First Observation of Lower Hybrid Drift Waves at the Edge of the Current Sheet in the Martian Magnetotail

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Received 2021 December 23; revised 2022 May 6; accepted 2022 May 20; published 2022 July 8

Abstract

Lower hybrid drift waves are commonly observed at plasma boundaries, playing an important role in plasma dynamics. Such waves have been widely investigated in the terrestrial magnetosphere but have never been reported in other planetary environments. Here, using the measurements from the Mars Atmosphere and Volatile Evolution mission, we present the first observation of electromagnetic lower hybrid drift waves at the edge of the current sheet on the dusk side of the Martian magnetotail, which should be locally excited rather than propagated from other regions. These plasma waves are associated with significant density gradients and magnetic field gradients. Based on the measured local plasma parameters and the sufficient condition for lower hybrid drift instability to be excited, we find that the proton density gradient is sharp enough to excite the lower hybrid drift instability. The analysis of the existence condition for lower hybrid drift instability indicates that these lower hybrid drift waves at the edge of the current sheet are generated through lower hybrid drift instability. The above results can improve our understanding of Mars’ magnetospheric dynamics.

Unified Astronomy Thesaurus concepts: Mars (1007); Planetary magnetospheres (997); Space plasmas (1544)

1. Introduction

Mars lacks an intrinsic global magnetic field powered by an active dynamo; it retains localized crustal magnetic fields (Acuña et al. 1998). The solar wind interactions with the Martian atmosphere and ionosphere lead to the formation of an induced magnetosphere (e.g., Nagy et al. 2004; Wang et al. 2020). As the solar wind flow is slowed down because of mass loading, and the interplanetary magnetic field (IMF) cannot be readily diffused into the conductive ionosphere, the IMF piles up on the dayside and drapes around Mars (e.g., Crider et al. 2004; Brain et al. 2006). The draped IMF extends downstream in the antisunward direction, to form the magnetotail on the nightside (e.g., Nagy et al. 2004; Fedorov et al. 2006). The magnetotail consists of the tail lobes with dominantly sunward and antisunward magnetic fields separated by the plasma sheet, the orientation of which changes in response to changes in the orientation of the upstream IMF (e.g., Crider et al. 2004; Connerney et al. 2015).

The Martian magnetotail is extremely complex and active, populated by a variety of field structures (e.g., Brain et al. 2007; Xu et al. 2017; Guo et al. 2021a) that facilitate the transport of mass, momentum, and energy through an assortment of processes, such as magnetic reconnection (e.g., Halekas et al. 2009; Harada et al. 2015a), flux rope evolution (e.g., DiBraccio et al. 2015; Hara et al. 2017), and current sheet flapping (DiBraccio et al. 2017), etc. Moreover, the Martian plasma sheet, filling with planetary ions, has been identified as a main ion escape channel (e.g., Fedorov et al. 2006; Barabash et al. 2007; Dubinin et al. 2011; Dong et al. 2015) due to tailward plasma flows (e.g., Dubinin et al. 2012; Harada et al. 2015b; Halekas et al. 2016; Inui et al. 2018). Additionally, the current sheet (or plasma sheet) can be characterized by a weaker magnetic field, a higher density, and a larger plasma beta. In particular, the crossings of the Martian current sheet could be identified by the reversals of $B_z$ together with $|B|$ decrease and plasma beta increase (e.g., DiBraccio et al. 2015; Harada et al. 2015b). Before and after crossing the current sheet, there are transition regions, i.e., the edge of the current sheet being host to various plasma waves. These plasma waves have been suggested to play an important role in converting energy, for instance, accelerating and scattering charged particles, modifying the distributions of ions and electrons (e.g., Fu et al. 2009, 2011, 2012, 2014a, 2014b, 2019; Cao et al. 2017; Yang et al. 2017; Liu et al. 2019, 2021a; Chen et al. 2021; Ren et al. 2021). Thus, investigating these waves can significantly advance our understanding of the microscale particle dynamics (e.g., Cao et al. 1998, 2013; Huang et al. 2018; Fowler et al. 2020; Fu et al. 2020a, 2020b, 2020c; Chen et al. 2021; Guo et al. 2021b; Yu et al. 2022; Liu et al. 2021b).

The lower hybrid drift waves (LHDWs) are considered to be mostly excited through the lower hybrid drift instability (LHDI; e.g., Gary & Eastman 1979; Bale et al. 2002; Norgren et al. 2012; Roytershteyn et al. 2012; Graham et al. 2019), and have been frequently observed within the boundary layers in the laboratory (e.g., Carter et al. 2001) and terrestrial space plasmas (e.g., Bale et al. 2002; Norgren et al. 2012; Chen et al. 2019; Liu et al. 2018). Other excitation mechanisms, including the modified two-stream instability (e.g., McBride et al. 1972; Wu et al. 1983) and ion ring instability (e.g., Akimoto et al. 1985; Cairns & Zank 2002; Winske & Daughton 2012; Soto et al. 2020), are also discussed in previous studies. Specifically, the LHDWs are abundant in the terrestrial magnetosphere and can transfer energies between the electrons and ions (e.g., Verdon et al. 2009). It is an important plasma wave mode in studying plasma dynamics. However, there has been no study of LHDWs in the Martian magnetosphere,
measurements are from the Solar Wind Ion Analyzer instrument of MAVEN in the edge of the current sheet in the Martian magnetotail. Based on observation of electromagnetic lower hybrid drift waves at the condition for lower hybrid drift instability to be excited, we study the LHDWs in the Martian magnetosphere. In this paper, using MAVEN (Jakosky et al. 2015) data, we reported the first observation of electromagnetic lower hybrid drift waves at the edge of the current sheet in the Martian magnetotail. Based on simultaneous observations of plasma parameters and the sufficient condition for lower hybrid drift instability to be excited, we discussed the generated mechanism of these LHDWs.

2. MAVEN Observations

All data used in this study are level-2 calibrated data from the MAVEN mission (Jakosky et al. 2015). Particularly, the magnetic field data from the Magnetometer (MAG; Connerney et al. 2015) and the electron data from the Solar Wind Ion Analyzer instrument (SWIA; Halekas et al. 2015), without mass resolution capability. The ion measurements are from high time resolution (4 s), four-dimensional (resolved in energy, azimuthal angle, elevation angle, and mass) “d1” data of the Supra-Thermal and Thermal Ion Composition instrument (STATIC; McFadden et al. 2015). STATIC also provides other ion data products, and we use the “c6” data product with a high resolution in mass to identify ion components. All the data are shown in Mars Solar Orbital (MSO) coordinates unless otherwise specified, in which X points from Mars toward the Sun, Y points opposite to the direction of Mars’ orbital velocity component perpendicular to X, and Z completes the orthogonal coordinate set. The wave event of interest was observed by MAVEN from 11:06:10 to 11:09:10 UT on 2018 May 16, when the spacecraft was located at $[-1.29, 1.48, -0.03]$ $R_M$ ($R_M$ is Martian radii) in MSO coordinates, as shown in Figures 1(a)–(b). Clearly, the MAVEN spacecraft is on the dusk side of the Martian magnetotail. It is worth noting that the distance of MAVEN from $X_{MSO}$ axis is about 1.48 $R_M$, indicating that even if the value of $Z_{MSO}$ is small, the spacecraft should not be near the plasma sheet of Mars (Fedorov et al. 2006). The black and green curves present the positions of the bow shock and the magnetic pileup boundary, respectively.

Figure 1. Mars Atmosphere and Volatile EvolutioN spacecraft locations in Mars’ magnetotail. (a) The location of MAVEN in the $X_{MSO}$–$Y_{MSO}$ plane; (b) the location of MAVEN in the $X_{MSO}$–$Z_{MSO}$ plane. The black and green lines represent the nominal positions of the bow shock and magnetic pileup boundary, respectively.
Figure 2. The overview of this event detected by Mars Atmosphere and Volatile EvolutioN (MAVEN) on 2018 May 16. (a) The magnetic field $B_x$, $B_y$, and $B_z$ components; (b) the ion density; (c) the ion velocity $V_{ix}$, $V_{iy}$, and $V_{iz}$ components; (d) the ion temperature; (e) the electron temperature; (f) the pitch angle distributions of electrons; (g) the omnidirectional differential energy fluxes of electrons. The red bar on top of Figure 2(a) indicates the time interval when waves are observed.

Figure 3 presents the polarization analyses of these waves during current sheet flapping. These waves appear from 11:07:21 UT to 11:07:24 UT (see black dotted lines in Figure 3). The plasma $\beta = 8\pi nk_B(T_i + T_e)/B^2$ is shown in Figure 3(b). It can be seen that $\beta$ is larger than unity during this interval. Moreover, the magnetic field perturbations, i.e., $\delta B$, are decomposed into the field-aligned and perpendicular components, and the results indicate that $\delta B_\parallel$ predominates as
Figure 3. Polarization analyses of these plasma waves. (a) The total magnetic field; (b) the plasma beta; (c) parallel and perpendicular components of the fluctuating ($f > 1$ Hz) magnetic field $\delta B$; (d) spectrogram of $B_\parallel$; (e) wave normal angle; (f) ellipticity of waves; (g) planarity of waves; (h) the ion mass spectrum; (i) the ion energy time spectra.
shown in Figure 3(c). Unfortunately, there are no measurements of the electric field (electric field waveforms or wave power) for this time interval of interest; we only calculated the power spectral density of magnetic field. Figure 3(d) shows the power spectral density of $B_{\parallel}$ with the purple curve illustrating the lower hybrid frequency $f_{lh} (\sim 4.57 \text{ Hz})$. Then the singular value decomposition (SVD) method (Santolik et al. 2003) is applied to the magnetic field data to obtain the wave normal angle (WNA; Figure 3(e)), ellipticity (Figure 3(f)), and planarity (Figure 3(g)). The value of the WNA varies between $0^\circ$ and $90^\circ$, with $90^\circ$ denoting perpendicular propagation and $0^\circ$ denoting parallel/antiparallel propagation. The value of ellipticity varies between minus one and one; one indicates right-hand circular polarization, minus one indicates left-hand circular polarization, and zero indicates linear polarization. The value of planarity varies between zero and one, the value of planarity close to one means that the other polarization parameters calculated by the SVD method are reliable. For our event, the values of planarity are close to one (see Figure 3(g)). Moreover, these waves appear in the vicinity of $f_{lh}$, from 2 to 12 Hz ($2 f_{ci} < f < 12 f_{ci} ; f_{ci} \sim 0.1 \text{ Hz}$), and exhibit nearly perpendicular propagation (WNA close to $90^\circ$) and linear polarization (the values of ellipticity are close to zero). All these features satisfy the properties of electromagnetic lower hybrid drift waves (e.g., Bale et al. 2002; Cairns & Zank 2002; Norgren et al. 2012; Graham et al. 2019). The strong gradient of magnetic field (see Figure 2(a)) and plasma density (see Figure 2(b)) at the edge of the current sheet may be responsible for the excitation of these waves, which will be discussed later. Furthermore, fast flow may cause Doppler shift; such an effect will also be considered below.

In general, lower hybrid drift waves are treated in electrostatic approximation, typically assuming a plasma beta less than one (e.g., Davidson & Gladd 1975). However, during 11:07:21 UT to 11:07:24 UT, the magnetic field is perturbed and $\beta$ is greater than one, which is consistent with the previous conclusion that LHDWs are accompanied by magnetic field fluctuations when $\beta > 1$ even though the LHDM mode is electrostatic (e.g., Daughton 2003; Norgren et al. 2012; Zhou et al. 2014; Graham et al. 2019). Moreover, previous studies have demonstrated that there is a clear correlation between $\delta B_{\parallel}$ and the electrostatic potential of the wave $\phi$, i.e., $\phi = -\frac{B_0}{n_{ci} e v_{th}} \delta B_{\parallel}$ (e.g., Norgren et al. 2012). Furthermore, both observations and simulations show that these magnetic field fluctuations associated with lower hybrid drift waves are often primarily in the direction parallel to the background magnetic field (e.g., Norgren et al. 2012; Graham et al. 2019), consistent with our observations (see Figure 3(c)). For lower hybrid drift waves, there is a clear correlation between $\delta B_{\parallel}$ and $\delta E_{\perp}$. The fluctuations of the electric field are dominated by $\delta E_{\perp}$, and the parallel magnetic field fluctuations $\delta B_{\parallel}$ peak at the same frequency (near the local lower hybrid frequency $f_{lh}$) as the perpendicular electric field fluctuations $\delta E_{\perp}$ (e.g., Bale et al. 2002; Norgren et al. 2012; Graham et al. 2019). Hence, in Figure 4, we calculate the magnetic field power spectral density in the parallel direction during 11:07:21–11:07:24 UT and find that the peak of parallel magnetic field fluctuations $\delta B_{\parallel}$ is at 0.98$f_{lh}$, very close to the lower hybrid frequency, and such a result is consistent with previous studies (e.g., Graham et al. 2019). Therefore, in the absence of electric field measurements, we can identify the electromagnetic lower hybrid drift wave mode by investigating the fluctuations of magnetic field. One

point that needs to be clarified is that the magnetic fluctuations in space may raise from a multitude of reasons, and fluctuations in the electric field should essentially be analyzed in the process of wave mode identification.

The mass-time spectrogram of ions (from the “c6” data product) is shown in Figure 3(h). We can see that the protons (H+) ($m/q = 1$ amu; amu is atomic mass unit) are dominant populations in the duration of the waves. Moreover, some O_{3}^{+} ($m/q = 32$ amu) ions are present after the magnetic dip (see Figure 3(h)), and they may originate from the Martian ionosphere (e.g., Barabash et al. 2007; DiBraccio et al. 2015; Steckiewicz et al. 2015; Inui et al. 2018). Figure 3(i) shows the omnidirectional differential energy fluxes of ions (from SWIA). We find that during the enhancement of ion fluxes of 400–800 eV (11:07:21–11:07:24 UT) strong waves also appeared. The nice correlation between protons and LHDWs is clearer, indicating that these waves may be locally excited rather than propagated from other regions. What is more, the excitation mechanism should be related to protons. Therefore, we further discuss the excitation of these LHDWs later.

3. Discussion

We note that the ion flow is fast during the period when these LHDWs are observed, so the Doppler effect should be considered. We use the minimum variance analysis (MVA) to determine the boundary layer normal $n$ by using magnetic field data from 11:07:19.092 to 11:07:33.279 UT. The MVA for this time period gave the $n = [0.84, -0.48, -0.26]$ in MSO coordinates with an eigenvalue ratio of $L_2/L_3 = 10$, which can be deemed as acceptable. We construct a new coordinate, since we are mainly interested in the dynamics taking place perpendicular to $B$. We take the average of $B$ during the relevant time interval and define this direction as $z$. The second direction is defined as $x = (z \times n) \times z$. This direction is thus the closest possible to the boundary layer normal but at the same...
time, perpendicular to $\mathbf{B}$. The third direction is defined as $y = z \times x$. Since the LHDWs propagate perpendicular to both magnetic field and density gradient directions (Kraul & Liewer 1971), the direction of $y$ is also the direction (parallel or antiparallel) of wave propagation. We thus obtained a local magnetic field-aligned coordinate system $\mathbf{xyz}$, $x = [0.53, -0.56, -0.63]$, $y = [-0.33, -0.83, 0.47]$, and $z = [-0.79, -0.04, -0.62]$. The frequency shift due to Doppler effect $f_D$ can be estimated by $\left(\frac{1}{2}\right) \mathbf{e}_y \cdot V_i$, where $\lambda$ is wavelength, $\mathbf{e}_y$ is the direction of wave propagation (i.e., $\mathbf{e}_y = \mp \mathbf{y}$), and $V_i$ is ion flow velocity. The wavelength is hard to estimate by single-spacecraft measurements. Therefore, we have to refer to a result as $113 \text{ km s}^{-1}$.

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