The Role of Upper Hybrid Waves in the Magnetotail Reconnection Electron Diffusion Region

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Abstract

Plasma waves are believed to play an important role during magnetic reconnection. However, the specific role of upper hybrid (UH) waves in the electron diffusion region (EDR) remains elusive, owing to the absence of high-resolution measurements. We analyze one EDR event in the magnetotail on 2017 July 11 observed by the Magnetospheric Multiscale (MMS) mission. To the best of our knowledge, this is the first time that intense UH waves have been observed in the EDR by MMS. The agyrotropic crescent-shaped electron distributions could result in the observed UH waves. Concomitant with the observations of UH waves, the agyrotropy parameter $\sqrt{Q}$ of the electrons decreases, implying that the UH waves could effectively scatter the electrons in the EDR. The good accordance of positive energy conversion ($\mathbf{J} \cdot \mathbf{E}^f > 0$, likely dissipation) and the observed UH waves indicates that UH waves may contribute to the energy conversion from the magnetic fields to the plasma particles during magnetic reconnection.

Unified Astronomy Thesaurus concepts: Plasma physics (2089); Plasma astrophysics (1261); Solar magnetic reconnection (1504); Magnetic fields (994); Earth (planet) (439)

1. Introduction

Magnetic reconnection is one of most common and important phenomena in astrophysical, space, and laboratory plasmas. It can effectively convert magnetic energy into plasma thermal and kinetic energies, resulting in a sudden change of the topology of magnetic field (e.g., Deng & Matsumoto 2001; Huang et al. 2012a, 2014, 2015, 2018; Fu et al. 2016, 2017; Torbert et al. 2018). The reconnection region consists of two scale structures: an ion diffusion region with the scale of ion inertial length, and an electron diffusion region (EDR) with the scale of electron inertial length (e.g., Sonnerup 1979; Vaivads et al. 2006; Huang et al. 2018). The EDR is the core region of magnetic reconnection, where the electrons decouple from the magnetic field lines. It is believed that electron-scale kinetic physics controls the processes of magnetic reconnection in the EDR (Burch et al. 2016). Due to the effect of the electromagnetic field in the EDR, the demagnetized electrons move along a meandering path and form crescent-shaped electron velocity distributions in the plane that are perpendicular to the ambient magnetic field (e.g., Lapenta et al. 2017; Zhou et al. 2019); this is an important indicator for the identification of the EDR.

The reconnection diffusion region is favorable to the generation of a series of waves due to the anisotropic velocity distribution functions (VDFs) of the plasma particles. Wave-particle interactions can play an important role in the diffusion region during magnetic reconnection. It is suggested that the waves may be the source of anomalous resistivity and can cause particle scattering and diffusion (Huba et al. 1977; Graham et al. 2017). Different waves associated with magnetic reconnection are observed in situ by the spacecraft; these include upper hybrid (UH) waves (e.g., Farrell et al. 2002, 2003; Graham et al. 2017; Burch et al. 2019), whistler waves (e.g., Deng & Matsumoto 2001; Cao et al. 2017; Huang et al. 2016, 2017, 2019), lower hybrid waves (e.g., Zhou et al. 2009, 2014), electrostatic solitary waves (e.g., Zhou et al. 2016), and Alfvén-whistler waves (Huang et al. 2010, 2012b). UH waves are high-frequency electrostatic modes that propagate perpendicularly to the ambient magnetic field. These waves can contribute to the diffusion and scattering of electrons (Graham et al. 2017). Recently, UH waves have been detected by spacecraft not only in the reconnection diffusion region (Farrell et al. 2002, 2003; Graham et al. 2017; Burch et al. 2019), but also at the flank of the magnetopause without the signatures of magnetic reconnection (Tang et al. 2019). Farrell et al. (2003) analyzed a UH wave observed by the Wind spacecraft in the diffusion region and concluded that UH waves can grow in regions where $\mathbf{dv}/\mathbf{dt} > 0$ of the electron VDFs. However, due to the limited temporal and spatial resolution of the data, further analysis of the kinetic physics occurring at electron scales was not possible. Although the amplitudes of the UH waves reported by Farrell et al. (2002) and Graham et al. (2017) were very large (i.e., hundreds of mV m$^{-1}$), their roles in the process of magnetic reconnection remain not fully understood (Vaivads et al. 2006). In this Letter, we investigate the UH waves in the EDR event reported by Torbert et al. (2018) using the unprecedented high-time-resolution data from the Magnetospheric Multiscale (MMS) mission, and try to understand their influence on the electron-scale kinetic physics during magnetic reconnection.

2. Observations

The data used in this work were provided by various instruments on board MMS when they were in burst mode. The Electric Double Probes (EDP; 8192 Hz) provided 3D electric
field data (Ergun et al. 2016; Lindqvist et al. 2016); the Fluxgate Magnetometer (128 Hz) and the Search-Coil Magnetometer (8192 Hz) recorded the DC and AC magnetic field data, respectively (Contel et al. 2016; Russell et al. 2016); the Fast Plasma Investigation (30 ms for electrons and 150 ms for ions) measured the plasma moments and the 3D VDFs of the plasma particles (Pollock et al. 2016).

At ~22:32:00–22:37:00 on 2017 July 11, the third spacecraft of MMS mission (MMS3) observed a reversal of ion flow (from tailward to earthward) and well Hall electromagnetic field, implying that MMS3 encountered an ion diffusion region. Figure 1 presents the detailed observations of the EDR and the UH waves, where all data are from MMS3 and shown in LNM coordinates ($L = [0.971, 0.219, -0.098]$, $M = [-0.234, 0.956, -0.18]$, $N = [0.054, 0.197, 0.979]$) (Geocentric Solar Magnetospheric (GSM) coordinates). During this interval, the amplitude of the $B_i$ component is small (0 ~ 1.5 nT), indicating that MMS3 is very close to the neutral sheet (Figure 1(a)). $V_j$ changes from negative to positive (Figure 1(b)), indicating a reversal of the electron flow. The $V_{en}$ is very large with a peak at ~17,000 km s$^{-1}$ (of the order of the local electron Alfvénic velocity, ~20,000–25,000 km s$^{-1}$). From the deviation of the electron (ion) velocity $V_{E,i,l}(l=1,2)$ and $E \times B$ drift velocity ($V_{E,l,B1}$) in Figure 1(c), one can see that the electrons and ions decouple from the magnetic field lines for most of the time interval. In the decoupling region marked by two black vertical dashed lines, strong energy conversion (Figure 1(h)), electron crescent distribution in the plane perpendicular to the ambient magnetic field (one case in Figure 1(l)), and a strong...

**Figure 1.** Overview of EDR and UH waves. All data are presented in LNM coordinate system unless specified. (a) Magnetic field of MMS3; (b) electron velocity; (c) L component of ion velocity perpendicular to magnetic field, $E \times B$ drift velocity and electron velocity perpendicular to magnetic field; (d) current density; (e) electron temperature; (f) electric field; (g) parallel electric field (red) and error (black); (h) $J \cdot E$; (i) electron differential energy flux; (j) hodogram of $E_{min}$ vs. $E_{max}$, where the red line is the direction of the ambient magnetic field. $E_{min}$ is the minimum variance direction of electric field and $E_{max}$ is the maximum variance direction of electric field determined by minimum variance analysis (MVA); (k) electron distribution in $\nu_{e,1}$-$\nu_{e,2}$ plane at 22:34:02.442, where $\nu_{e,1}$ is along $k_0 \times B_0$, $\nu_{e,2}$ is along $B_0 \times (k_0 \times B_0)$, $k_0$ is the wave vector, and $B_0$ is the unit vector of ambient magnetic field, the black line in (l) indicates the projection of wave vector in the plane; (m) 1D electron distribution along $k_0$ direction, the red line is the measurements of spacecraft, the red and purple dashed lines are Maxwellian fit to the red line and the blue line is the sum; (n) dispersion relation and growth rate predicted from the fitted distribution. The black dashed lines in Figures 1(a)-(j) mark the EDR.
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Figure 2. Relationship between the UH wave and energy conversion and electron agyrotropy. (a) L component of magnetic field; (b, e, h, k) agyrotropic parameter $\sqrt{Q}$; (c, f, i, l) $J \cdot E'$; (d, g, j, m) power spectra of electric field.

Figure 2 presents the power spectral density of the electric field. One can see a strong power enhancement around $f_{\text{th}}$ ($\sim$1800 Hz, UH frequency in the red line) with a broad frequency band between $\sim$240 and $\sim$3000 Hz in the EDR. We filtered the electric field data and analyzed the polarization of this emission by minimum variance analysis (MVA; Sonnerup & Scheible 1998). The wave vector $k_0 = [-0.0547, -0.8422, 0.5364]$ (GSM) determined by MVA is $\sim$107° with respect to the ambient magnetic field $B_0$, implying that this emission propagates quasi-perpendiculary to $B_0$. The hodogram of the $E_{\text{max}}$ and $E_{\text{min}}$ shows that this emission is linearly polarized (Figure 1(k)). Combining the linear polarization and quasi-perpendicular propagation, we can identify this electrostatic emission as UH waves (Graham et al. 2017; Tang et al. 2019). To the best of our knowledge, this is the first observations of UH waves in the EDR.

It has been suggested that agyrotropic electron beam can excite the UH waves (Graham et al. 2017; Tang et al. 2019). Based on this hypothesis we examined whether the electron agyrotropy of electrons ($Q > 0.1$ in Figure 2(i)) are detected, indicating that MMS encountered EDR in agreement with the identification of Zenitani et al. (2011), Torbert et al. (2018), and Huang et al. (2018). A unipolar $E_0$ is observed in EDR ($\sim$22:34:03, Figure 1(g)). The unipolar $E_0$, with an amplitude up to $-20 \text{ mV m}^{-1}$, has a duration of $\sim$180 ms, which is a typical feature of double layers (e.g., Wang et al. 2014). Double layers have been observed in the auroral region and the separatrix region of magnetic reconnection (Block 1972; Wang et al. 2014). This double layer was in EDR without being followed by the electron holes and was observed only by MMS3. This double layer propagated away from the X-line soon after it was generated by magnetic reconnection, which may explain why the other three spacecraft could not observe it.

Figure 1(j) presents the power spectral density of the electric field. One can see a strong power enhancement around $f_{\text{th}}$ ($\sim$1800 Hz, UH frequency in the red line) with a broad frequency band between $\sim$240 and $\sim$3000 Hz in the EDR. We filtered the electric field data and analyzed the polarization of this emission by minimum variance analysis (MVA; Sonnerup & Scheible 1998). The wave vector $k_0 = [-0.0547, -0.8422, 0.5364]$ (GSM) determined by MVA is $\sim$107° with respect to the ambient magnetic field $B_0$, implying that this emission propagates quasi-perpendiculary to $B_0$. The hodogram of the $E_{\text{max}}$ and $E_{\text{min}}$ shows that this emission is linearly polarized (Figure 1(k)). Combining the linear polarization and quasi-perpendicular propagation, we can identify this electrostatic emission as UH waves (Graham et al. 2017; Tang et al. 2019). To the best of our knowledge, this is the first observations of UH waves in the EDR.

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crescent distribution in the plane perpendicular to magnetic field (Figure 1(i)) can generate UH waves. First, a 1D electron phase space density along the wave vector direction (+V1,2 in Figure 1(f)) with an unambiguous positive gradient is fitted by two Maxwellian distributions (Figure 1(m)) in order to obtain information about the high-speed agyrotropic electron beam (nbe/nv = 0.01, where nbe is the density of beam, and nv is the ambient density, and Vbe = 2.02 × 10^4 km s^-1, where Vbe is the velocity of the beam). Second, with the maximum of the electric field (~40 mV m^-1, Figure 1(f)), the wave energy density is estimated to be \( W_E = \varepsilon_0 |E|^2 / 2 \approx 7.1 \times 10^{-15} \text{ J m}^{-3} \), where \( \varepsilon_0 \) is vacuum conductivity. The energy density of the agyrotropic electron beam is estimated to be \( W_{be} = m_ne_{be}V_{be}^2 / 2 \approx 6.5 \times 10^{-13} \text{ J m}^{-3} \), where \( m_n \) is the electron mass. Therefore, \( W_{be} \) is much larger than \( W_E \), indicating that the agyrotropic electron beam can provide enough free energy for the generation of these UH waves. Third, we solved the linear dispersion relation based on the Maxwellian distributions fit, and found (Figure 1(n)) that the maximum growth rate \( \gamma = 0.0412 \omega_pe \) (electron plasma frequency) occurs at \( f' = 1.042 f_{pe} \) and wavenumber \( k_{\lambda_D} \approx 1.156 \). Then the wavelength \( \lambda \) is estimated to be \( \sim 3.7 \text{ km} \), i.e., \( \sim 5.4 \lambda_D \), where \( \lambda_D \) is Debye length \( \sim 688 \text{ m} \). The phase speed \( v_{ph} \) is predicted to be \( 1.92 \times 10^4 \text{ km s}^{-1} \), which is very close to the speed of the largest positive gradient in Figure 1(m). With the prediction of \( v_{ph} \) based on the linear dispersion relation and \( E_{max} \sim 40 \text{ mV m}^{-1} \) from the observations, the wave potential \( \Phi \) is estimated to be \( 23.8 \text{ V} \). Thus, the UH waves can trap electrons with speed \( v_T = v_{ph} \pm \sqrt{2q_e \Phi / m_n} \approx [1.92 \pm 0.29] \times 10^4 \text{ km s}^{-1} \) (where \( q_e \) represents the electric charge), which is indicated by the green dashed lines in Figure 1(m). One can see that these lines cover most of the positive gradient. Therefore, the UH waves could be resulted from the agyrotropic electron beam.

To investigate the role that such intense UH waves play in the electron-scale kinetic physics in the EDR, we show in Figure 2 the electron agyrotropy parameter \( \sqrt{Q} \) and energy conversion in electron frame \((J \cdot E')\). From the L component of magnetic field in Figure 2(a), one can deduce that MMS3 gets into the deepest EDR. Strong UH waves are simultaneously observed by all four MMS spacecraft, indicating that the occurrence region of UH waves is at least as large as (or even larger than) the volume of the MMS tetrahedron (the separation between the MMS spacecraft is 21 km). \( \sqrt{Q} \), calculated from the full electron pressure tensor (Swisdak 2016), is a parameter that quantifies the agyrotropy of electrons. The larger is \( \sqrt{Q} \), the stronger is agyrotropy of the electrons. \( \sqrt{Q} \) of all four MMS spacecraft are higher inside of the EDR than outside of the EDR, with the peaks at \( \sim 0.2 \), which indicates strong agyrotropy in the EDR (e.g., Zhou et al. 2019). However, one can note that \( \sqrt{Q} \) decreases to nearly half of the peak (i.e., has one dip) when the intense UH waves are observed in the EDR for all spacecraft, which can be explained by the scattering and diffusion of electrons resulting in smoothing out the agyrotropy by the UH waves.

For the non-magnetized plasma in EDR, the diffusion coefficient of the UH waves can be calculated using the formula given by LaBelle & Treumann (1988):

\[
D = \eta_m / \mu_0 = (c/\omega_e^2) \nu_m, \tag{1}
\]

where \( \eta_m \) is the anomalous resistivity, \( \mu_0 \) is permeability of vacuum, \( c \) is speed of light, \( \omega_e \) is electron cyclotron frequency, and \( \nu_m \) is anomalous collision frequency:

\[
\nu_m = \frac{\varepsilon_0 \delta E^2}{2 m_n\nu_f (\gamma_{\max})}. \tag{2}
\]

With \( \omega_e = 30 \times 2\pi \text{ rad s}^{-1} \), \( \delta E = 40 \text{ mV m}^{-1} \), \( n_e = 0.0356 \text{ cm}^{-3} \), \( \nu_i = (V_e - V_i) \cdot k_0 = 1.2298 \times 10^4 \text{ km s}^{-1} \) (drift velocity), \( \gamma_{\max} = 0.0412 \omega_pe \), \( \nu_{f,\max} = 1.92 \times 10^5 \text{ km s}^{-1} \) (maximum phase speed), the diffusion coefficient \( D \) is 1.7353 \times 10^{13} \text{ m}^2 \text{s}^{-1}. For this EDR (350–500 km × 60 km), Torbert et al. (2018), the diffusion time is 0.121–0.1729 s (3.6–5.2 electron cyclotron period), which suggests that the UH waves can cause a fast diffusion of the electron. In addition, the positive energy conversion in electron frame of the reference \((J \cdot E' > 0)\) with energy transferred from the magnetic field to the plasma particles are simultaneously detected with the intense UH waves in EDR, which may indicate that the observed UH waves are highly correlated with the observed energy “dissipation.”

3. Discussion and Conclusions

The fast release of magnetic energy during collisionless magnetic reconnection has been a long-standing question. Anomalous resistivity, resulting from the ion-electron drag when the relative motion exceeds the ion acoustic speed, has been suggested as a possible explanation (Yamada et al. 2010). It has been proposed that the waves can play an important role in the formation and enhancement of anomalous resistivity. Huba et al. (1977) demonstrated that lower hybrid drift instability can be a source of anomalous resistivity. Magnetic reconnection experiments established a positive correlation between the magnetic fluctuations up to lower hybrid frequency and fast reconnection (Ji et al. 2004). Zhou et al. (2009) reported the observations of electrostatic lower hybrid waves at the separatix region and electromagnetic lower hybrid waves inside reconnection diffusion region. They estimated the anomalous resistivity provided by the electromagnetic lower hybrid waves. However, the electric field due to anomalous resistivity provided by the lower hybrid waves is only 0.2 times of the average reconnection field \( E_c \), which is also smaller than that obtained from Vlasov simulations (Silin et al. 2005). Huang et al. (2012b) applied quasi-linear theory to estimate the anomalous resistivity provided by the turbulence around the ion cyclotron frequency in the ion diffusion region, and found that the estimated electric field due to anomalous resistivity is close to typical values of reconnection electric field in the magnetotail.

Omura et al. (1996) studied the generation mechanism of electrostatic solitary waves by the simulations with the initial condition of bump-on-tail electron distribution. They found that a coherent Langmuir wave grows and traps the bump electrons, then the potential structures of the Langmuir waves coalesce with each other to form electrostatic solitary waves. 3D particle-in-cell simulations of magnetic reconnection also revealed that the development of electron holes (electrostatic solitary waves), evolved from the collapse of turbulence generated by electron beam near the X-line and separatix region, can lead to strong electron scattering associated with anomalous resistivity (Drake et al. 2003). However, here we did not observe electrostatic solitary waves and Langmuir waves in the EDR. Strong energy dissipation \((J \cdot E' > 0)\), enhancements of electron scattering, and intense UH waves are
simultaneously detected by four \textit{MMS} spacecraft. We deduce that the anomalous resistivity is \(2.18 \times 10^5 \ \Omega \ m\) from (1), which is one order of magnitude larger than that reported in Zhou et al. (2009), and the electric field provided by this anomalous resistivity is 11.5 mV m\(^{-1}\), which is of the order of the reconnection electric field (Figure 1(f)). Therefore, we suggest that the observed UH waves could contribute to strong electron scattering leading to the enhancement of anomalous resistivity and energy dissipation.

With the help of unprecedented high-time-resolution electron-scale measurements from \textit{MMS}, we investigated UH waves in the EDR in detail. The amplitude of the UH waves is up to 40 mV m\(^{-1}\). The UH waves are linearly polarized and propagate quasi-perpendicular to the ambient magnetic field. By solving the linear dispersion relation of the bi-Maxwellian VDF fitting the electron observations and calculating the energy range of electrons that the waves can trap, we found that the agyrotropic electron beam can excite the observed UH waves. The UH waves are coincident with the decrease of the agyrotropy parameter \(\sqrt{Q}\), which implies that the UH waves can scatter and diffuse the electrons in EDR. The good matching between the positive energy conversion (\(J \cdot E' > 0\), likely dissipation) and the dip of agyrotropy \(\sqrt{Q}\) and the UH waves indicate that UH waves may be responsible for the anomalous resistivity and may contribute to the energy conversion from the magnetic field to the plasma particles during magnetic reconnection.

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