

# Ultrafast Measurements of Whistler Waves in Electron-only Magnetic Reconnection

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## Article

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# Ultrafast Measurements of Whistler Waves in Electron-only Magnetic Reconnection

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## Abstract

Magnetic reconnection, a fundamental energy conversion process, underpins a multitude of eruptive phenomena across the universe<sup>1-12</sup>. Compared to the traditional standard magnetic reconnection with ion coupling, the recently discovered electron-only magnetic reconnection operates at strikingly diminutive spatial scales, imposing formidable observational constraints on resolving its intrinsic physical processes, most critically within its core region—near the X-line. Consequently, the intrinsic mechanism governing electron-only magnetic reconnection remains largely enigmatic. Leveraging high-resolution data from NASA’s MMS mission, we present unprecedented observations of two types of whistler waves in electron-only magnetic reconnection: right-handed whistler waves near the X-line, excited by perpendicular anisotropy electron distributions via second order cyclotron resonance, contrasted by left-handed whistler waves in the outflow jet. The outflow-associated whistler waves reside within a magnetic hole coupled to the Hall magnetic field. Beyond these distinct features diverging from standard magnetic reconnection, hallmark phenomena analogous to standard magnetic reconnection—specifically flux pileup region in the outflow—is also identified for the first time in this electron-only regime. Our observations may provide novel insights into the magnetic reconnection and the microscale dynamics in space and astrophysical plasmas.

## Introduction

Magnetic fields permeate the universe as fundamental repositories of electromagnetic energy whose topological reconfigurations drive catastrophic energy release—a universal process exemplified by Earth’s geomagnetic storms and substorms<sup>1-3</sup>, stellar flares and coronal mass ejections<sup>4-8</sup>, flares and jets in accretion system<sup>9-11</sup>, and even disruptions of controlled fusion experiments<sup>12</sup>. Magnetic reconnection is of particular importance to this process<sup>12-14</sup>, wherein energy stored in magnetic fields is rapidly converted to heat and kinetic energy of plasma as magnetic fields break and reconnect to change their topology, leading to plasma heating and bi-directional plasma jets.

Magnetic reconnection initiates in current sheet, with its physical characteristics exhibiting dependence on the spatial scale of current sheet. A well-acknowledged picture of magnetic reconnection, termed standard magnetic reconnection with ion coupling<sup>12,15-18</sup>, has garnered considerable scientific interest over the past few decades, with its features of sufficiently large current sheet enabling both ions and electrons couple to it while ion-electron mass disparity induces scale separation phenomena. Recently, a novel type of magnetic reconnection, termed electron-only magnetic reconnection<sup>19</sup>, was discovered in a microscale current sheet in the

turbulent magnetosheath downstream of Earth's bow shock, which exclusively involves electrons, without ions' participation due to insufficient space for ions coupling. The transition from standard magnetic reconnection to electron-only magnetic reconnection is triggered when the size of current sheet contracts to smaller than  $\sim 10 d_i$  (ion inertial length)<sup>20,21</sup>. The presence of Hall magnetic field topology persists as a unifying feature across both reconnection regimes<sup>20,23</sup>, while the prominent features distinguishing electron-only magnetic reconnection from standard magnetic reconnection lies in the absence of bi-directional ion jets and much faster reconnection rate (i.e. faster magnetic flux transport)<sup>20,24</sup>.

Electron-only magnetic reconnection is prevalent in plasma turbulence due to abundant self-generated microscale current sheets, actively mediating its energy conversion and cascade<sup>21,25</sup>. The novel regime has additionally been discovered in plasma jets produced by standard magnetic reconnection<sup>26,27</sup>, as well as in interactions between solar wind and mini-magnetosphere induced by crustal magnetic field of celestial bodies lacking intrinsic magnetic fields, as exemplified by lunar plasma environments<sup>28,29</sup>. Even in large-scale current sheet, electron-only magnetic reconnection possibly acts as the transition phase from quiet current sheet to standard magnetic reconnection<sup>30,31</sup>. Furthermore, electron-only reconnection has been produced in laboratory plasma experiments<sup>32</sup>.

Despite the novel electron-only magnetic reconnection has been observationally confirmed across diverse plasma environments, its strikingly diminutive spatial scale imposes formidable observational constraints on direct measurements of its intrinsic physical processes, most critically within its core region—near the X-line. Moreover, in previous observations by spacecraft, spacecraft often traversed the reconnection current sheet along its normal direction—trajectory *I* in Fig. 1, thereby precluding unambiguous determination of whether the X-line was encountered. Consequently, the intrinsic mechanism governing electron-only magnetic reconnection remains largely enigmatic. Earth's magnetotail serves as a nature laboratory for deciphering this intricate mystery through two unique advantages: (1) the larger plasma inertial length facilitates larger spatial scale of electron-only magnetic reconnection; and (2) the X-line occasionally propagates along its jet's direction—trajectory *II* in Fig. 1, enabling definitive evidence of X-line identification—coincident reversal variations in normal magnetic field and electron jet<sup>33,34</sup>.

In this study, we present a pioneering investigation on this outstanding question by capturing whistler waves at both the X-line and outflow jet within an electron-only magnetic reconnection in Earth's magnetotail. The observation was made by NASA's Magnetospheric

Multiscale (MMS) satellites, which was designed to study microscale physical processes in magnetic reconnection by providing unprecedented high-cadence in situ measurements<sup>35-40</sup>. Utilizing MMS high-resolution data, we fully resolved the excitation of right-handed polarization whistler waves at the X-line, and unveiled left-handed polarization feature of whistler waves within a magnetic hole coupled to the Hall magnetic field.

## Results

### An electron-only magnetic reconnection in Earth's magnetotail

On 02 August 2020 at 14:45:50-14:47:20 Universal Time (UT), the four MMS spacecrafts, in a tetrahedral formation separated by  $\sim 37$  km, were at  $[-28.0, -1.8, 4.0] R_E$  (Earth's radii) in geocentric solar magnetospheric (GSM) coordinates. The MMS spacecraft, while cruising in the magnetotail plasma sheet—a region characterized by significant hot plasma populations (Fig. 2a, 2b), detected an earthward ( $V_{ix} > 0$ ) high-speed plasma flow (Fig. 2e). At approximately 14:46:35 UT, an electron-only magnetic reconnection was observed in this high-speed plasma flow, as distinctly delineated by teal arrows in Fig. 2c and 2d. This event is characterized by a pronounced weakening of the magnetic field magnitude (Fig. 2c), a distinct bipolar variation in the electron velocity  $V_{ex}$  component accompanied by an enhancement of the electron velocity  $V_{ey}$  component (Fig. 2d), while notably lacking corresponding bipolar variations in the ion velocity (Fig. 2e).

A local current sheet (LMN) coordinate system was adopted to orient the observation data to the usual two-dimensional view of magnetic reconnection (Fig. 2f), with  $L$  aligned to the direction of jet and reconnecting magnetic field,  $M$  along the out-of-plane (X-line) direction of reconnection plane, and  $N$  normal to the reconnection current sheet. The LMN coordinate system was obtained by the minimum variation analysis on magnetic field ('Minimum variation analysis' in Methods). A zoom-in view of this event during the interval 14:46:28-14:46:42 UT is presented in Fig. 2g-2m. At approximately 14:46:35.60 UT, a coincident reversal from positive to negative in both magnetic field  $B_N$  component and electron velocity  $V_{eL}$  component—indicated by teal arrows in Fig. 2g and 2j—was observed, providing definitive evidence for encounter of an X-line propagating along the L-direction. As expected for an electron-only magnetic reconnection, the electron bi-directional outflow jets achieved super-Alfvénic velocity (+500 and  $-1500$  km/s along  $\pm L$  directions; Fig. 2j), while the ion flows demonstrated no dynamic response during the reconnection interval (Fig. 2k). Here, the Alfvén velocity,  $V_A = |B|/\sqrt{\mu_0 m_i n_i}$ , is  $\sim 242$  km/s, evaluated using averaged magnetic field magnitude of 8 nT and number density of  $0.52 \text{ cm}^{-3}$  during this interval. During the traversal

across the X-line from the +L-direction jet to the -L-direction jet, the MMS spacecraft gradually migrated from the  $B_L > 0$  side of the reconnection current sheet toward the proximity of the neutral line ( $B_L = 0$ ), subsequently moving along the neutral line. Such trajectory, shown in Fig. 1f, is evidenced by the decline of  $B_L$  from  $\sim 10$  nT to  $\sim 2$  nT followed by its stabilization at this baseline level (Fig. 2g).

As the MMS traversed toward the neutral line, electron number density exhibited an enhancement from  $\sim 0.4$  to  $\sim 0.53$   $\text{cm}^{-3}$  (Fig. 2i), revealing a density asymmetry across this reconnection current sheet with  $N_{\text{high}}/N_{\text{low}} \geq 1.3$ . Such density asymmetry would modulate the quadrupole configuration of the Hall magnetic field<sup>16,41,42</sup>, leading to a compression of the two quadrants at low-density side while an expansion of the other two quadrants at high-density side, as illustrated in Fig. 2f. This asymmetric compression and expansion produced a bipolar  $B_M$  signature (negative-to-positive) along the X-line traversal trajectory (Fig. 2f), following guide field ( $B_g \approx 2.2$  nT) subtraction. The ratio of guide field to the reconnection magnetic field,  $B_g/B_L$ , for this event is estimated to less than 22%. During approach toward the neutral line, the electric field  $E_N$  component exhibited a negative-to-positive bipolar variation (Fig. 2h). This bipolar signature emerges prior to traversal across the neutral line, which is attributed to density asymmetry as well<sup>16</sup>. Following the traversal across this X-line, a negative enhancement of  $B_N$  accompanied by reduction of number density immediately exhibited in the -L-direction jet, (Fig. 2g and 2i), consistent with the physical pictures of flux pile-up region (FPR) in standard magnetic reconnection<sup>43</sup>. Concurrently, a magnetic hole (MH) emerged in the jet (Fig. 2g), characterized by a depletion of magnetic field magnitude and coupled to the Hall magnetic field in quadrant IV. It is the first evidence of FPR and MH existing in electron-only magnetic reconnection.

Quantitative analysis reveals pronounced energy conversion within the electron jet, where the  $\mathbf{J} \cdot \mathbf{E}'$  reaches  $-0.2$  nW/m<sup>3</sup> (Fig. 2l), indicative of kinetic-to-electromagnetic energy transfer. In contrast, the X-line vicinity exhibited weaker energy exchange ( $\mathbf{J} \cdot \mathbf{E}'$  up to  $0.04$  nW/m<sup>3</sup>) with reversed electromagnetic-to-kinetic conversion polarity (Fig. 2l). The energy conversion  $\mathbf{J} \cdot \mathbf{E}'$  is dominated by the contribution of the components perpendicular to the magnetic field (Fig. 2l). Electron temperature near the X-line exhibited a primary temperature increment of  $\Delta T_e \sim 80$  eV, with FPR coincident observations showing a subsequent  $\Delta T_e \sim 120$  eV enhancement (Fig. 2m), demonstrating staged energization processes in this electron-only magnetic reconnection.

### Whistler waves near the X-line

Obvious fluctuations in all three magnetic components exhibited in the X-line vicinity (Fig. 2g and Fig. 3a), indicative of the presence of electromagnetic waves therein. To determine the wave properties, we conducted polarization analysis using the well-acknowledged singular value decomposition ('Wave polarization analysis' in Methods). Intense wave emissions are observed in both electric and magnetic fields (Fig. 3c, 3d), exhibiting a spectral enhancement between  $\sim 3$  Hz and  $\sim 10$  Hz, with power peaking at  $\sim 0.1 f_{ce}$  ( $f_{ce}$  is the electron cyclotron frequency). The waves have large positive ellipticity of approximately 1 (Fig. 3e), wave normal angle smaller than  $\sim 25^\circ$  (Fig. 3f), and large planarization degree of approximately 1 (Fig. 3g), indicating they are right-handed circularly polarized whistler waves. We further calculated the wavevector  $\mathbf{k}_{sc}$  and wave speed  $V_{ph}$  based on the wave dispersion relation in spacecraft rest frame resolved through the cross-power spectral analysis using four spacecraft observations ('Wave dispersion relation obtained by cross power spectral analysis' in Methods), as shown in Fig. 4a-4c. The obtained  $\mathbf{k}_{sc}$  corresponding to the maximum wave power is determined as  $3.13 \times 10^{-5} \times [-0.06, 0.25, 0.97]$  in the field-aligned coordinates ('Field-aligned coordinate' in Methods). This orientation results in a wave normal angle of approximately  $15^\circ$  with respect to the background magnetic field. The propagating direction obtained by the cross-power spectral analysis is consistent with that obtained by the minimum variation analysis and Timing analysis ('Minimum variation analysis' and 'Timing analysis' in Methods). The normalized wavenumber is  $|\mathbf{k}_{sc}|d_e = 0.23$ , where  $d_e \equiv c/\omega_{pe} \approx 5.31 \times n_e^{-1/2}$  is the electron inertial length. This yields  $d_e = 7.3$  km for measured mean number density  $n_e = 0.53 \text{ cm}^{-3}$ . The frequency  $f_{sc}$  corresponding to the maximum wave power is  $\sim 6$  Hz, yielding wave speed  $|V_{ph}| = 2\pi f_{sc}/|\mathbf{k}_{sc}| = 1204 \text{ km/s}$ .

The Doppler-shift effect imposed by high-velocity electron jet on whistler waves becomes non-negligible at these low frequencies, requiring explicit consideration in the analysis<sup>44</sup>. The frequency in plasma rest frame is determined as  $\sim 7.8$  Hz (or equivalent to  $\sim 0.1 f_{ce}$ ) by the Doppler-shift relation,  $f_{pl} = f_{sc} - \mathbf{k}_{sc} \cdot \mathbf{V}_{eflow}/2\pi$ , where the electron bulk velocity in the field-aligned coordinates  $\mathbf{V}_{eflow} = [374 \text{ } -397 \text{ } -247] \text{ km/s}$  and magnetic field  $B_0 = 2.7 \text{ nT}$  are averaged measurements in the X-line vicinity. The electron cyclotron frequency  $f_{ce} = 76 \text{ Hz}$  is calculated using  $f_{ce} = q_e B_0 / 2\pi m_e$ . The wavenumber in the plasma rest frame is obtained through  $|\mathbf{k}_{pl}| = 2\pi f_{pl}/|V_{ph}|$ , yielding the normalized wavenumber  $|\mathbf{k}_{pl}|d_e = 0.3$ .

The field-aligned Poynting fluxes exhibit positive dominance with sporadic negative excursions (Fig. 3h), suggesting local excitation of whistler waves. This energy propagation pattern correlates with observed electron pitch-angle distributions showing higher fluxes near

90° compared to near 0° (Fig. 3b). The anisotropic nature of electron distribution was further quantitatively demonstrated through pitch-angle-resolved electron phase space density (PSD) measurements (Fig. 4d), where electrons with energy higher than 800 eV exhibit a pronounced enhancement at 90° relative to 0° pitch angles (i.e. perpendicular anisotropy distribution). The observed electron distribution was successfully reproduced through a model comprised of five bi-Maxwellian distributions (solid curves in Fig. 4d). To examine whether the observed whistler waves were locally excited near the X-line, we conducted a kinetic instability analysis through dispersion relation calculations, adopting this five-component bi-Maxwellian model as input parameters (‘Instability analysis and electron distribution fitting’ in Methods). This local anisotropic electron distribution provided free energy sufficient to sustain whistler waves growth, with positive growth rates emerging in the frequency range  $f \sim 0.03\text{--}0.13 f_{ce}$  (corresponding to wavenumbers  $|\mathbf{k}_{pl}|d_e \sim 0.15\text{--}0.41$ ) for whistler waves propagating at  $\theta=15^\circ$  (Fig. 4e). Peak growth rate ( $\gamma/\omega_{ce}=0.02$ ) is resolved at  $(f/f_{ce}, |\mathbf{k}_{pl}|d_e) = (0.09, 0.30)$ , quantitatively aligned with the observed maximum in spectral power centered at  $(0.10f_{ce}, 0.30d_e^{-1})$ , as denoted by asterisk (Fig. 4e). Whistler waves are predominantly excited through second-order cyclotron resonances (‘Resonant energy’ in Methods), where normal ( $m = +2$ ) and anomalous ( $m = -2$ ) resonant electrons at 1383 eV and 1132 eV respectively exhibit perpendicular anisotropy (Fig. 4f). Whereas first-order ( $m = \pm 1$ ) cyclotron resonant electrons below 800 eV show no measurable anisotropy (Fig. 4f), Landau resonance ( $m = 0$ ) electrons demonstrates no field-aligned beam features. The reduced PSD of electrons at 0° pitch-angle compared to those at 180° suggests that second-order anomalous cyclotron resonance—characterized by resonant electrons exhibiting parallel velocities (‘Resonant energy’ in Methods)—likely dominates whistler waves excitation.

### Whistler waves in magnetic hole within outflow jet

A magnetic hole (MH)—characterized by a depletion of magnetic field magnitude—emerged in the  $-L$ -direction electron jet, which was detected by all four MMS spacecrafts (Fig. 5c). This MH exhibited coupling with the Hall magnetic field in quadrant IV, due its depletion primarily stemmed from reductions in  $B_M$  component (Fig. 5b). Analysis of spacecraft configuration and  $B_L$  intensity measurements near the X-line (Fig. 5a) demonstrates that MMS3 exhibited the closest proximity to the neutral line, followed sequentially by MMS2, MMS1, and MMS4 with progressively larger displacements. Consistently, spacecraft in closer proximity to the neutral line recorded stronger Hall magnetic fields (Fig. 5b), indicating the central region of Hall fields in quadrant IV resides adjacent to the neutral line, as illustrated in the schematic diagram (Fig. 2f). Whereas within the MH (Fig. 5c), MMS3 recorded the smallest

reduction in magnetic field magnitude ( $\Delta B \sim 0.23$  nT), while MMS1 observed the most significant weakening ( $\Delta B \sim 1.37$  nT), followed by MMS4 ( $\Delta B \sim 1.24$  nT) and MMS2 ( $\Delta B \sim 1.08$  nT). This spatial pattern indicates that this MH's center was displaced along the +N direction relative to the Hall magnetic field's center, with MMS1 having successfully captured this MH's core region during its traverse.

Magnetic field fluctuations were also detected in this MH (Fig. 5a-5c). Consistently, wave emissions are observed as well (Fig. 3c, 3d), exhibiting a spectral enhancement between  $\sim 8$  Hz and  $\sim 20$  Hz. The waves have positive ellipticity of approximately 0.5 (Fig. 3e), large wave normal angle  $> 30^\circ$  (Fig. 3f), and large planarization degree of approximately 1 (Fig. 3g), indicating they are right-handed elliptically polarized oblique-propagating whistler waves. The whistler waves were also observed by MMS1 (Extended Data Fig. S1). Wave properties were further analyzed using MMS1 measurements, which captured this MH's core region. The wave dispersion was resolved by using the Bellan method based on Ampere's law ('Wave dispersion relation based on Ampere's law' in Methods). The peak wave power occurs at frequency  $f_{sc} \sim 14$  Hz (or equivalent to  $0.13 f_{ce}$  with  $B_0 = 3.96$  nT) and normalized wavenumber  $|\mathbf{k}_{sc}| d_e \sim 0.64$ , yielding wave speed  $|\mathbf{V}_{ph}| = 2\pi f_{sc} / |\mathbf{k}_{sc}| = 1029$  km/s (Fig. 5e). The negative parallel wavenumbers (Fig. 5d) and the negative field-aligned Poynting fluxes (Extended Data Fig. S1h), indicating that the whistler wave had a propagation velocity component anti-parallel to the background magnetic field. The wave propagating direction was estimated as  $(-0.75, -0.28, -0.60)$  in the field-aligned coordinates using the minimum variation analysis. This orientation yields a wave normal angle of approximately  $50^\circ$  with respect to the background magnetic field, which is consistent with the results obtained from the SVD method (Extended Data Fig. S1). The frequency in plasma rest frame is determined as  $f_{pl} \sim -3.5$  Hz by the Doppler-shift relation, where the electron bulk velocity in the field-aligned coordinates  $\mathbf{V}_{eflow} = [-1562, 196, -281]$  km/s are averaged measurements in the MH. This negative frequency indicates the polarization reversals to left-handed sense in the plasma rest frame. The left-handed polarization was possibly attributed to wave-wave interactions<sup>45,46</sup>.

## Conclusions

In summary, this study presents unprecedented observations of whistler waves in electron-only magnetic reconnection, exhibiting distinct characteristics from those reported in standard magnetic reconnection with ion-coupling. The right-handed whistler waves near the X-line are excited by perpendicular anisotropy electron distributions via second-order cyclotron resonance, while those in the outflow jet exhibit left-handed polarization. The outflow-associated whistler

waves reside within a magnetic hole coupled to the Hall magnetic field. Furthermore, phenomenon analogous to standard magnetic reconnection—specifically flux pileup region in the outflow—is also identified in this electron-only regime. These groundbreaking discoveries not only elicit further exploration into the internal physical processes of electron-only magnetic reconnection, but also provide novel insights into the microscale dynamics in space and astrophysical plasmas.

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## Figure Legends

**Fig. 1. Schematic showing electron-only magnetic reconnection within high-speed plasma flow in Earth's magnetotail, along with two typical spacecraft trajectories traversing the reconnection region.** The trajectory I—along the normal direction—precludes unambiguous determination of whether the X-line was encountered. The trajectory II—along the jet's direction—enables definitive evidence of X-line identification, namely coincident reversal variations in normal magnetic field and electron jet.

**Fig. 2. An electron-only magnetic reconnection in Earth's magnetotail observed by MMS on 02 August 2020.** **a-e**, Ambient plasma environment during interval 14:45:50-14:47:20 Universal Time (UT) showing ion energy spectrum of the differential energy fluxes (**a**), electron energy spectrum of the differential energy fluxes (**b**), magnetic field (**c**), electron bulk velocity (**d**), and ion bulk velocity (**e**). **f**, Schematic of observations in the two-dimensional view ( $L - N$  plane) of magnetic reconnection and configuration of four spacecraft in the  $L - N$  plane. **g-m**, Zoomed-in interval (14:46:28-14:46:42 UT marked between two gray vertical lines in **a-e**) showing magnetic field (**g**), electric field (**h**), electron number density (**i**), electron bulk velocity (**j**), ion bulk velocity (**k**), energy conversion in electron rest frame (**l**), and electron temperature (**m**), which present the definitive observational evidence of the X-line in the electron-only magnetic reconnection. The teal arrows in **g**, **j**, and **l** denote the X-line. The data in **a-e** are displayed in the geocentric solar magnetospheric (GSM) coordinates, while the data in **f-m** are displayed in the local current sheet (LMN) coordinates. The LMN coordinate is obtained by MVA on magnetic field during 14:46:33-14:46:36 UT, showing  $L = (0.85, 0.26, 0.46)$ ,  $M = (-0.46, 0.80, 0.39)$ , and  $N = (-0.27, -0.54, 0.80)$  in the GSM coordinate. These data are made by MMS3, as MMS3 exhibited the closest proximity to the neutral line ( $B_L = 0$  denoted by dashed curves in **f**).

**Fig. 3. Wave polarization analysis.** **a**, Magnetic field. **b**, Pitch-angle distributions of electrons

with energy of 0.8-10 keV. **c**, Power spectral density of the electric field. **d**, Power spectral density of the magnetic field. **e**, Ellipticity. **f**, Wave normal angle. **g**, Planarity. **h**, Normalized Poynting flux parallel to the magnetic field. The red and black curves in **c-h** denote electron cyclotron frequency ( $f_{ce}$ ) and  $0.1f_{ce}$ , respectively. The teal arrow in **a** denotes the X-line. These data are made by MMS3.

**Fig. 4. Dispersion relation and generation of whistler waves near the X-line.** **a-c**, Observed dispersion relation showing wave power in  $k_{\perp 1} - k_{\parallel}$  plane (**a**), wave power in  $k_{\perp 2} - k_{\parallel}$  plane (**b**), and wave power versus frequency and wave number (**c**). The red arrows and line are obtained by searching the strongest power. The observed dispersion relation is shown in spacecraft rest frame and calculated using cross-spectrum analysis based on magnetic fields measured by four spacecraft. **d**, Observed and fitted electron phase space densities as a function of pitch-angle. The circles and the curves are observed and fitted distributions, respectively. **e**, Predicted dispersion relation (blue) and growth rate (red) in plasma rest frame for waves with normal angle of  $15^\circ$ , and a comparison with the observed dispersion relation upon accounting for Doppler-shift effect (asterisk). **f**, Energies of electrons resonating with whistler waves.  $m = 0, 1, -1, 2$ , and  $-2$  represent Landau resonance, normal cyclotron resonance, anomalous cyclotron resonance, second order normal cyclotron resonance, and second order anomalous cyclotron resonance. These data displayed in **d-f** are based on MMS3 measurements.

**Fig. 5. The whistler waves in a magnetic hole coupled with the Hall magnetic field within the outflow jet.** **a-c**, Four MMS spacecraft observations of magnetic field  $B_L$  component (**a**),  $B_M$  component (**b**), and magnitude (**c**). The teal arrow in **b** denotes the X-line. **d-e**, Dispersion relation of whistler waves in the magnetic hole resolved based on Ampere's law showing wave power in  $|k_{\perp}| - k_{\parallel}$  plane (**d**) and wave power versus frequency and wave number (**e**). The red line is obtained by searching the strongest power. These data in **d-e** are made by MMS1 due to it captured the core region of magnetic hole.

## Methods

### Minimum variation analysis

Minimum variation analysis (MVA) is used to estimate the direction normal to a current layer or wave front based on single-spacecraft data. Many vector measurements,  $\mathbf{B}^m$  ( $m = 1, 2, 3, \dots, M$ ), are made during an encounter of a current layer or wave. Along the normal direction ( $\mathbf{n}$ ), the field-component set  $\{\mathbf{B}^m \cdot \mathbf{n}\}$  ( $m = 1, 2, 3, \dots, M$ ) has minimum variance. Therefore,  $\mathbf{n}$  is determined by minimization of

$$\sigma^2 = \frac{1}{M} \sum_{m=1}^M \left| \left( \mathbf{B}^m - \frac{1}{M} \sum_{m=1}^M \mathbf{B}^m \right) \cdot \mathbf{n} \right|^2 \quad (1)$$

which is subject to the normalization constraint  $|\mathbf{n}|^2 = 1$ . Using the Lagrange multiplier method to find the direction of minimum variance, the problem ultimately reduces to solving

for the eigenvalues and eigenvectors of matrix  $M_{\mu\nu}^B = \frac{1}{M} \sum_{m=1}^M B_{\mu} B_{\nu} - \frac{1}{M^2} \sum_{m=1}^M B_{\mu} \sum_{m=1}^M B_{\nu}$ <sup>47</sup>,

where the subscripts  $\mu, \nu = 1, 2, 3$  denote cartesian components along the  $X, Y, Z$  system. Ordered by descending eigenvalues, the three corresponding eigenvectors characterize the directions of maximum, intermediate, and minimum variance for the field components along each vector. The eigenvector characterizing minimum variance is identified as the normal direction of a current layer or wave front.

The local current sheet ( $LMN$ ) coordinate was obtained by MVA on magnetic field during 14:46:33-14:46:36 UT, showing  $L = (0.85, 0.26, 0.46)$ ,  $M = (-0.46, 0.80, 0.39)$ , and  $N = (-0.27, -0.54, 0.80)$  in the geocentric solar magnetospheric (GSM) coordinate. The propagating direction of the whistler waves near the X-line was estimated as  $(-0.06, 0.20, 0.98)$  in the field-aligned coordinate.

For the whistler waves in the magnetic hole within the outflow jet, the estimated propagation directions, derived from measurements by four satellites, exhibit significant divergence, with  $(-0.75, -0.28, -0.60)$  for MMS1,  $(-0.89, 0.40, -0.24)$  for MMS2,  $(-0.71, -0.06, -0.70)$  for MMS3, and  $(-0.18, -0.39, -0.90)$  for MMS4 in the field-aligned coordinate. This indicates inapplicability of methods based on four spacecraft measurements to analysis wave dispersion relation.

### Field-aligned coordinate

Field-aligned coordinate is a curvilinear coordinate where one axis (typically denoted as  $\parallel$ ) is aligned with the ambient magnetic field  $\mathbf{B}_0$ , while the other two axes ( $\perp_1, \perp_2$ ) span the plane perpendicular to  $\mathbf{B}_0$ . Hence,

$$\mathbf{e}_{\parallel} = \frac{\mathbf{B}_0}{|\mathbf{B}_0|}, \mathbf{e}_{\perp 1} = \frac{\mathbf{e}_{\parallel} \times \mathbf{x}}{|\mathbf{e}_{\parallel} \times \mathbf{x}|}, \mathbf{e}_{\perp 2} = \mathbf{e}_{\parallel} \times \mathbf{e}_{\perp 1} \quad (2)$$

where  $\mathbf{x}$  represents  $(1, 0, 0)$  in geocentric solar magnetospheric (GSM) coordinates.

### Timing analysis

Timing analysis is used to estimate normal direction and propagation velocity of a structure or wave front when it is sequentially detected by four spacecraft<sup>48</sup>, since

$$(\mathbf{V}t_{\alpha\beta}) \cdot \mathbf{n} = \mathbf{r}_{\alpha\beta} \cdot \mathbf{n} \quad (3)$$

where  $\mathbf{r}_{\alpha\beta}$  and  $t_{\alpha\beta}$  are the separation vector and time difference between any spacecraft pair. Based the Timing analysis, the propagating velocity of the whistler waves near the X-line is estimated as  $1230 \times (-0.14, 0.12, 0.98)$  km/s.

### Wave polarization analysis

The wave vector is determined by the linearized Faraday's law

$$\mathbf{n} \times \mathbf{E} = c\mathbf{B} \quad (4)$$

where  $\mathbf{n} = \mathbf{k}c/w$  is a dimensionless vector which has the modulus of the wave refractive index and the direction of the wave vector, and  $c$  is the speed of light. Based on spectral analysis of three-dimensional magnetic and electric fields, the wave polarization can be resolved by the singular value decomposition (SVD) method<sup>49</sup>.

#### Wave dispersion relation obtained by cross power spectral analysis

The wave dispersion relation can be resolved using the cross power spectral between the magnetic or electric fields measured by four spacecraft. The phase difference  $\Delta\psi$  between the detected waves by any spacecraft pair is determined by

$$\Delta\psi = \arctan\left(\frac{\text{Im}(\langle W_\alpha(f, t)W_\beta^*(f, t) \rangle)}{\text{Re}(\langle W_\alpha(f, t)W_\beta^*(f, t) \rangle)}\right) \quad (5)$$

where  $W_\alpha$  and  $W_\beta$  are the wavelet transforms of detected fields by any spacecraft pair. The corresponding wave vector for a specific frequency can be then determined by incorporating the inter-spacecraft separation<sup>50</sup>. To prevent phase aliasing, this method remains valid only when the inter-spacecraft separation is maintained below half the wavelength. For the whistler waves near the X-line, its wave velocity is estimated as  $\frac{\delta E}{\delta B} \sim 1380$  km/s, yielding the wavelength of  $\frac{\delta E}{\delta B} \times \frac{1}{f} \sim 230$  km. The estimated half the wavelength surpasses the inter-spacecraft separation ( $\sim 37$  km), indicating applicability of cross power spectral analysis on the whistler waves near the X-line.

#### Wave dispersion relation based on Ampere's law

The wave dispersion can be also resolved based on Ampere's law

$$\mu_0 \delta \mathbf{J} = i\mathbf{k} \times \delta \mathbf{B} \quad (6)$$

where  $\mu_0$ ,  $\delta \mathbf{J}$ ,  $\mathbf{k}$ , and  $\delta \mathbf{B}$  are magnetic permeability in empty space, wave current density, wavevector, and wave magnetic field, respectively. Based on this equation, the wave vector can be directly calculated from measurements by single spacecraft<sup>51</sup>.

#### Instability analysis and electron distribution fitting

To investigate the generation of whistler waves, the local dispersion relation was calculated using a general kinetic dispersion relation solver for magnetized plasma (PDRK)<sup>52</sup>. A model composed of five bi-Maxwellian distribution functions<sup>53</sup> was employed to fit the averaged electron phase space density observed between 14:46:35.10 and 14:46:35.80 UTC so

as to obtain the input parameters of PDRK. The model reads

$$f(v_{\parallel}, v_{\perp}) = \sum_{j=1}^5 \frac{n_e^j}{(\sqrt{\pi} v_{th}^j)^3} \exp\left(-\left(\frac{v_{\parallel} - v_d^j}{v_{th}^j}\right)^2\right) \cdot \frac{T_{\parallel}^j}{T_{\perp}^j} \exp\left(-\left(\frac{v_{\perp}^2}{\frac{T_{\perp}^j}{T_{\parallel}^j} (v_{th}^j)^2}\right)\right) \quad (7)$$

where  $j$  denotes different electron populations,  $v_{\parallel}$  and  $v_{\perp}$  are the parallel and perpendicular velocity,  $n_e$ ,  $v_{th}$ ,  $v_d$ ,  $T_{\parallel}$ , and  $T_{\perp}$  are the number density, electron thermal velocity, drift velocity parallel to the magnetic field, parallel and perpendicular temperature. The fitting parameters are: (1)  $n_e=0.2 \text{ cm}^{-3}$ ,  $T_{\parallel}=5 \text{ eV}$ ,  $T_{\perp}=5 \text{ eV}$ ,  $v_d=0 \text{ km/s}$ ; (2)  $n_e=0.15 \text{ cm}^{-3}$ ,  $T_{\parallel}=200 \text{ eV}$ ,  $T_{\perp}=150 \text{ eV}$ ,  $v_d=0 \text{ km/s}$ ; (3)  $n_e=0.17 \text{ cm}^{-3}$ ,  $T_{\parallel}=400 \text{ eV}$ ,  $T_{\perp}=700 \text{ eV}$ ,  $v_d=2000 \text{ km/s}$ ; (4)  $n_e=0.17 \text{ cm}^{-3}$ ,  $T_{\parallel}=700 \text{ eV}$ ,  $T_{\perp}=700 \text{ eV}$ ,  $v_d=-2000 \text{ km/s}$ ; (5)  $n_e=0.03 \text{ cm}^{-3}$ ,  $T_{\parallel}=1500 \text{ eV}$ ,  $T_{\perp}=1800 \text{ eV}$ ,  $v_d=0 \text{ km/s}$ .

### Resonant energy

The energy of resonant electrons is obtained by the following equation<sup>44,54</sup>

$$E_R = \frac{1}{q_e} \frac{B_0^2}{2\mu_0 n_e} \frac{\omega_{ce}}{\omega \cos^2 \theta} \left( \cos \theta - \frac{\omega}{\omega_{ce}} \right) \left( -m + \frac{\omega}{\omega_{ce}} \right)^2 \quad (8)$$

where  $q_e$ ,  $B_0$ ,  $\mu_0$ ,  $n_e$ ,  $\omega_{ce}$ ,  $\omega$ ,  $\theta$ , and  $m$  are the electron charge, ambient magnetic field, magnetic permeability in vacuum, electron number density, electron cyclotron angular frequency, angular frequency of the whistler waves, wave normal angle of the whistlers, and resonance mode. For the whistler waves near the X-line, the parameters are used:  $B_0 \sim 2.7 \text{ nT}$ ,  $n_e \sim 0.53 \text{ cm}^{-3}$ ,  $\omega_{ce} \sim 475 \text{ rad/s}$ ,  $\omega = 0.1 \omega_{ce}$ ,  $\theta \sim 15^\circ$ .  $m = 0, 1, -1, 2$ , and  $-2$  represent Landau resonance, normal cyclotron resonance, anomalous cyclotron resonance, second order normal cyclotron resonance, and second order anomalous cyclotron resonance. The minimum resonant velocity can be calculated by  $v_{\parallel} = (\omega - m \omega_{ce})/k_{\parallel}$ <sup>55</sup>, where  $k_{\parallel}$  is the parallel wave number. Near the X-line, whistler waves exhibit distinct resonance velocity alignments: parallel to the magnetic field for the  $m = -2$  mode, and antiparallel for the  $m = 2$  mode.

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## Data availability

The data used in this study are publicly available from the MMS Science Data Center (<https://lasp.colorado.edu/mms/sdc/public/about/browse-wrapper/>).

## Code availability

All of the data plots in this study are generated with the IRFU-Matlab software, which is publicly available by downloading from <https://github.com/irfu/irfu-matlab>.

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## Author contributions

Z.Z.C. carried out the data processing, contributed to the data analysis, and prepared the manuscript. H.S.F. and J.B.C. oversaw the research project and gave suggestions. J.Y. contributed to the data processing and participated in the interpretation of the data. O.L.C. offered constructive comments and suggestions. C.T.R., C.J.P., O.L.C., P.A.L., and R.E.E.

contributed to instrument development, operations and data processing. J.L.B. led the MMS mission. T.Y.W. gave suggestions on data interpretation. Z.Z.G., J.W., and J.C. gave suggestions on the manuscript. Y.Y. drew the cartoon picture.

## **Competing interests**

The authors declare no competing interests.

## **Additional information**

**Extended data** is available for this paper at nature.com.

**Supplementary information** is available at www.nature.com.

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## **Extended data figure legends**

**Extended data Fig. 1. Wave polarization analysis based on MMS1 measurements. a,** Magnetic field. **b,** Pitch-angle distributions of electrons with energy of 0.8-10 keV. **c,** Power spectral density of the electric field. **d,** Power spectral density of the magnetic field. **e,** Ellipticity. **f,** Wave normal angle. **g,** Planarity. **h,** Normalized Poynting flux parallel to the magnetic field. The red and black curves in **c-h** denote electron cyclotron frequency ( $f_{ce}$ ) and  $0.1f_{ce}$ , respectively.

## Figures

Fig. 1

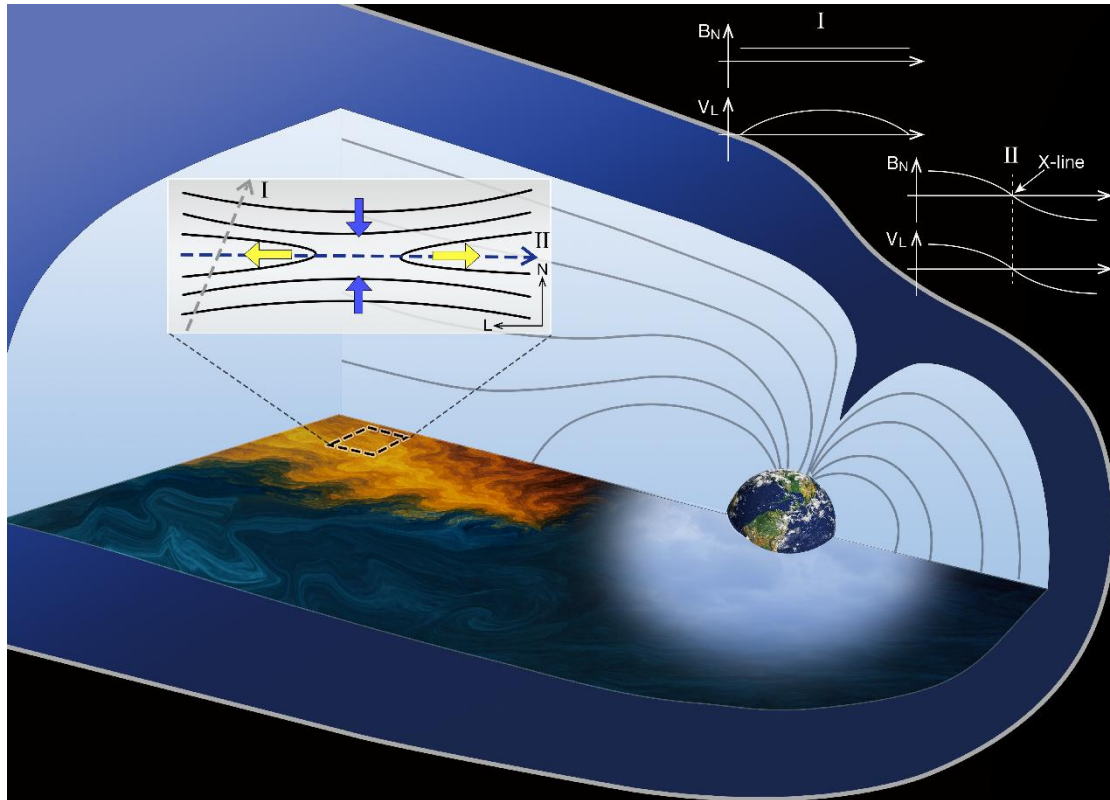


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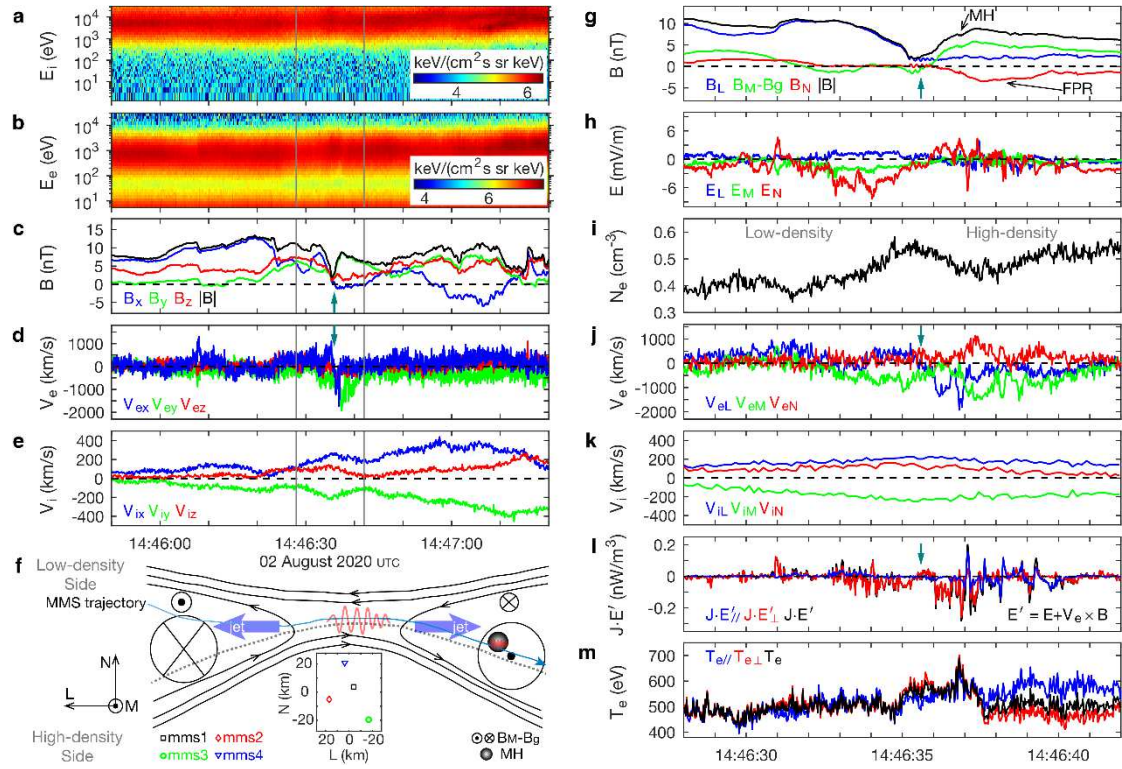


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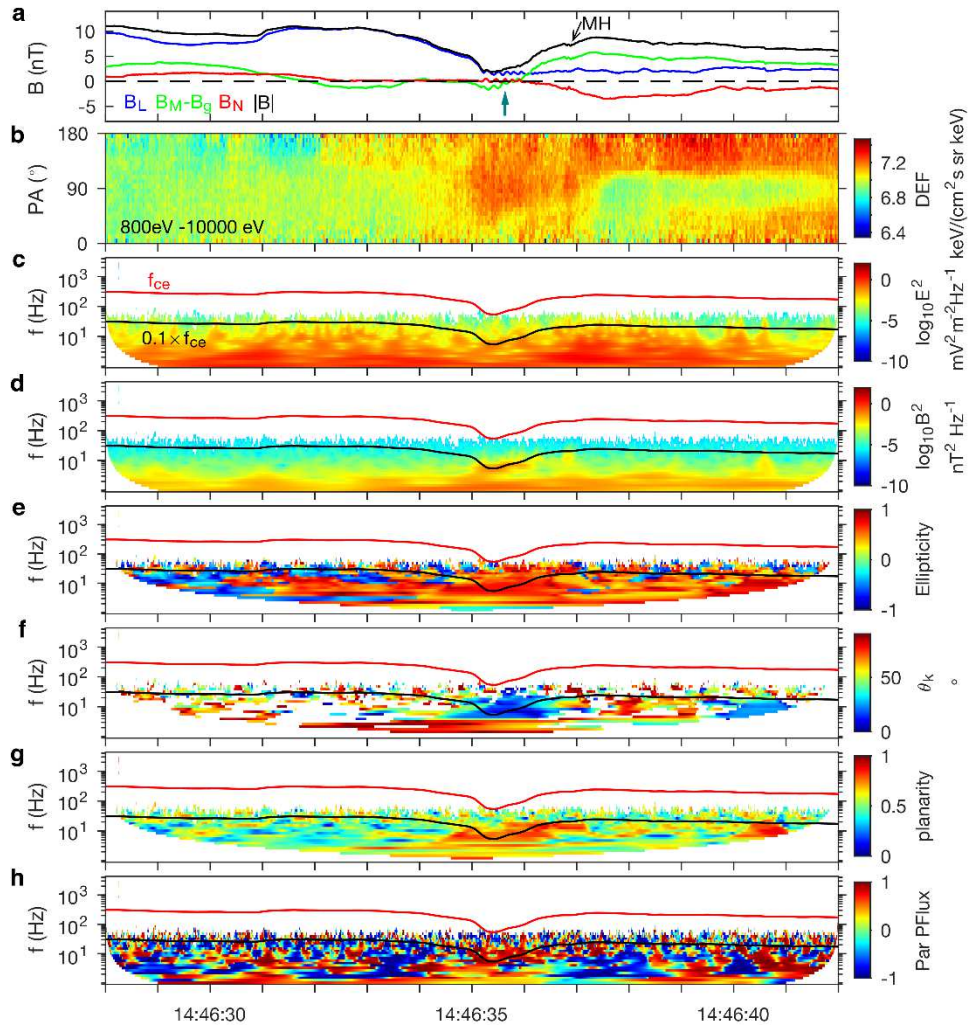


**Fig. 3. Wave polarization analysis.** **a**, Magnetic field. **b**, Pitch-angle distributions of electrons with energy of 0.8-10 keV. **c**, Power spectral density of the electric field. **d**, Power spectral density of the magnetic field. **e**, Ellipticity. **f**, Wave normal angle. **g**, Planarity. **h**, Normalized Poynting flux parallel to the magnetic field. The red and black curves in **c-h** denote electron cyclotron frequency ( $f_{ce}$ ) and  $0.1f_{ce}$ , respectively. The teal arrow in **a** denotes the X-line. These data are made by MMS3.

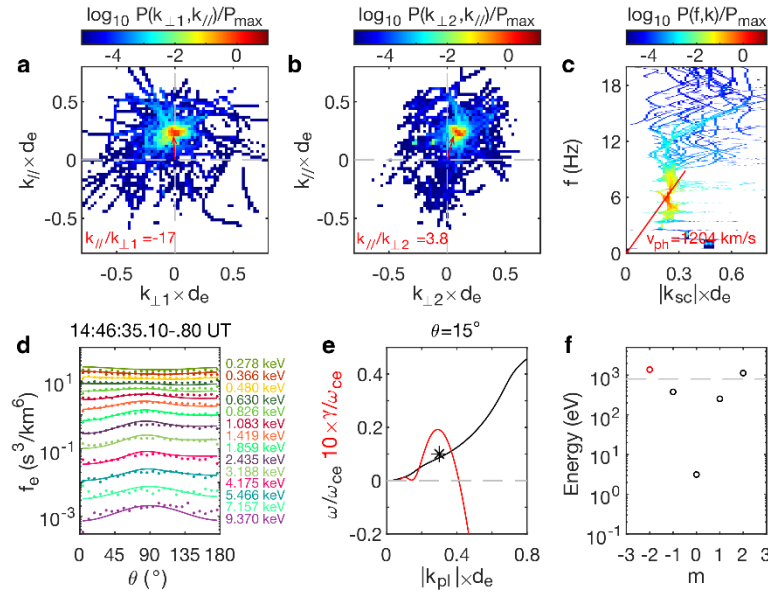


**Fig. 4. Dispersion relation and generation of whistler waves near the X-line.** a-c, Observed dispersion relation showing wave power in  $k_{\perp 1} - k_{\parallel}$  plane (a), wave power in  $k_{\perp 2} - k_{\parallel}$  plane (b), and wave power versus frequency and wave number (c). The red arrows and line are obtained by searching the strongest power. The observed dispersion relation is shown in spacecraft rest frame and calculated using cross-spectrum analysis based on magnetic fields measured by four spacecraft. d, Observed and fitted electron phase space densities as a function of pitch-angle. The circles and the curves are observed and fitted distributions, respectively. e, Predicted dispersion relation (blue) and growth rate (red) in plasma rest frame for waves with normal angle of  $15^{\circ}$ , and a comparison with the observed dispersion relation upon accounting for Doppler-shift effect (asterisk). f, Energies of electrons resonating with whistler waves.  $m = 0, 1, -1, 2$ , and  $-2$  represent Landau resonance, normal cyclotron resonance, anomalous cyclotron resonance, second order normal cyclotron resonance, and second order anomalous cyclotron resonance. These data displayed in d-f are based on MMS3 measurements.

Fig. 5

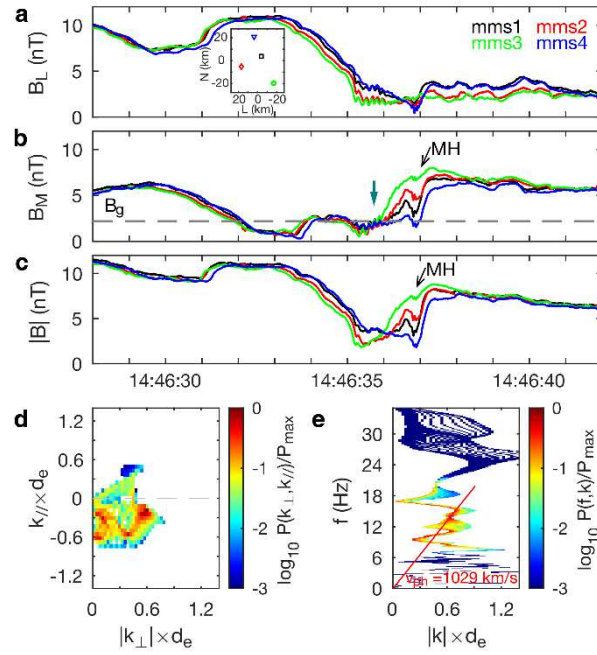
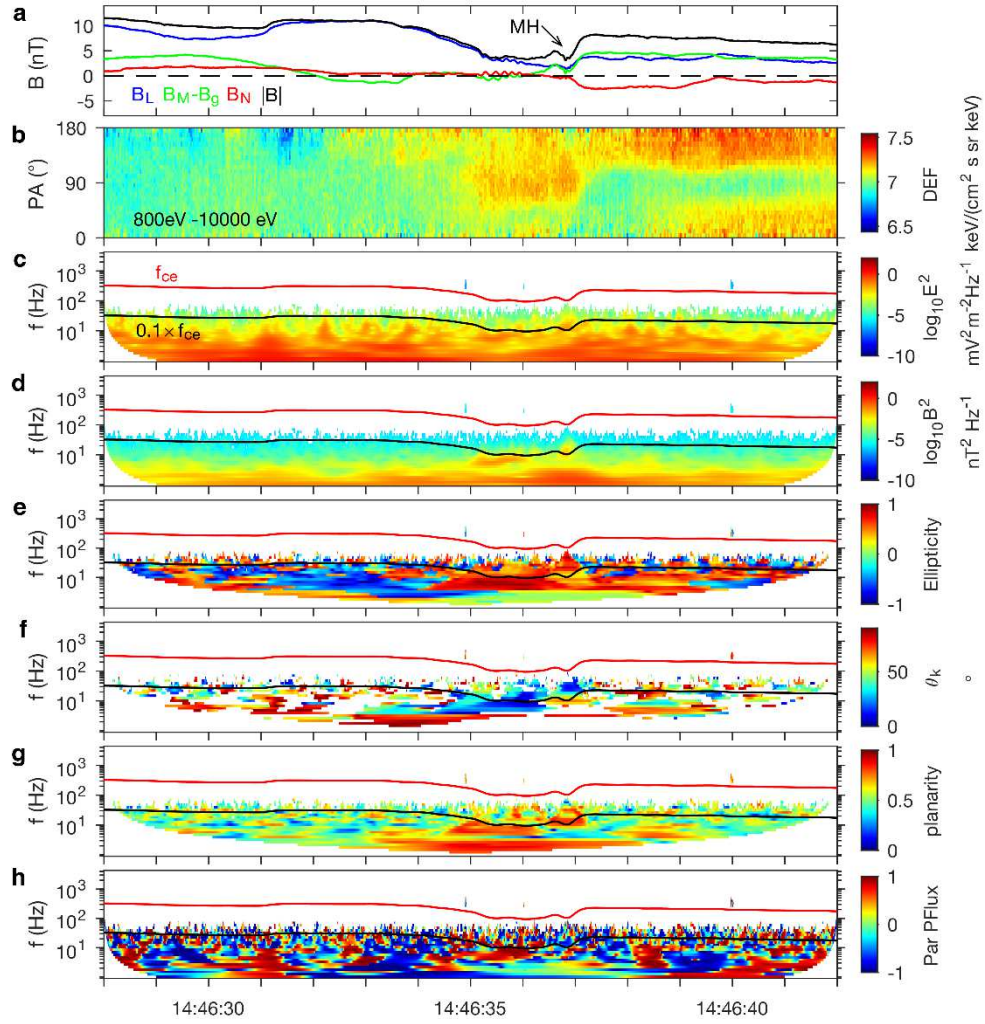


**Fig. 5. The whistler waves in a magnetic hole coupled with the Hall magnetic field within the outflow jet. a-c, Four MMS spacecraft observations of magnetic field  $B_L$  component (a),  $B_M$  component (b), and magnitude (c). The teal arrow in b denotes the X-line. d-e, Dispersion relation of whistler waves in the magnetic hole resolved based on Ampere's law showing wave power in  $|k_{\perp}| - k_{\parallel}$  plane (d) and wave power versus frequency and wave number (e). The red line is obtained by searching the strongest power. These data in d-e are made by MMS1 due to it captured the core region of magnetic hole.**

## Extended data

Extended data Fig. 1



**Extended data Fig. 1. Wave polarization analysis based on MMS1 measurements. a,** Magnetic field. **b,** Pitch-angle distributions of electrons with energy of 0.8-10 keV. **c,** Power spectral density of the electric field. **d,** Power spectral density of the magnetic field. **e,** Ellipticity. **f,** Wave normal angle. **g,** Planarity. **h,** Normalized Poynting flux parallel to the magnetic field. The red and black curves in **c-h** denote electron cyclotron frequency ( $f_{ce}$ ) and  $0.1f_{ce}$ , respectively.