Using the Magnetospheric Multiscale Mission to Examine Electric Fields in Turbulent Plasmas

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Key Points

- Using NASA's Magnetospheric Multiscale, we examine in detail how generalised Ohm's Law shapes the turbulent electric field for the first time
- Results provide insight into the interplay between the Hall and electron pressure terms, which is important for understanding turbulent dissipation
- Ohm's Law allows a direct examination of the relative importance of linear and nonlinear dynamics

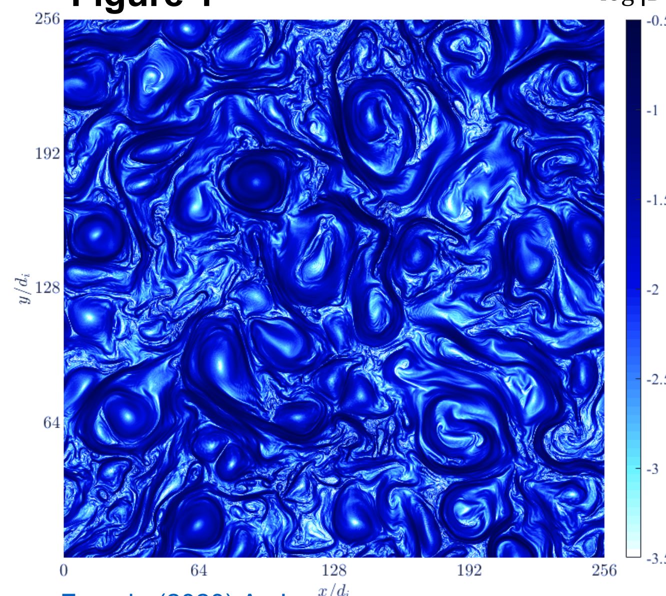
Turbulence is a fundamental process for particle energization in plasmas throughout the Universe, from the solar wind and planetary magnetospheres to accretion discs and galaxy clusters

Turbulence is charaterised by **highly-nonlinear fluctuations across a wide range of length scales** (Fig 1)

Many space plasmas are collisionless, resulting in a variety of possible mechanisms for dissipating the fluctuation energy

Disentangling these dissipation mechanisms is a major open problem in plasma turbulence research

Figure 1



Franci+ (2020) ApJ

Analyzing Electric Fields in Collisionless Plasmas

Figure 2

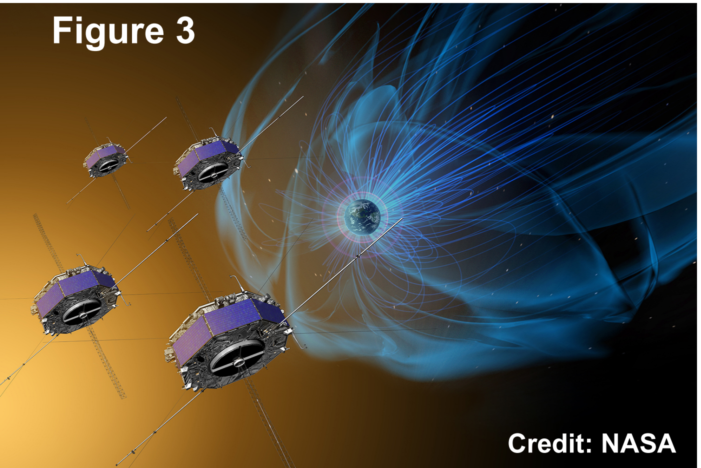
$-\boldsymbol{u}\times\boldsymbol{B}$	$\boldsymbol{E}_{MHD}$	Magnetic Field "Frozen-In" to ion fluid
$\frac{1}{en}\boldsymbol{J}\times\boldsymbol{B}$	$\boldsymbol{E}_{Hall}$	Magnetic Field "Frozen-In" to electron fluid
$-\frac{1}{en}\nabla\cdot\boldsymbol{P}_e$	$\boldsymbol{E}_{P_e}$	Correction due to electron thermal motions
$\frac{m_e}{e^2 n}\nabla\cdot\left(\boldsymbol{uJ}+\boldsymbol{Ju}-\frac{\boldsymbol{JJ}}{en}\right)+\frac{m_e}{e^2 n}\frac{\partial \boldsymbol{J}}{\partial t}$	$\boldsymbol{E}_{Inertia}$	Correction due to difference between ion and electron inertia
$\sum_{\ell=1}^{\infty}\left(-\frac{m_e}{m_i}\right)^{\ell}\boldsymbol{\mathcal{M}}_\ell$	$\boldsymbol{E}_{\delta m_e}$	Finite electron mass corrections

$$\boldsymbol{E}_{Ohm} = -\boldsymbol{u}\times\boldsymbol{B} + \frac{1}{en}\boldsymbol{J}\times\boldsymbol{B} - \frac{1}{en}\nabla\cdot\boldsymbol{P}_e + \frac{m_e}{e^2 n}\nabla\cdot\left(\boldsymbol{uJ}+\boldsymbol{Ju}-\frac{\boldsymbol{JJ}}{en}\right) + \frac{m_e}{e^2 n}\frac{\partial \boldsymbol{J}}{\partial t} + \sum_{\ell=1}^{\infty}\left(-\frac{m_e}{m_i}\right)^{\ell}\boldsymbol{\mathcal{M}}_\ell$$

$$\boldsymbol{\mathcal{M}}_\ell = \frac{2}{en}\boldsymbol{J}\times\boldsymbol{B} - \frac{1}{en}\nabla\cdot(P_e + P_i) + \frac{m_e}{e^2 n}\left[\nabla\cdot\left(\boldsymbol{uJ}+\boldsymbol{Ju}-(1+2\ell)\frac{\boldsymbol{JJ}}{en}\right)+\frac{\partial \boldsymbol{J}}{\partial t}\right]$$

Since magnetic fields ($\boldsymbol{B}$) do no work, electric fields ($\boldsymbol{E}$) are required to exchange energy between $\boldsymbol{B}$ and the particles → $\boldsymbol{E}$ is key to understanding both turbulent dissipation and the nonlinear dynamics

In collisionless plasmas, $\boldsymbol{E}$ is governed by a **generalised Ohm's Law** in which the different terms correspond to different dynamical processes (**Fig. 2**)



NASA's **Magnetospheric Multiscale (MMS)** mission consists of 4 closely spaced satellites, providing 3D, high-time-resolution, multipoint plasma measurements (**Fig. 3**)

MMS is uniquely capable of directly probing nearly all the terms in Ohm's Law down to length scales approaching those of electron motions [e.g. Torbert+ (2016) *GRL*]

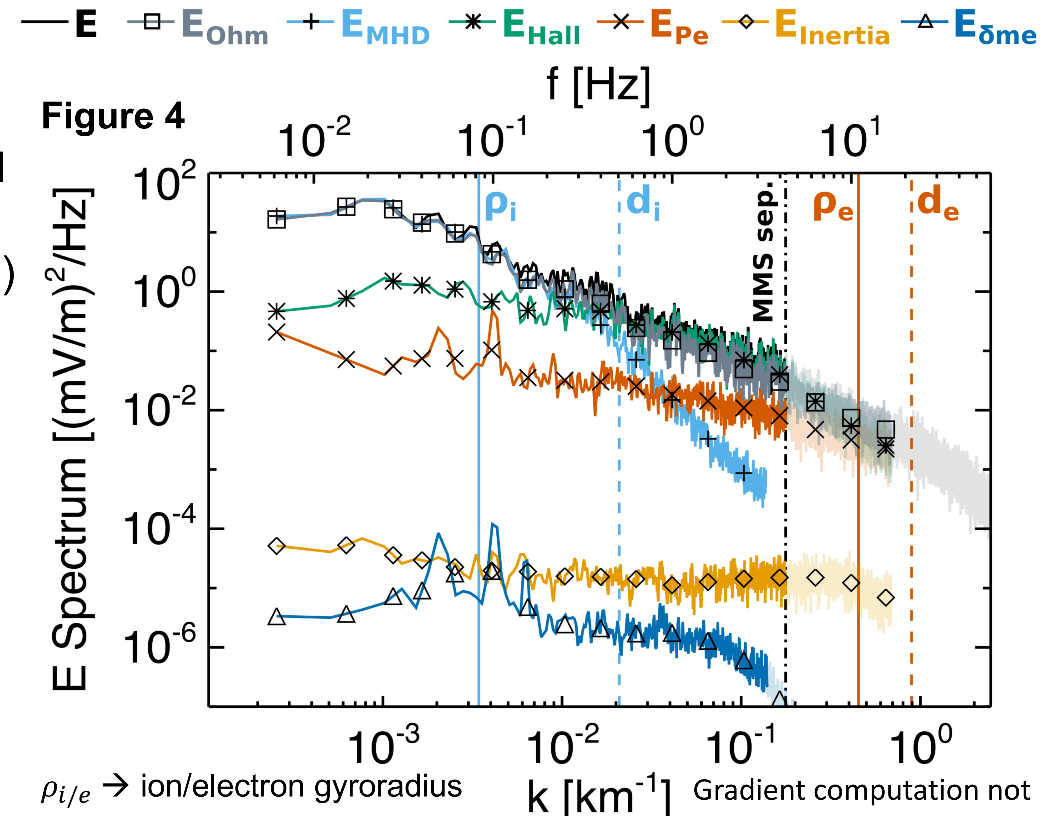
How do the terms in Ohm's Law behave as a function of scale?

Three intervals of MMS data from Earth's magnetosheath are analysed
[Results from one interval are shown here as an example]

Timeseries of each Ohm's Law term are computed and then the power spectra are compared to the power spectrum of the directly measured $\boldsymbol{E}$ (**Fig. 4**)

Frequencies are converted to wavenumbers using the average flow velocity → $k = 2\pi f / U_0$

Figure 4



$\rho_{i/e}$ → ion/electron gyroradius
$d_{i/e}$ → ion/electron inertial length
MMS sep. → spacecraft separation

Gradient computation not reliable at scales smaller than MMS sep.

Results

Good agreement between measured $\boldsymbol{E}$ and $\boldsymbol{E}_{Ohm}$

$\boldsymbol{E}_{MHD}$ provides dominant contribution at large scales, indicating $\boldsymbol{B}$ is frozen-in to ion fluid flows

$\boldsymbol{E}_{Hall}$ makes largest contribution at sub-ion scales → scale of transition typically occurs near

$$kd_i \sim \frac{\delta u_{rms}}{\delta b_{rms}/\sqrt{\mu_0 m_i n}}$$

$\boldsymbol{E}_{P_e}$ provides non-zero contribution to sub-ion scale electric field

$\boldsymbol{E}_{inertia}$ and $\boldsymbol{E}_{\delta m_e}$ are negligible across observed scales, as expected
[Only the spatial gradient portions were computable from data]

Figure 5

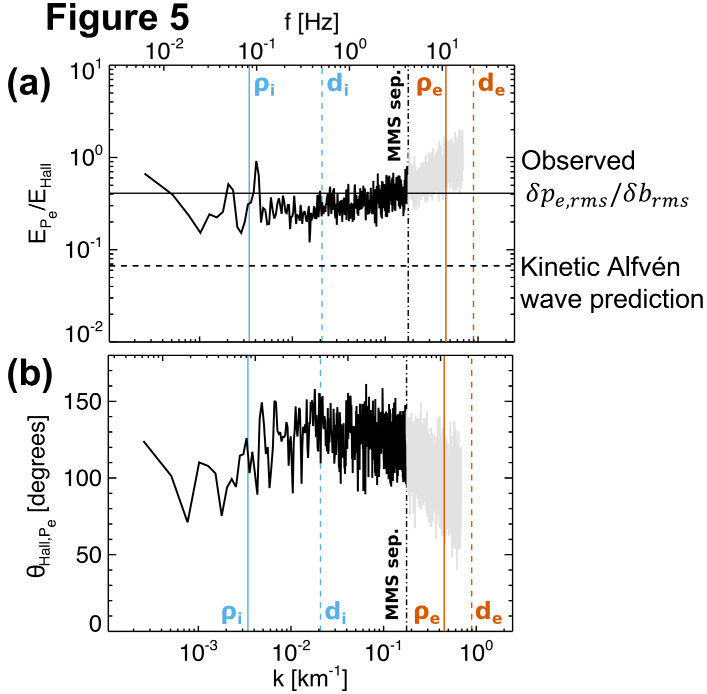
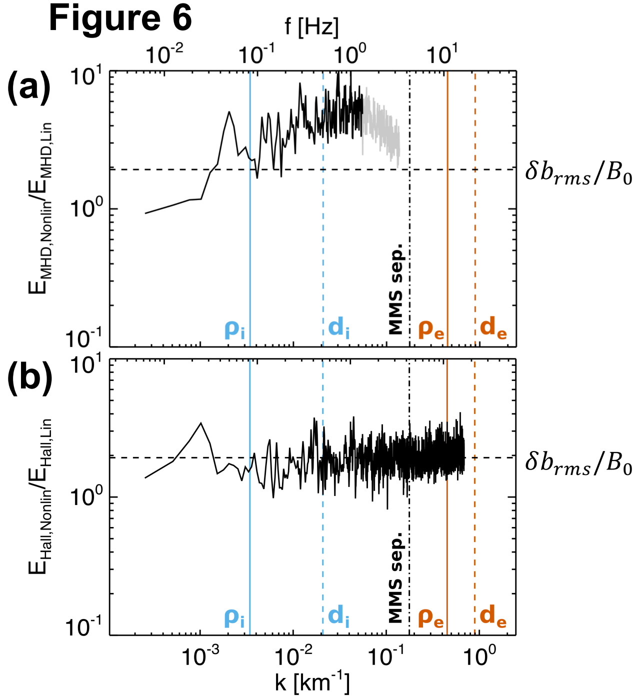


Figure 6



Hall and Electron Pressure Terms

Interplay between $\boldsymbol{E}_{Hall}$ and $\boldsymbol{E}_{P_e}$ important because $\boldsymbol{E}_{P_e}$ can provided a *non-ideal* electric field that can energise electrons and contribute to dissipation

$\boldsymbol{E}_{Hall}$ dominates over $\boldsymbol{E}_{P_e}$, but $\boldsymbol{E}_{P_e}$ is stronger than expected from typical kinetic Alfvén wave predictions (**Fig. 5a**) [Boldyrev+ (2013) ApJ]
→ magnetic reconnection may lead to excess $\boldsymbol{E}_{P_e}$ [Stawarz+ (2019) ApJL]

Partial anti-alignment between $\boldsymbol{E}_{Hall}$ and $\boldsymbol{E}_{P_e}$ fluctuations at sub-ion scales (**Fig. 5b**) → degree of alignment linked to relative importance of ion and electron dynamics in supporting sub-ion scale currents

Linear & Nonlinear Terms

$$\boldsymbol{E}_{MHD} = \boxed{-\delta\boldsymbol{u}\times\boldsymbol{B}_0} \boxed{-\ \delta\boldsymbol{u}\times\delta\boldsymbol{b}} \qquad \boldsymbol{E}_{Hall} = \boxed{\delta\boldsymbol{j}\times\boldsymbol{B}_0/en} + \boxed{\delta\boldsymbol{j}\times\delta\boldsymbol{b}/en}$$

In $\boldsymbol{E}_{MHD}$ (**Fig. 6a**), nonlinear to linear term ratio increases at sub-ion scales → caused by decrease in alignment of δu and δb at sub-ion scales [consistent with Parashar+ (2018) *PRL*]

In $\boldsymbol{E}_{Hall}$ (**Fig. 6b**), ratio of nonlinear to linear terms is ~ $\delta b_{rms}/B_0$ at all scales

Results suggest a balance of linear and nonlinear timescales at both MHD and sub-ion scales that is set by $\delta b_{rms}/B_0$