observations in space physics but also for related basic plasma theories and numerical simulations.

1. Introduction

Kinetic-scale magnetic dips (KSMDs) are a significant depression of magnetic field strength with a scale size close to or less than a proton gyroradius (ρ_i). These structures have been observed both in the Earth's magnetospheric plasma sheet (e.g., Ge et al., 2011; Gershman et al., 2016; Goodrich et al., 2016; Sun et al., 2012; Sundberg et al., 2015; Yao et al., 2016; Zhima et al., 2015; Zhang et al., 2017) and magnetosheath (e.g., Huang, Sahraoui, et al., 2017; Yao et al., 2017). In addition to observational investigations, KSMDs have also been extensively studied through theoretical analysis and numerical simulations (e.g., Balikhin et al., 2012; Haynes et al., 2015; Ji et al., 2014; Li et al., 2016; Roytershteyn et al., 2015). The KSMD structures have similar observational characteristics to the magnetic mirror mode (MM; Tsurutani et al., 1982; Yao, Shi, Liu, et al., 2018), magnetic hole (MH), and interplanetary magnetic decreases (MD; Shi et al., 2009; Tsurutani et al., 1994, 1999; Tsurutani, Dasgupta, et al., 2002; Tsurutani et al., 2009; Xiao et al., 2010, 2014) reported in previous studies; however, their formation processes and relevant physics are distinct. The classifications, generation mechanisms, and related studies (e.g., proton cyclotron and Langmuir waves inside the MD) for the MM, MH, and MD are well discussed by Tsurutani et al. (2011) and related works (Lin et al., 1996; Tsurutani, Galvan, et al., 2002; Tsurutani, Dasgupta, et al., 2002; Tsurutani et al., 2005, 2018).

The magnetosheath is a turbulent plasma environment where energy conversion, particle acceleration, and mass and momentum transport take place. Many of these key processes involve kinetic-scale physics. With measurements of high-temporal cadence from the Magnetospheric Multiscale (MMS) mission (Burch et al., 2016), the KSMDs and some possible related structures were reported in the turbulent magnetosheath (Huang, Sahraoui, et al., 2017; Yao et al., 2017; Yao, Shi, Guo, et al., 2018) and are thought to play an important role in dissipating energy (Huang, Sahraoui, et al., 2017). In addition, from recent two- and three-dimensional particle-in-cell simulations, the KSMDs were found in turbulent magnetized plasmas (Haynes et al., 2015; Roytershteyn et al., 2015). Though KSMDs in turbulent plasmas have been studied both by observations and simulations, whether there is energy dissipation or conversion in KSMDs, and how this occurs are not yet understood.

Plasma waves are important processes in converting energy, accelerating and scattering charged particles, and modifying the distributions of ions and electrons (e.g., Li, Zhou, Zong, Chen, et al., 2017; Li, Zhou, Zong, Rankin, et al., 2017; Lin et al., 1996; Shi et al., 2013, 2014; Sun et al., 2015; Thorne et al., 2006, 2010; Tsurutani, Galvan, et al., 2002; Zhang et al., 2010; Zong et al., 2007). If plasma instabilities develop within the KSMDs, waves could be locally generated in KSMDs and absorb free energy from plasma and may propagate out of the KSMDs. In addition, waves can be used as a tool to infer microscale particle dynamics, which could significantly advance our understanding of the KSMD dynamics.

Whistler mode electromagnetic waves have been observed in magnetic depressions in the terrestrial magnetosheath for more than 40 years. They are known as *lion roars* with central frequencies ~100 Hz, and the magnetic depressions are termed as *mirror mode* (e.g., Smith et al., 1969; Smith & Tsurutani, 1976; Tsurutani et al., 1982). It should be noted that the mirror mode is not a kinetic-scale structure (Tsurutani et al., 2011). Here we just giving an example of similar waves detected in larger-scale structures. Over the past decades, a majority of works focused on lion roars associated with magnetohydrodynamic-scale magnetic depressions. However, these waves were seldom observed in KSMDs due to the low time resolution of available observations. Electrostatic solitary waves (ESWs) are characterized by solitary or continuous bipolar electric field pulses parallel to the background magnetic field (Lakhina et al., 2000; Matsumoto et al., 1997). They were first observed in the plasma sheet boundary layer as a component of broadband electrostatic noise (Matsumoto et al., 1994, 1997) and were widely observed in space plasmas, such as in the solar wind (Mangeney et al., 1999), the distant magnetosheath (Kojima et al., 1997), the plasma sheet boundary (Cattell et al., 1999), the Earth's bow shock (Bale et al., 1998; Matsumoto et al., 1997), the magnetopause (Matsumoto et al., 2000; Mozer et al., 1997), and the magnetotail (Andersson et al., 2009; Le Contel et al., 2017; Tao et al., 2011). Their spatial sizes are on the order of several Debye lengths and could be generated from the two-stream instability (e.g., Goldman et al., 1999). A possible generation mechanism is that the parallel electric field component of two obliquely propagating proton cyclotron waves accelerate electrons toward each other, providing free energy for the generation of the ESWs (Tsurutani et al., 2003). Because of the ESW's nonlinear generation process, they are termed as *electron phase-space density holes*, and they
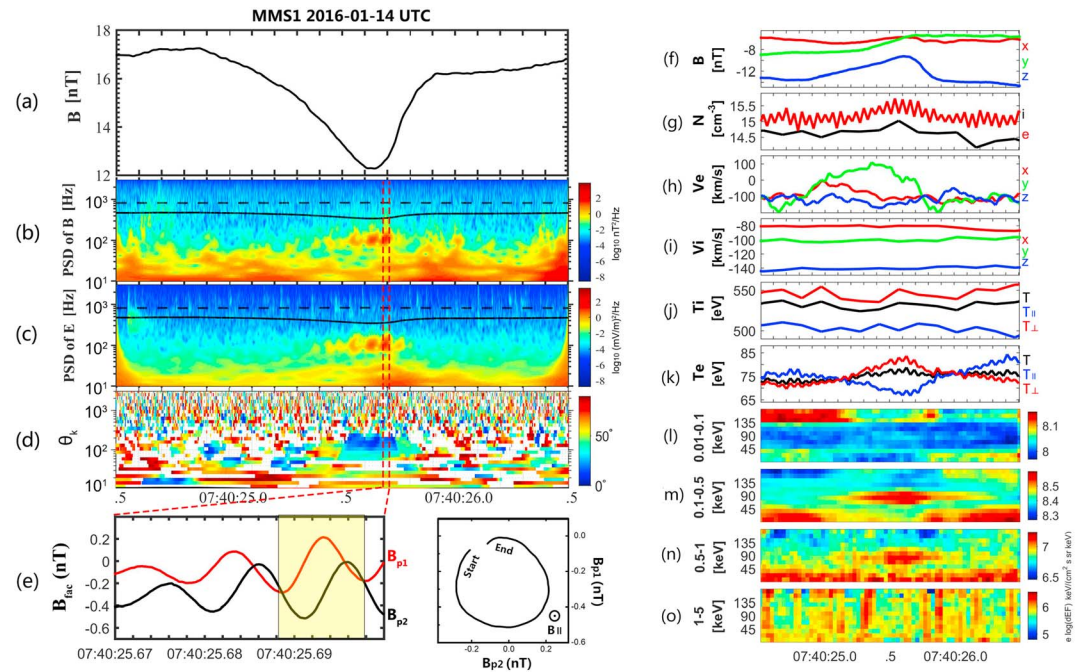
Figure 1. Whistler mode waves (WHs) observed in the kinetic-scale magnetic dips (KSMDs). (a) Total magnetic field strength. (b and c) Power spectral densities (PSDs) of the electric and magnetic fields overplotted with the electron cyclotron frequency (solid line) and ion plasma frequency (dashed line). (d) Wave normal angle. (e) Magnetic field in field-aligned coordinates and their hodograph during a short interval marked by the two vertical dashed lines in the above panels. The B_{P1} and B_{P2} are the magnetic field of two perpendicular directions. (f) Magnetic field components. (g) Ion and electron number densities. (h and i) Ion and electron velocity components. (j and k) Ion and electron temperatures. Plasma properties in (g)–(k) are calculated by taking the moments from the 3-D particle distributions from 10 eV to 30 keV. (l–o) Electron pitch angle distributions.

can be modeled using the Bernstein-Greene-Kruskal modes (e.g., Chen & Parks, 2002a, 2002b; Muschietti, et al., 1999). Another interpretation for ESWs observed in space plasmas is that these structures could be ion- and electron-acoustic solitons (e.g., Lakhina et al., 2018; Rubia et al., 2017).

In this study, we report new discoveries of various kinds of electromagnetic and electrostatic waves within the dayside magnetosheath KSMDs. These waves include whistler mode waves (WHs), ESWs, and electron cyclotron waves (ECWs). The source and generation mechanisms of these waves, and their effects and importance are discussed. The data and event selection criterion are shown in the supporting information.

2. Observations

2.1. Observations of Electromagnetic Waves

Figure 1 shows an example associated with WH activity observed by MMS1 at [9.2, −4.0, −0.9] R_E (Earth radii). The total magnetic field strength shown in Figure 1a decreases significantly from 16.6 to 12.3 nT in ~1 s. The scale of the KSMD is ~1.4 ρ_i (ρ_i ~140 km, calculated from the background magnetic field B = 16.6 nT and ion energy E = 540 eV), obtained from the averaged background ion bulk velocity (V ~190 km/s) and the duration (Δt ~1 s), assuming that the structure is convected by the magnetosheath flow. Figures 1b and 1c display the power spectral densities of the magnetic and electric fields related to the KSMD. Strong magnetic and electric wave powers at ~100 Hz are found in the center of the KSMD. Their central frequency f is ~0.25 f_{ce} (the local electron cyclotron frequency, black solid line) and is much lower than f_{pi} (the ion plasma frequency, black dashed line). The wave normal angle (θ_k) is ~15°, nearly parallel to the ambient magnetic field (Figure 1d, obtained from the singular value decomposition method; Santolík et al., 2003). The waves are right-handed circularly polarized, as can be seen from the perpendicular magnetic field variation during the time interval indicated by the yellow shaded region in Figure 1e. These wave characteristics indicate that the waves are electromagnetic WHs. By estimating $|\Delta E_{\perp p1}/\Delta B_{\perp p2}|$, where
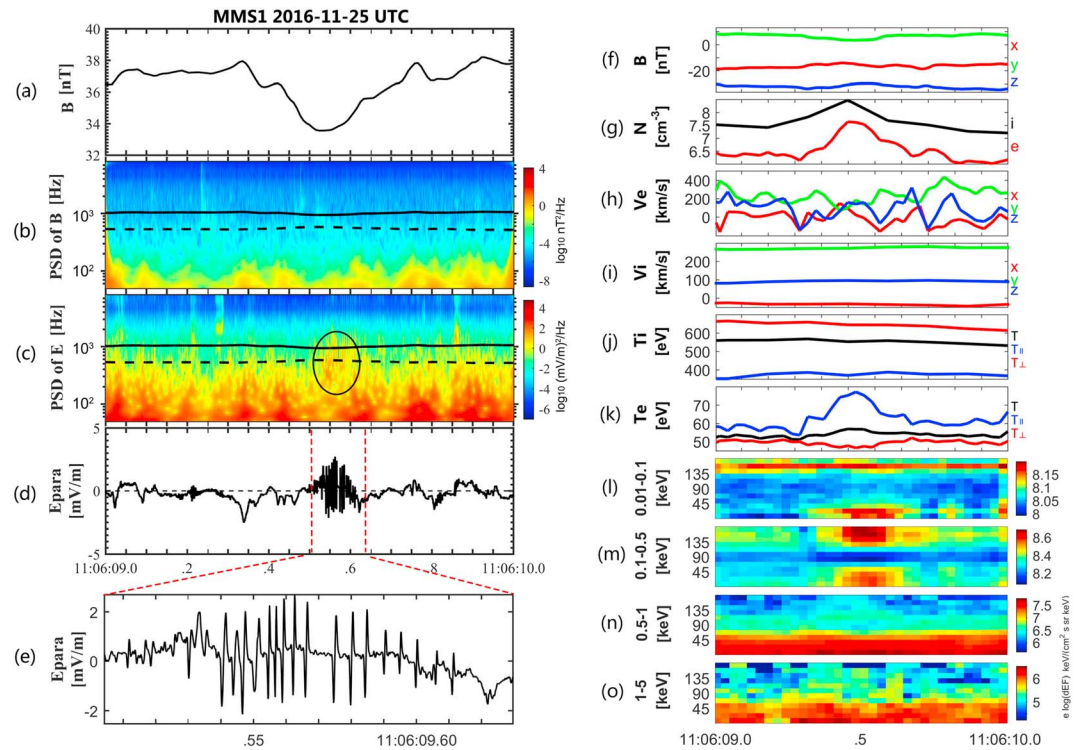
Figure 2. Electrostatic solitary waves (ESWs) observed in the KSMDs. (a–c) and (f–o) same as Figure 1. (d and e) Parallel electric field and an expanded view of the parallel electric field during a selected period. Plasma properties in (g–k) are calculated by taking the moments from the 3-D particle distributions from 10 eV to 30 keV.

$\Delta E_{\perp p1}$ and $\Delta B_{\perp p2}$ are the perpendicular wave electric and magnetic fields, we found that the phase speed of the wave (v_{ph}) is ~2,500 km/s.

In Figure 1, the depression of the magnetic field in the KSMD is mainly due to the change in the z component (Figure 1f, blue line); variations of plasma density are not obvious for both ions and electrons (Figure 1g). The ion and electron number densities given here are not the total densities but measured over a limited energy range. This results in an apparent inequality in ion and electron number densities reported in this study, see details in the supporting information. In addition, the ion temperatures do not change significantly across the KSMD, whereas the electron temperature anisotropy $T_{e\perp}/T_{e\parallel}$ develops a value substantially greater than unity in the same interval, as shown in Figure 1k. It is shown that electron fluxes increase near 90° from 0.1 to 1 keV (Figures 1l and 1m), which leads to the temperature anisotropy. According to the cyclotron resonance condition (e.g., Cao et al., 2017; Fu et al., 2012; Kennel & Engelmann, 1966; Wilson et al., 2013), the minimum resonant electron energy is of 130–160 eV. Anisotropic electron distributions are observed in Figures 1l and 1m over the energy range of 100–1,000 eV, suggesting that the WHs could possibly be generated by these anisotropic electron populations (e.g., Gary & Karimabadi, 2006; Huang et al., 2012; Fu et al., 2011; Li, Bortnik, et al., 2017).

2.2. Observations of Electrostatic Waves

Figure 2 shows an overview of a KSMD event associated with ESWs observed at [10.3, 5.7, 0.2] R_E by MMS1. The total magnetic field strength, displayed in Figure 2a, shows a rapid decrease from ~38 to ~33 nT in 0.4 s. The scale of the KSMD is ~1.9 ρ_i, obtained from V ~300 km/s (assuming nonpropagating structure in the magnetosheath flow) and Δt ~0.4 s, and ρ_i ~62 km from B = 38 nT and E = 550 eV. Given that there were no significant corresponding magnetic fluctuations (Figure 2 bc), the waves appear to be electrostatic and their frequencies are close to f_{ce} and f_{pi}. Significant bi-polar structures in the parallel wave electric field can be in Figure 2e. These features are observed by all four MMS spacecraft, and we thus use the timing method (Paschmann et al., 1998; Russell et al., 1983) to determine their propagation velocities. The results
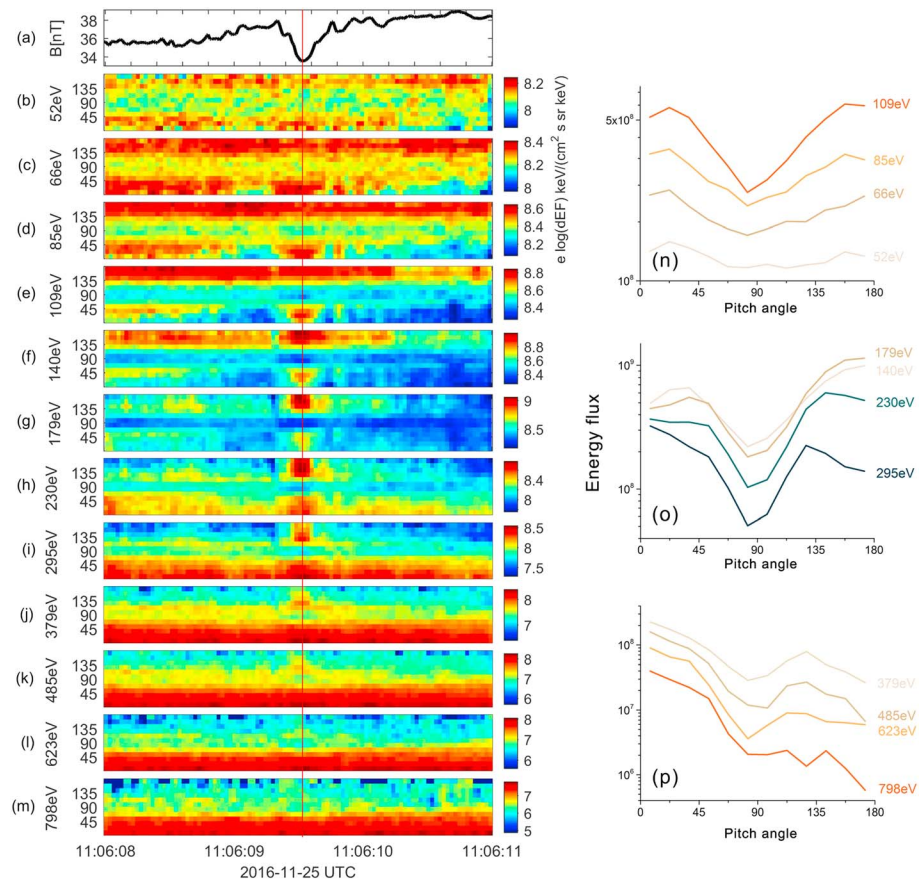
Figure 3. (a) Total magnetic field strength. (b–m) Electron pitch angle distributions. (n–p) Energy fluxes versus pitch angle, at the time marked by the red vertical line in (a)–(m).

range from 4350 km/s to 4970 km/s. This corresponds to a resonant electron energy of several tens eV. The densities of both ions and electrons are enhanced within the KSMD (Figure 2g). The ion bulk velocity and temperatures do not change significantly across the KSMD (Figures 2i-2j), but the electron temperature anisotropy decreases from $T_{e\perp}/T_{e\parallel} \approx 0.86$ outside to $T_{e\perp}/T_{e\parallel} \approx 0.61$ inside the structure. From the electron PADs measured by MMS1, we find that the electron energy fluxes mainly rose near 0° and 180° pitch angles from 0.1 keV to 0.5 keV (Figure 2m), suggesting that the ESWs may be generated by the electron two-stream instability (e.g., Chen et al., 2003; Goldman et al., 1999).

Figure 3 displays the details of the electron PADs. The parallel and antiparallel energy fluxes increased significantly from ~80 eV to ~300 eV inside the KSMD, and the perpendicular energy fluxes were always lower than that of the other angles (Figures 3b-3l). It is clear that the energy fluxes near 90° from ~80 eV to ~700 eV were lower than that of the other pitch angles from Figures 3a–3m. In previous studies, Yao et al. (2017) found KSMDs in the magnetosheath with perpendicular energy fluxes increasing from ~80 eV to ~800 eV. Similar features were reported in the Earth's plasma sheet by Sun et al., 2012 and Gershman et al. (2016) and in the magnetosheath by Huang, Sahraoui, et al. (2017). In a recent statistical study, Huang, Du, et al. (2017) showed that the electron fluxes at 71–850 eV were significantly enhanced at ~90° pitch angles for most events in the magnetosheath. However, these observed features are opposite to our finding. It should be noted that, although the increase of the energy fluxes in parallel and antiparallel directions could make the perpendicular energy fluxes appear reduced, this is actually not the case, since the perpendicular energy fluxes inside the KSMD are comparable or less than that of the background in Figures 3b-3m. These observations may be understood by the following interpretation. Before the ESWs generation, the energy fluxes have a peak at ~90° pitch angles. Then the parallel and antiparallel electric fields of the ESWs make the electrons difficult to be trapped within the small (ion gyroradius) scale magnetic dip. Therefore the observed

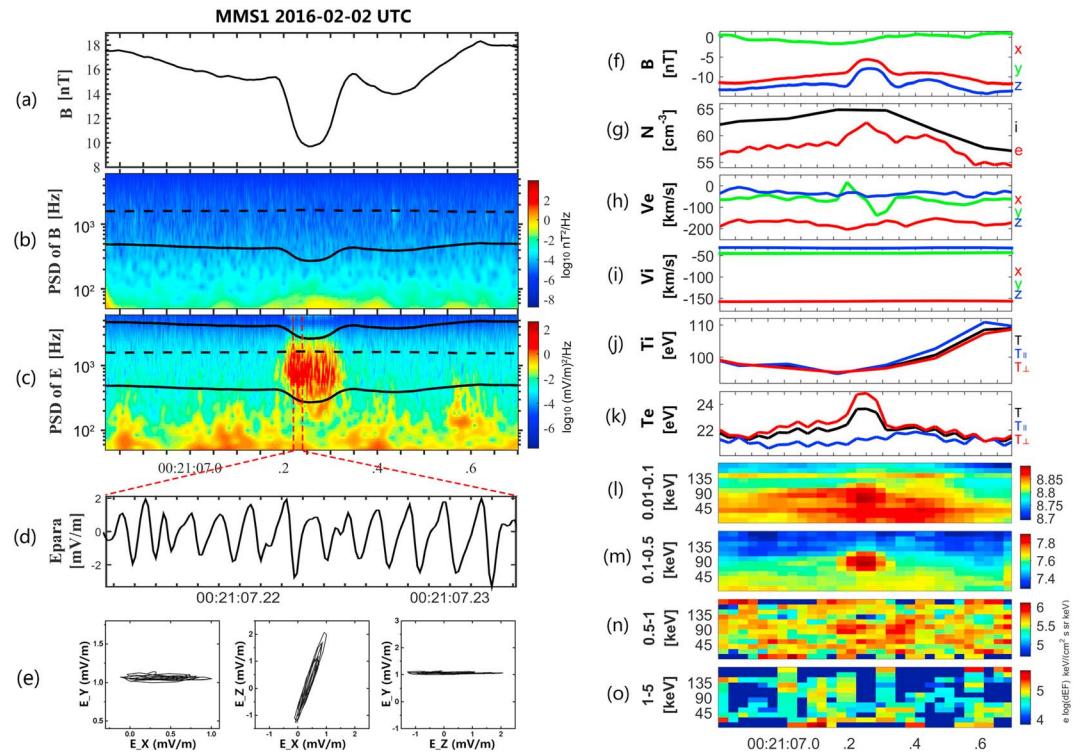**Figure 4.** Electron cyclotron waves (ECWs) observed in the KSMDs. (a–c) and (f–o) same as Figure 1. The black solid lines in (c) indicate the f_{ce} and $3f_{ce}$. The black dash line is the ion plasma frequency. (d) Parallel electric field. (e) Hodographs of electric field. Plasma properties in (g–k) are calculated by taking the moments from the 3-D particle distributions from 10 eV to 30 keV.

energy flux will increase in parallel and antiparallel directions, and decrease in perpendicular direction when the spacecraft passes through the structure.

Figure 4 shows another kind of electrostatic wave observed by MMS1. The length scale in this case is ~0.4 ρ_i, from V ~160 km/s (assuming nonpropagating structure in sheath flow), Δt ~0.15 s, and ρ_i ~64 km from the B = 16 nT and E = 105 eV. The location of the event was [6.6, −10.0, −1.2] R_E. There is a close correlation between the depression in the magnetic field and the increase of the electric field power spectral densities. These waves populated a frequency range from 0.3 to 1.2 kHz, which corresponds to the range from f_{ce} to $3f_{ce}$. The maximum amplitude of the waves was ~5 mV/m and no magnetic field perturbation was observed. The wave mode was linearly polarized, as shown in Figure 4e. These are possibly electrostatic ECWs or EBWs (e.g., Baumjohann & Treumann, 1996; Huang et al., 2016; Tang et al., 2013). The magnetic field strength predominately decreases in x and z components (Figure 4f, red and blue lines). An increase in electron number density (Figure 4g, red line) and strong bipolar signature in the y component of the electron velocity (Figure 4h, green line) were detected. Once again, the ion bulk velocity and temperature do not change significantly across the KSMD (Figures 4i and 4j), but here the $T_{e\perp}/T_{e\parallel}$ shows a significant increase across the event (Figure 4k). Figures 4l–4n show the electron PADs from MMS1. Electron fluxes near 90° increased both in Figures 4l and 4m. Generally, ECWs are thought to be excited by instabilities due to electron temperature anisotropies or loss cone distributions (e.g., Ashour-Abdalla & Kennel, 1978; Horne & Thorne, 2000; Vaivads et al., 2006). However, loss cone distributions were not observed in the electron PADs in this event. Shown in Figures 4l and 4m, the energy fluxes were asymmetric in parallel and antiparallel directions and significantly enhanced at ~90° pitch angles. This enhancement results in the temperature anisotropy shown in Figure 4k. Therefore, we infer that the ECWs in this case may be driven by the temperature anisotropy.

2.3. Statistical Results

A rough statistical analysis is shown in Figure 5. In total, 77 events associated with the three types of waves that we have discussed above are included in this statistics. Twenty-three events are related to the WHs, and
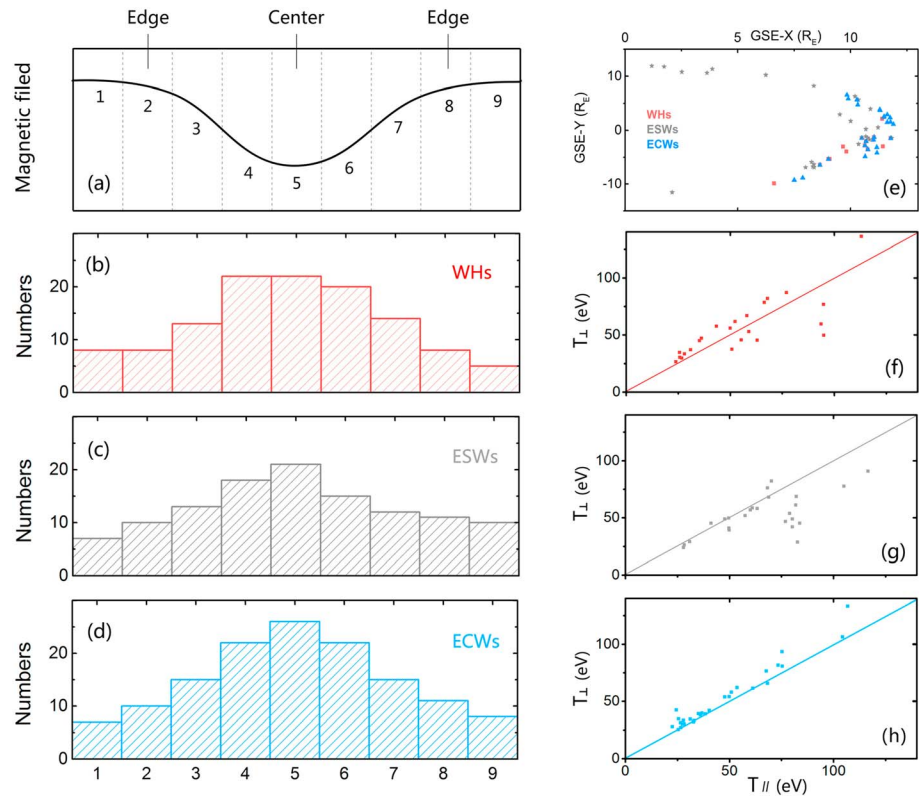
Figure 5. Statistical analysis results of the waves. (a) Normalized magnetic dip profile. The numbers indicate the locations with respect to the magnetic dip profile. (b–d) Event numbers versus their locations. (e) Position of the events in geocentric solar ecliptic (GSE) coordinates. (f–h) Electron perpendicular temperature versus parallel temperature of the three types of events. One point represents one event.

25 and 29 events are observed with the ESWs and ECWs, respectively. We investigate the locations within the KSMD where these events are observed. Event locations within the magnetic dip are binned into nine sections as shown in Figure 5a (for more details, please see the supporting information). It can be seen that the occurrence rates for the WHs, ESWs, and ECWs are higher in the center and lower at the edges of KSMD (Figures 5b–5d). If the waves are continuously excited by plasma instabilities inside the KSMDs and propagate from their source, the spacecraft would have more chance to observe the waves in the center of the dip than that at other locations. Thus, we consider that the KSMDs are a possible source for various kinds of waves. More discussions are presented in the next section.

Figure 5e shows the positions of these events in GSE coordinates. Since most of the MMS burst mode data are provided during the magnetopause crossing, the events observed in this study are near the dayside magnetopause (in the magnetosheath). Figures 5f–5h show the perpendicular electron temperature versus the parallel temperature inside the KSMD for each event. In Figure 5f, according to the electron temperature ratio, the statistical results are divided into two classes ($T_{e\perp} > T_{e\parallel}$ and $T_{e\parallel} > T_{e\perp}$). It is accepted that unstable WHs can be generated by electron temperature anisotropy (e.g., Gary & Karimabadi, 2006; Huang et al., 2012; Huang et al., 2018; Fu et al., 2014) or electron beams (e.g., Feldman et al., 1983; Tokar et al., 1984; Tokar & Gumeft, 1985; Zhang et al., 1999). This suggests that the generation mechanisms could include the electron transverse temperature anisotropy ($T_\perp > T_\parallel$) and electron beams (more likely to appear as $T_\parallel > T_\perp$, for more details, please see the supporting information). For the ESWs, the temperature anisotropies for the majority of the events (~84%) are less than 1 in Figure 5g. From Figure 3 we know that this is caused by the increase of energy flux in parallel and antiparallel directions. This is consistent with the generation mechanism in previous studies (e.g., Chen et al., 2003; Goldman et al., 1999). On the contrary, for 93% of the ECW events, the temperature anisotropies are greater than 1 in Figure 5h. Hence, one can infer that the generation of the ECWs and the electron temperature anisotropies are linked.

3. Discussions

Measurements from in situ field instruments are usually sampled at much higher rates than those from particle instruments. Therefore, the observations of the waves from field instruments provide the highest cadence evidence of kinetic-scale processes within KSMDs. In our study, about one third (77/253) of the events are associated with various kinds of waves. Since these strong wave activities may play important roles in plasma microphysics and may contribute to the energy transfer in space plasma, it is therefore pivotal to understand the relation between the waves and the KSMDs. The statistical results imply that the waves are locally generated in the KSMDs, and thus, the KSMDs could provide a favorable condition for wave generation. For instance, previous studies have shown that electrons with ~90° pitch angle were trapped inside KSMDs in turbulent plasmas and that electron vortices were coupled with KSMDs (e.g., Huang, Sahraoui, et al., 2017; Yao et al., 2017). These lead to higher electron temperature anisotropy inside the structure. The temperature anisotropy may thus provide the free energy required for the excitation and growth of these waves. In previous studies, the existences of KSMDs in turbulent plasmas were studied both by observations and simulations. We therefore consider that the KSMD can transfer energy from turbulent plasmas to the waves.

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