Direct observations of anomalous resistivity and diffusion in collisionless plasma

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Coulomb collisions provide plasma resistivity and diffusion but in many low-density astrophysical plasmas such collisions are extremely rare. Scattering of particles by electromagnetic waves can lower the plasma conductivity. Such anomalous resistivity due to wave-particle interactions could be crucial to many processes, including magnetic reconnection. It has been suggested that waves provide both diffusion and resistivity, which can support the reconnection electric field, but this requires direct observation to confirm. Here, we directly quantify anomalous resistivity, viscosity, and cross-field electron diffusion associated with lower hybrid waves using measurements from the four Magnetospheric Multiscale (MMS) spacecraft. We show that anomalous resistivity is approximately balanced by anomalous viscosity, and thus the waves do not contribute to the reconnection electric field. However, the waves do produce an anomalous electron drift and diffusion across the current layer associated with magnetic reconnection. This leads to relaxation of density gradients at timescales of order the ion cyclotron period, and hence modifies the reconnection process.
Most of the visible universe is composed of plasma, consisting of ions and electrons. The behavior of plasma is governed by electromagnetic forces. In low-density solar and astrophysical plasmas Coulomb collisions are typically extremely rare, meaning that collisions between particles do not play a role in the behavior of the plasma and cannot provide plasma resistivity and diffusion. However, the scattering of particles by electromagnetic waves can introduce effective collisions, lowering the plasma conductivity. Such anomalous resistivity due to wave-particle interactions is thought to be crucial to a wide variety of collisionless plasma processes. One process where anomalous effects are thought to be important is magnetic reconnection, which is a fundamental plasma process providing explosive energy releases by reconfiguring magnetic field topology. In particular, it has been suggested based on theoretical and numerical results that waves can provide both diffusion and resistivity, which can potentially support the reconnection electric field, and the out-of-plane electric field responsible for sustaining reconnection.

One wave that has received significant attention as a source of anomalous effects is the lower hybrid wave. Lower hybrid waves are found at frequencies between the ion and electron cyclotron frequencies and are driven by plasma gradients and the associated cross-field currents. Previous attempts to calculate anomalous terms concluded that the anomalous resistivity was small, while cross-field particle diffusion associated could be significant. However, these estimates relied on density fluctuations inferred from the spacecraft potential, electron velocities inferred from the electric and magnetic fields assuming electrons remain frozen in, and often single spacecraft measurements. An external electric field can modify the spacecraft potential, making density fluctuations associated with waves inferred from the spacecraft potential unreliable. Similarly, it is unclear how well the frozen-in approximation works without direct measurements. Recent observations have shown that electrons remain close to frozen in, although pressure fluctuations associated with the waves can cause some deviation from the ideal frozen in condition. Thus, calculations of anomalous resistivity, viscosity, and cross-field diffusion based on direct particle measurements are needed to determine the role of lower hybrid waves.

In this work, we directly measure and quantify anomalous resistivity, viscosity, and cross-field electron diffusion associated with lower hybrid waves using the high-resolution fields and particle measurements from the four MMS spacecraft. We show that anomalous resistivity is balanced by viscosity (momentum transport), and thus the waves do not contribute to the reconnection electric field. However, the waves do produce an anomalous electron drift and diffusion across the current layer associated with magnetic reconnection. This can lead to the relaxation of density gradients at timescales of order the ion-cyclotron period, which counteracts steepening of density gradients caused by magnetic reconnection and hence modifies the process.

Results

Magnetic reconnection and case study. A region where reconnecting current sheets and potential anomalous effects can be found is the terrestrial equatorial magnetopause, the boundary between the shocked solar wind in the magnetosheath and the magnetosphere (Fig. 1a). Magnetic reconnection occurs between the high-density magnetosheath and the more tenuous magnetosphere. This result in reconnection being asymmetric with strong density gradients across the boundary. Figure 1b shows the result from a numerical simulation (see Methods, subsection Simulation description) designed to illustrate the magnetopause reconnection event presented in Fig. 2. The approximate orbit of MMS moving from the magnetosheath to the magnetosphere is indicated, with the turbulent magnetopause separating the two regions. The density fluctuations on the low-density side of the reconnection region are due to lower hybrid waves, which are driven by the strong density gradients in this region.

Figure 2 provides an overview of a magnetopause reconnection event observed by MMS. We use MMS electric field data and magnetic field data, and electron and ion data. In particular, to investigate fluctuations in the electron and ion distributions associated with waves, we use particle moments sampled at 7.5 and 37.5 ms, respectively. The electron sampling rate is high enough to resolve the local lower hybrid frequency and is unique and essential for comparisons with the lower hybrid waves.

Magnetic field data from one MMS spacecraft is shown in Fig. 2a in a local current sheet coordinate system: the current sheet normal points along $\mathbf{N}$, $\mathbf{L}$ is along the anti-parallel magnetic field direction, and $\mathbf{M} = \mathbf{N} \times \mathbf{L}$ completes the right-hand coordinate system. The local coordinates are determined using a minimum variance analysis of $\mathbf{B}$. The magnetopause crossing is characterized by a reversal in $B_1$ from negative in the high-density magnetosheath to positive in the low-density magnetosphere (Fig. 2b). The electron diffusion region (EDR), as indicated by the electron and ion jets reported previously in ref. Based on four-spacecraft observations, we estimate the current sheet velocity to be $\approx 40$ km s$^{-1}$ sunward in the $\mathbf{N}$ direction.

The components of the electric field $\mathbf{E}$ perpendicular and parallel to the magnetic field $\mathbf{B}$ are shown in Fig. 2c. The most intense waves are observed on the low-density side of the current sheet, mainly perpendicular to $\mathbf{B}$ in the $\mathbf{N}$ and $\mathbf{M}$ directions, with some intermittent smaller-amplitude higher-frequency fluctuations parallel to $\mathbf{B}$ (close to the $\mathbf{L}$ direction). We identify the waves as lower hybrid drift waves driven by the diamagnetic current at the density gradient (Fig. 2b). Lower hybrid waves occur between the ion and electron gyrofrequencies. The waves have a frequency of around $\approx 10$ Hz, a phase speed of $v_B \approx 140$ km s$^{-1}$, and a wavenumber of $k_{\rho_e} \approx 0.428$, where $\rho_e$ is the thermal electron gyroradius. The analysis techniques used to determine the wave properties are detailed in ref. These waves have been proposed as a source of anomalous resistivity and can be important for magnetic reconnection. Some recent studies concluded that the waves are relatively unimportant, while others conclude that the waves are important for ongoing reconnection.

Figure 2d shows the perpendicular and parallel components of $\mathbf{V}_e$ of the lower hybrid waves. The fluctuations are well resolved and the electron moments can be used to calculate the associated anomalous terms. Large $\mathbf{V}_e$ fluctuations are observed not only in the perpendicular but also in the direction parallel to $\mathbf{B}$, indicating that the wave vector is not exactly perpendicular to $\mathbf{B}$. This means the waves can potentially heat electrons. Figure 2e shows $\mathbf{E}$ and the electron and ion convection terms $-\mathbf{V}_e \times \mathbf{B}$ and $-\mathbf{V}_i \times \mathbf{B}$ in the $\mathbf{M}$ direction. Throughout the interval $\mathbf{E} \approx -\mathbf{V}_e \times \mathbf{B}$ meaning the electrons move together with the magnetic field (are approximately frozen in) as expected for lower hybrid waves. In contrast, $-\mathbf{V}_i \times \mathbf{B}$ remains close to zero. Although ion moments do not fully resolve the waves, this is consistent with the ions being unmagnetized, with only small perturbations in $\mathbf{V}_i$. This results in large-amplitude fluctuating currents, which are in turn responsible for fluctuations in $\mathbf{B}$ (Fig. 2a). Figure 2f displays density fluctuations normalized to the background density, associated with the waves. Large normalized perturbations, $\delta n_e/n_e > 0.1$, and electric field fluctuations suggest that anomalous resistivity may be significant.
Anomalous terms associated with waves. To evaluate the effects of waves on the plasma we divide the quantities into fluctuating and quasi-stationary components, \( Q = \langle Q \rangle + \delta Q \) where \( \langle Q \rangle \) corresponds to spatial or temporal averaging over fast fluctuations and \( \delta Q \) corresponds to fluctuations. Anomalous resistivity is effectively a force on charged particles due to waves, so we analyse a momentum equation. The electron momentum equation for a collisionless plasma is

\[
m_e \frac{\partial (n_e V_e)}{\partial t} + m_e \mathbf{V} \cdot (n_e V_e \mathbf{V}) + \mathbf{V} \cdot \mathbf{P}_e + n_e e (\mathbf{E} + \mathbf{V} \times \mathbf{B}) = 0,
\]

where \( e, n_e, m_e, \), and \( \mathbf{P}_e \) are the unit charge, electron density, mass, bulk velocity, and pressure tensor, respectively, and \( \mathbf{E} \) and \( \mathbf{B} \) are the electric and magnetic fields. Introducing fluctuations, neglecting time derivatives, and averaging yields

\[
\langle \mathbf{E} \rangle + \langle \mathbf{V} \times \mathbf{B} \rangle = - \frac{\mathbf{V}}{\langle n_e \rangle} - \frac{m_e}{\langle n_e \rangle} \mathbf{V} \cdot (\langle n_e \rangle \langle \mathbf{V} \rangle) + \mathbf{D} + \mathbf{T} + \mathbf{I}.
\]

Here \( \mathbf{D}, \mathbf{T}, \) and \( \mathbf{I} \) are the anomalous drag (sometimes called resistivity), anomalous viscosity (momentum transport), and anomalous Reynold’s stress, respectively. These quantities are defined as

\[
\mathbf{D} = - \frac{\langle \delta n_e \delta \mathbf{E} \rangle}{\langle n_e \rangle},
\]

\[
\mathbf{T} = - \frac{n_e \langle \mathbf{V} \times \mathbf{B} \rangle}{\langle n_e \rangle} + \langle \mathbf{V} \rangle \times \langle \mathbf{B} \rangle,
\]

\[
\mathbf{I} = - \frac{m_e}{e \langle n_e \rangle} \left[ \mathbf{V} \cdot \langle n_e \mathbf{V} \mathbf{V} \rangle - \mathbf{V} \cdot (\langle n_e \rangle \langle \mathbf{V} \rangle) \left( \langle \mathbf{V} \rangle \right) \right].
\]

We define the total anomalous contribution to equation (2) as \( \mathbf{R} = \mathbf{D} + \mathbf{T} + \mathbf{I} \). We find that the contributions of \( \mathbf{I} \) are negligible compared with \( \mathbf{D} \) and \( \mathbf{T} \), so they are neglected in the following analyses (see Methods, subsection Estimating the anomalous terms for an example and details).

We study the electron continuity equation to find anomalous flows due to fluctuations

\[
\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \mathbf{V}) = \langle \delta n_e \delta \mathbf{E} \rangle = \mathbf{R}.
\]

A cross-field diffusion coefficient \( D_\perp \) relates the electron density and velocity fluctuations to the density gradient in the direction normal to the boundary

\[
D_\perp = \frac{\langle \delta n_e \delta V_e \rangle}{\langle n_e \rangle}. \tag{7}
\]

A gradient relaxation timescale can be estimated as

\[
\tau_n = \left( \frac{1}{n_e} \frac{\partial}{\partial t} \right)^{-1} \approx \left[ \frac{\partial}{\partial n_e} \left( \frac{D_\perp}{|\mathbf{B}|} \right) \right]^{-1}. \tag{8}
\]

For lower hybrid waves, it has not been previously possible from observations to directly evaluate the terms involving electron density or velocity fluctuations, such as \( \langle \delta n_e \delta \mathbf{E} \rangle \).

Anomalous contributions from lower hybrid waves. Figure 3a shows the lower hybrid waves from one MMS spacecraft and Fig. 3b–e display the anomalous terms \( \mathbf{D}, \mathbf{T}, \) anomalous electron flow \( V_{n,anom} \) in the \( \mathbf{N} \) direction, and the diffusion coefficient \( D_\perp \) in the \( \mathbf{N} \) direction, obtained by combining data from all four spacecraft (see Methods, subsection Estimating the anomalous terms). The terms \( \mathbf{D} \) and \( \mathbf{T} \) have a maximum amplitude of \( 0.8 \pm 0.2 \text{ mV m}^{-1} \) (Fig. 3b, c), a small fraction (~2%) of the amplitude of the waves. For comparison, the reconnection electric field associated with magnetopause reconnection is expected to be \( \sim 1 \text{ mV m}^{-1} \) for fast reconnection, comparable to the peak magnitudes of \( \mathbf{D} \) and \( \mathbf{T} \). Both \( \mathbf{D} \) and \( \mathbf{T} \) are predominantly in the \( \mathbf{M} \) direction and \( \mathbf{D} \approx -\mathbf{T} \). This is similar to the result found from the simulation in ref. 33. The directions of \( \mathbf{D} \) and \( \mathbf{T} \) remain the same while the lower hybrid waves are observed, although some
Examples of anomalous terms from lower hybrid waves. Figure 4 shows two different magnetopause crossings observed on 02 December 2015 (Fig. 4a–d) and 14 December 2015 (Fig. 4e–h). In Fig. 4a–d the spacecraft crossed from the magnetosphere to the magnetosheath. The spacecraft crossed the EDR at around 01:14:56 UT, close to the neutral point. The lower hybrid waves are observed for $\approx 10$ s on the magnetospheric side of the boundary. In Fig. 4e–h the spacecraft crossed the EDR from the magnetosheath to the magnetosphere, with the lower hybrid waves observed on the magnetospheric side, $D_M < 0$ and $T_M > 0$, such that $\mathbf{D} + \mathbf{T}$ is small, and a significant $V_{N,anom}$ is observed. For the 14 December 2015 event $\mathbf{D}$ and $\mathbf{T}$ have a significant component in the $\mathbf{L}$ direction due to the significant $B_M$ (guide field). In both events, the anomalous terms are negligible at the neutral point (indicated by the magenta lines in Fig. 4).
corresponding to larger amplitude and $D$ show the same qualitative behavior as the 06 December 2015 event: anomalous terms. To summarize, the two events presented in Fig. 4 cases, the uncertainties are smaller than the peak values of the field electron diffusion toward the magnetosphere are observed. In $\delta E$ is small. Large anomalous $D$ and $T$ both reach about 0.5 mV m$^{-1}$ but have opposite signs so the contribution to $E$ is small. Large anomalous flows and cross-field electron diffusion toward the magnetosphere are observed. In all three cases the peak values of $D$ and $T$ are $\sim$2% of the maximum amplitude of $\Delta E$.

Statistical results. Figure 5 shows statistics from magnetopause crossings where high-resolution particle moments are available and lower hybrid waves are observed. We divide each event into (1) EDR crossings, where the waves are observed adjacent to EDR regions identified in ref. 37. (2) Reconnection events, where the waves are observed at boundaries where reconnection signatures, such as ion outflows, are observed. (3) Non-reconnection events, where no clear reconnection signatures are observed.

In each case the largest $D$ was in the $-M$ direction and the largest $T$ was in the $M$ direction. Figure 5a shows the maximum $T$ ($|T|_{\text{max}}$) versus the maximum $D$ ($|D|_{\text{max}}$) and the associated uncertainties for each event. Here $|D|_{\text{max}}$ and $|T|_{\text{max}}$ can reach $\sim 1.5$ mV m$^{-1}$, with $|T|_{\text{max}}$ increasing approximately linearly with $|D|_{\text{max}}$. Both peak at approximately the same time, so for all cases $R \approx 0$. We find that $|T|_{\text{max}}$ tends to be slightly smaller than $|D|_{\text{max}}$, possibly due to small deviations from the frozen-in condition for electrons due to fluctuations in the electron pressure due to density fluctuations. The largest $D$ and $T$ correspond to magnetic reconnection events and EDRs, although more non-reconnection events need to be analyzed.

Figure 5b shows the values of $D_{1\perp}$ where $|V_{N,\text{anom}}|$ peaks versus the maximum $-V_{N,\text{anom}}$. Here $D_{1\perp}$ tends to increase as $-V_{N,\text{anom}}$ increases. Each case corresponds to diffusion from higher to lower densities. We find that $D_{1\perp}$ ranges from $0.05 \times 10^{9}$ to $2 \times 10^{9}$ m$^{2}$ s$^{-1}$, i.e., from small to very significant diffusion. The largest $-V_{N,\text{anom}}$ and $D_{1\perp}$ tend to occur close to EDRs, although there are cases where $-V_{N,\text{anom}}$ and $D_{1\perp}$ are also small near EDRs. Thus, cross-field diffusion and associated broadening are expected to be highly variable during magnetopause reconnection. The results suggest that $D_{1\perp}$ may be the largest close to the...
EDR, although further work and more events are required to confirm this.

Discussion
We find that for lower hybrid waves the anomalous terms $D$, $T$, and $V_{\text{anom}}$ can be accurately determined from the data and that $R = D + T \approx 0$, so the contribution to the reconnecting electric field is negligible because electrons are approximately frozen in. However, the diffusion coefficient $D_{\perp}$ and $V_{\text{anom}}$ can often be significant, corresponding to transport from the higher-density magnetosheath to the lower-density magnetosphere, producing significant broadening of the magnetopause density gradient.

Overall, these direct observations of anomalous terms in collisionless plasma open a new window to investigate fundamental plasma physics. Directly evaluating all terms involved in wave-particle interactions will show which processes are important, and which are not, in many astrophysical plasmas. In many reconnection events, the lower hybrid waves are observed over several seconds at large amplitude, which suggests that the density gradient is driven by ongoing reconnection, while lower hybrid waves counter this.

Methods

Estimating the anomalous terms. For each event we rotate the vector quantities into LMN coordinates, where $N$ is normal to the magnetopause pointing sunward, $L$ is along the reconnecting magnetic field direction, and $M$ completes the coordinate system and is close to the guide-field direction. We determine the coordinate system using a minimum variance analysis of $B$ across the magnetopause. The reliability of the $N$ direction is confirmed by determining the boundary normal velocity using four-spacecraft timing analysis, as well as minimum variance analysis of the current density $J$. In most cases, the uncertainty in the coordinate system directions are small and do not significantly affect the results.

Ideally, the quantities in equation (2) are computed from an ensemble average in the $M$ direction. With MMS we must use a four-spacecraft average to estimate these quantities. For all events, the spacecraft were in tetrahedral configurations with spacecraft separations ranging from ~15 to ~5 km. These separations are well below ion spatial scales at the magnetopause, but larger than electron spatial scales, which is ideal for studying lower hybrid waves. To calculate the anomalous and background quantities we use the following procedure:

1. We resample all field data to the sampling frequency of the high-resolution (7.5 ms) electron moments and perform a four-spacecraft timing analysis on $B_{\perp}$ at the current sheet to determine the boundary normal velocity and the time delays between the spacecraft. Typical boundary normal speeds range from $-10$ to $-100$ km s$^{-1}$.

2. We use the time delays to offset the spacecraft times so all spacecraft cross the boundary layer at the same time as MMS1.
Fig. 5 Statistics of anomalous terms. Anomalous terms are calculated from 22 magnetopause current sheets with lower hybrid waves. The black points indicate EDR crossings, red points indicate reconnection crossings outside the EDR, and green points indicate boundary crossings without clear evidence of reconnection. The maximum values of the anomalous viscosity and anomalous drag for each event, $\langle |T|_{\text{max}} \rangle$ and $\langle |D|_{\text{max}} \rangle$, are comparable. The diffusion coefficient $D_{\text{L}}$ tends to increase with the negative of the anomalous flow $V_{\text{N,anom}}$ up to tens of km s$^{-1}$, indicating significant flow from high to low density in the direction normal for large $D_{\text{L}}$ a $|T|_{\text{max}}$ versus $|D|_{\text{max}}$, $D_{\text{L}}$ versus $-V_{\text{N,anom}}$. The dashed line in panel (a) indicates $|D|_{\text{max}} = |T|_{\text{max}}$. The horizontal and vertical lines indicate the uncertainties of $|D|_{\text{max}}$ and $|T|_{\text{max}}$ in (a) and $V_{\text{N,anom}}$ and $D_{\text{L}}$ in (b). See Methods, subsection Estimating the anomalous terms for details on the calculation of the uncertainties.

(3) To obtain the non-fluctuating terms $\langle \delta Q \rangle$ we average the time-shifted quantities over the four spacecraft and bandpass filter below 5 Hz. At the magnetopause the lower hybrid waves are typically found at frequencies 10 Hz < $f$ < 30 Hz.

(4) To obtain $\delta Q$ associated with the lower hybrid wave fluctuations we bandpass filter $Q$ above 5 Hz. The specific bandpass frequency does not significantly modify the results, as long as it is not too high to significantly remove lower hybrid wave power.

(5) We obtain $\langle \delta Q \delta Q \rangle$ by averaging $\delta Q$ over the four spacecraft then low-pass filter the result below 5 Hz to remove any remaining higher-frequency fluctuating components.

To evaluate equation (4) we expand it to obtain

$$T_1 = \langle \delta V_N \delta B \rangle - \langle \delta V_B \delta B \rangle + \left( \langle \delta V_N \delta V_B \rangle - \langle \delta V_B \delta V_N \rangle \right) \langle \delta \nu \delta V_N \rangle$$

(9)

$$T_2 = \langle \delta V_N \delta B \rangle - \langle \delta V_B \delta B \rangle + \left( \langle \delta V_N \delta V_B \rangle - \langle \delta V_B \delta V_N \rangle \right) \langle \delta \nu \delta V_B \rangle$$

(10)

$$T_3 = \langle \delta V_N \delta B \rangle - \langle \delta V_B \delta B \rangle + \left( \langle \delta V_N \delta V_B \rangle - \langle \delta V_B \delta V_N \rangle \right) \langle \delta \nu \delta V_N \rangle$$

(11)

All terms are calculated to determine $T$, although we find that only the components involving $\langle \delta V \delta V \rangle$ are significant. The uncertainties in the anomalous terms are calculated from the uncertainties in the electron moments and assuming a 10% uncertainty in the gain of the electric field caused by the spacecraft moving relative to a magnetized plasma, and there can be small changes in the gain due to changes in the plasma conditions. The uncertainties in the electron moments are based on the counting statistics of the particle distributions. This is only available at 30 ms sampling, so we assume that the uncertainties are four times larger for the 7.5 ms moments we use, due to the reduced azimuthal sampling. The magnitude of the uncertainties of the particle moments are compared with the magnitude of the envelope of the fluctuating quantities to estimate the relative uncertainties.



Estimates of the anomalous contributions from the electron inertial term and time derivative in equation (1) indicate that they are much smaller than $D$ and $T$ due to the $m_i/e$ dependence. The $M$ component of the anomalous inertial terms (anomalous Reynold’s stress) can be well approximated by assuming that the anomalous terms in $I$ vary primarily in the $N$ direction, which is given by

$$I_{MN} = \frac{m_i}{e(n_i)} \langle \sigma \nu \delta V_M \delta V_N \rangle$$

(12)

Since the method of obtaining the anomalous terms equation (12) relies on four-spacecraft averaging, the four spacecraft cannot be used to calculate the gradient associated with these terms. Therefore, the gradient is approximated assuming these quantities move past the spacecraft at the boundary normal velocity, such that $\delta \nu = -\nu_B \delta t$, where $\nu_B$ is the boundary normal velocity estimated from the four-spacecraft timing of the current sheet. The values of $I_{MN}$ obtained from equation (12) are significantly smaller than $D$ and $T$ and do not significantly contribute to $R$.

As an example, Fig. 6 shows $I_{SB}$ estimated from equation (12) and a comparison with $D_{SB}$ and $T_{SB}$ for the 06 December 2015 event (Figs. 2, 3). Figure 6a shows the electric field associated with the lower hybrid waves from MMS1. In Fig. 6b we plot the anomalous terms $\langle \delta V_B \delta V_N \rangle$, $\langle \delta V_B \delta V_L \rangle$, $\langle \delta V_N \delta V_L \rangle$, and $\Gamma = \langle n_e \rangle \langle \delta V_B \delta V_N \rangle$ and $\langle \delta V_B \delta V_L \rangle$ for the 5 Hz low-pass filter used there. The term being proportional to $V_{\text{N,anom}}$ in contrast, $\langle n_e \rangle \langle \delta V_B \delta V_N \rangle$ and $\langle \delta V_B \delta V_L \rangle$ fluctuates with very little offset from zero. This is due to the lack of consistent correlation between the $\delta V_N$ and $\delta V_L$ associated with the lower hybrid waves. As a result, $\Gamma$ fluctuates and is similar to $\langle n_e \rangle \langle \delta V_B \delta V_N \rangle$. In Figure 6c we plot $I_{SB}$ for 1 and 10 Hz bandpass filtered below 1 Hz to remove the fluctuations. We find that $I_{SB}$ fluctuates around zero when the 5 Hz low-pass filter is used. There is negligible large-scale offset, as seen for the <1 Hz case. Thus, $I_{SB}$ for the 5 Hz low-pass filter is underestimated. In Fig. 6d we plot $D_{SB}$ and $T_{SB}$ for the 5 Hz bandpass filter. We find that $I_{SB}$ is much smaller than $D_{SB}$ and $T_{SB}$. Both $D_{SB}$ and $T_{SB}$ have clear background components, in contrast to $I_{SB}$.

Similar results are found for the other events, and there is no clear evidence that $I_{SB}$ can significantly contribute to $R$ for lower hybrid waves. We conclude that the contribution of $I_{SB}$ to the total anomalous electric field is negligible based on MMS observations.

This differs from the results of three-dimensional simulations on the magnetosheath side, which have found that $I_{SB}$ could be significant. Possible reasons for these differences are:

(1) Artificial plasma conditions, such as reduced electron to ion mass ratio and reduced ratio of electron plasma to cyclotron frequency, are needed to run 3D simulations.

(2) When spatially averaging over the $M$ direction in simulations very low-frequency fluctuations, such as current sheet kinking, are typically included, which can lead to large anomalous terms that are not due to lower hybrid waves. In observations, we used a high pass-filter of 5 Hz, which removes such low-frequency fluctuations, if they are present.

Simulation description. We model the 06 December 2015 event using the fully kinetic iPIC code. The code uses an implicit moment method, which allows the cell size to exceed the Debye length. The code x, y, z coordinates point in the $L$, $N$, and $M$ directions used in this letter. The simulation is initialized with two thin current sheets of width 1d, and at $L = 2d$, at $y = 1.5L$ and $y = 3L$, respectively, where $d$ is the ion inertial length in the magnetosheath. The ion-to-electron mass ratio is $m_i/m_e = 256$ and the speed of light to the reference Alfvén speed ratio is $c/V_A = 103$. The parameters used to set up the asymmetric force balance are $B_L = 3$ nT, $B_T = 1$ nT, $T_e = 14$ cm$^{-3}$, $32$ eV, $1200$ eV $\vec{B}$ on the magnetosheath side and $[73$ nT, $-16$ nT, $1.85$ cm$^{-3}$, $164$ eV, $3900$ eV] $\vec{B}$ on the magnetospheric side.

The simulation is performed in two steps:

(1) Asymmetric magnetic reconnection is first run in two dimensions in $x - y$ coordinates in a double periodic domain. The size of the domain is $L_x \times L_y = 2822 \times 1038$ km$^2$ and is resolved by 1728 x 648 cells. A weak localized perturbation at $(L_x, L_y/4)$ is used to initiate reconnection.

(2) The three-dimensional (3D) simulation is initialized at time $t_0 = 35$ once steady-state reconnection is reached, where $\Omega_e$ is the angular ion-cyclotron frequency. The initial conditions of the 3D simulation are the fields and
particle information from the 2D run and replicated in the z-direction. The computational domain is \( L_x \times L_y \times L_z = 2822 \times 1058 \times 117.5 \text{ km}^3 \) and is resolved by 1728 \times 648 \times 72 cells. This replicated geometry is suitable for investigating instabilities, such as the lower hybrid drift instability, with wavelengths short compared with \( L_x \).

**Data availability**

MMS data were available at https://lasp.colorado.edu/mms/sdc/public. The data can be found in the following directories: mms#/fpi/brst/l2/des-qmoms/ for the highest resolution electron moments, mms#/fgm/brst/l2/des-qmoms/ for the background magnetic field, mms#/fpi/brst/l2/des-moms/ for the background electron moments, mms#/fpi/brst/l2/des-qmoms/ for the highest resolution electron moments, and mms#/fpi/brst/l2/des-qmoms/ for the highest resolution ion moments. Source data required to generate the figures in this paper can be found at https://github.com/danbgraham/anomres44 and are available on request. The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

**Code availability**

All figures and data analyses were performed using the IRFU-Matlab data analysis package, which is available at https://github.com/irfu/irfu-matlab. The scripts and functions required to compute the anomalous terms and reproduce the simulation code are available on request. The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Author contributions

D.B.G. carried out the data analysis, primary interpretation of the data, and manuscript writing. Y.V.K., M.A., and A.V. contributed to data interpretation and manuscript preparation. A.D. provided simulation support. J.F.D., C.N., I.L.B., K.J.H., and K.D. contributed data interpretation. O.L.C., P.A.L., A.C.R., D.J.G., and C.T.R. provided data support.

Competing interests

The authors declare no competing interests.

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