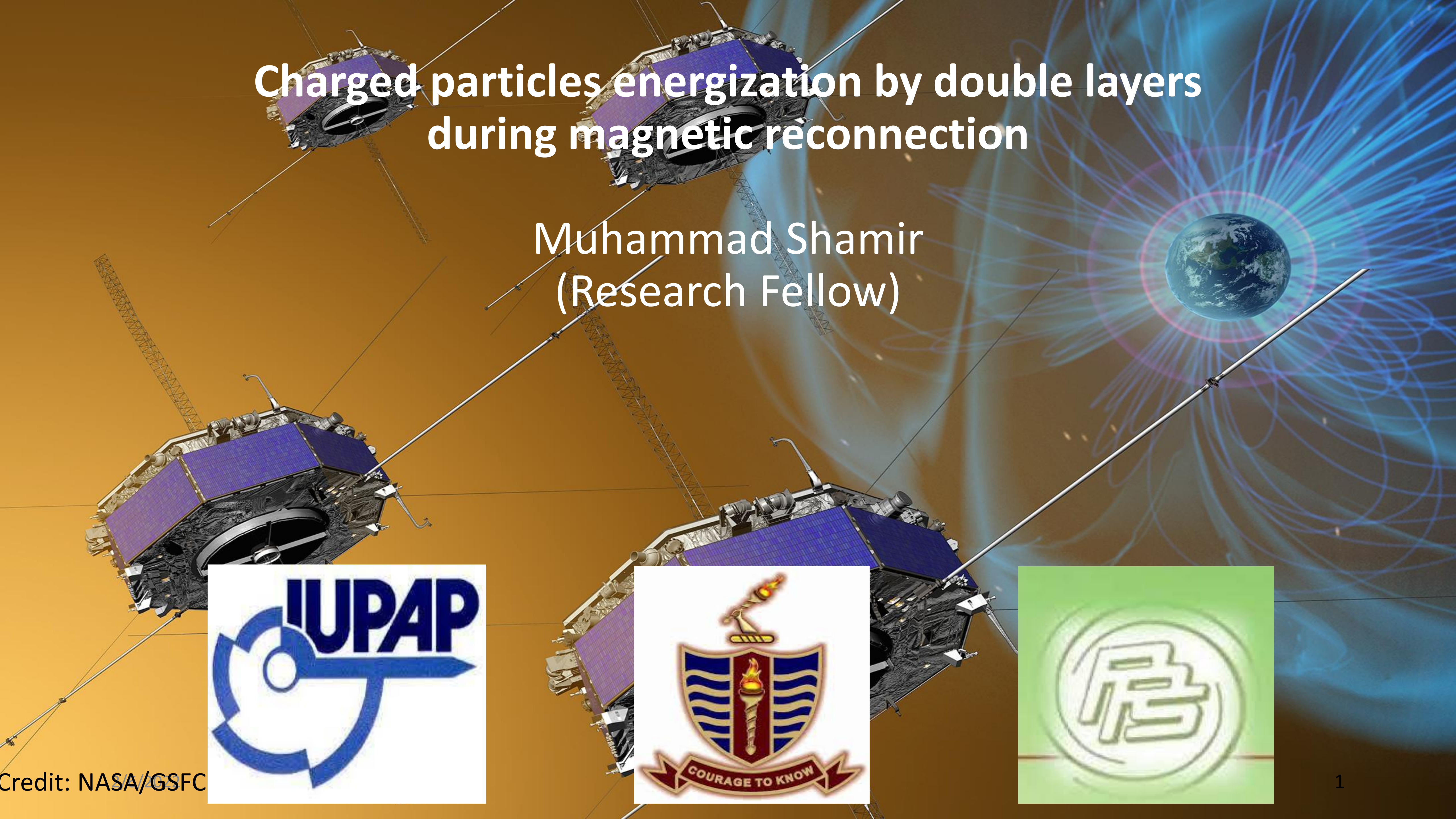

Charged particles energization by double layers during magnetic reconnection

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(Research Fellow)

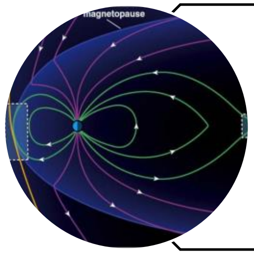
Credit: NASA/GSFC

The entire MMS team and instrument PIs for data access

The *International Union of Pure and Applied Physics* (*IUPAP*)

Pakistan Physical Society (PPS) and

the whole organizing team



Co-authors and my advisor Prof. Dr. G. Murtaza

Outline

- Double layers

a) Introduction
b) Observations and Applications
c) Magnetic reconnection and the formation of double layers

- Theoretical Model
- Results
- Magnetospheric Multiscale Mission (MMS) Observations
- Conclusion

- Double layer (DL) is a nonlinear structure in a plasma comprising two parallel sheets of opposite charge. These charged layers give rise to a strong electric field along with a sharp change in potential across the DL.

- Auroral zone (Mozer et al. 1977, Temerin et al. 1982) , Plasma sheet (Ergun et al. 2009), Magnetic reconnection sites (Cattell et al. 2002; Mozer & Pritchett 2010), the solar wind (Bale et al. 1996; Williams et al. 2005).

- DLs may also be considered as an important mechanism that transfers kinetic energy from the strahl-electron heat flux to thermal energy of solar wind protons (Borovsky & Gary 2014).
- Inside the separatrix regions, strong electric fields may occur, and the potential drop across the separatrix region can be up to several kV, which may energize ions passing through this region (Lindstedt et al. 2009).
- Numerous DLs are continuously created during magnetic reconnection and propagate away from the X-line (Wang et al. 2014)

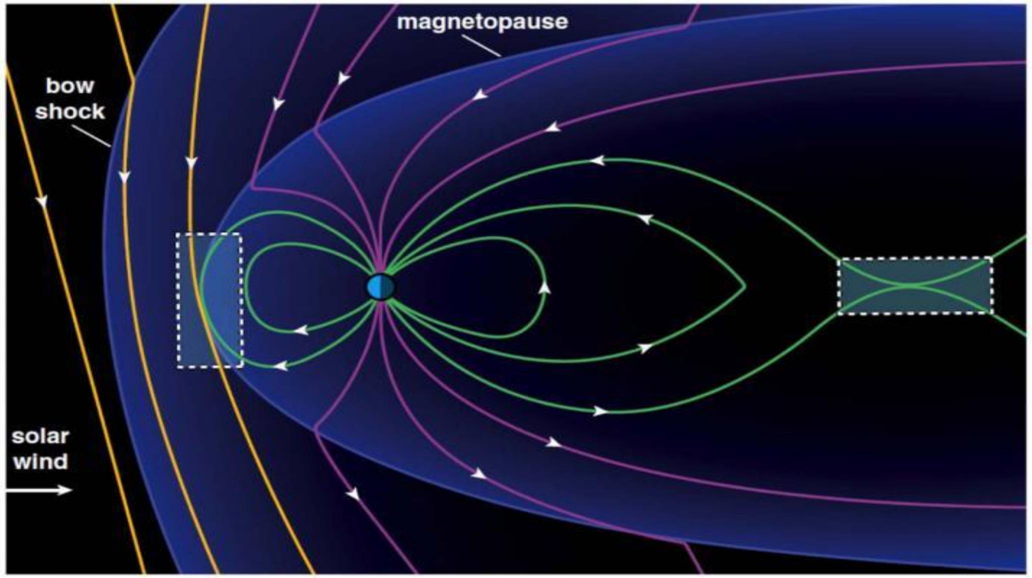
Magnetic reconnection and formation of double layers

There are two fundamental conditions for magnetic reconnection

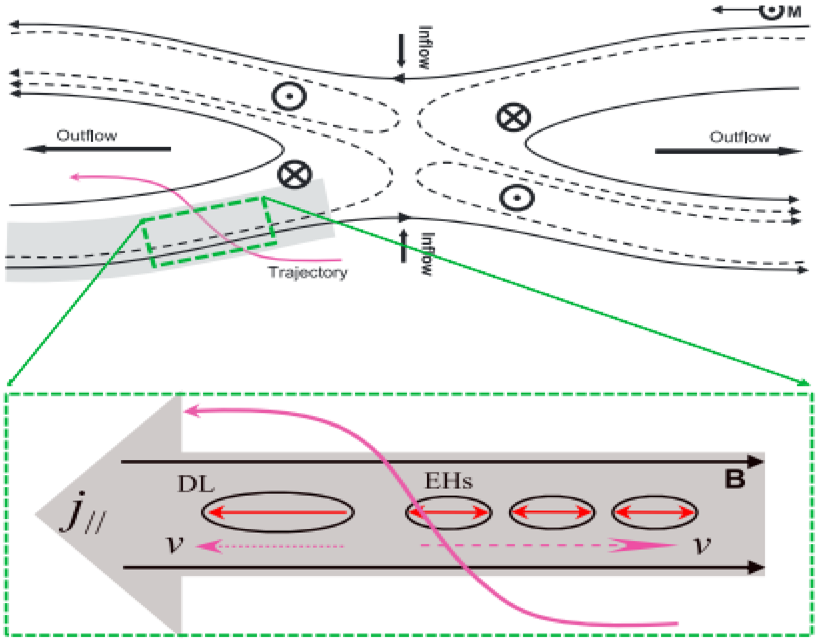
a) The magnetic field lines must be in opposite direction

b) Breakdown of the frozen-in condition i.e., $E + V \times B \neq 0$

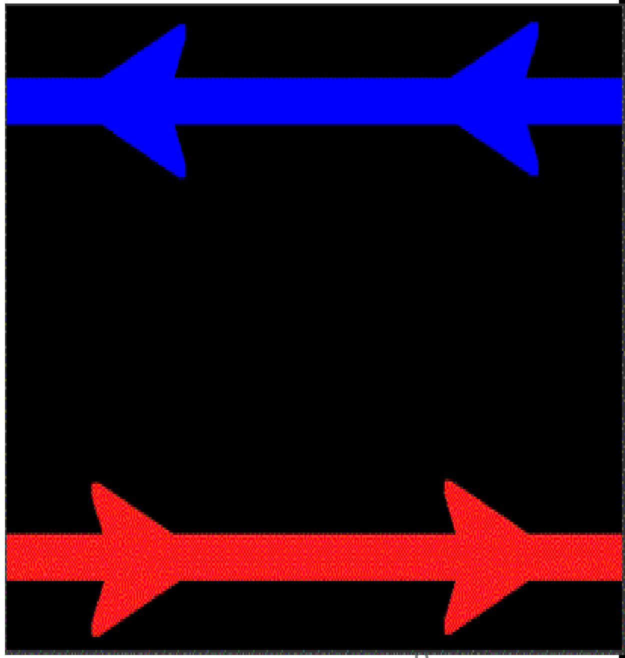
- During this process, ions are demagnetized in certain wider regions while electrons with small gyro-radii remain magnetized, resulting in local charge separation that may lead to the formation of DLs.



Credit: NASA



Adapted from Wang et al. 2014



Theoretical Model

- low β electron-ion plasma consisting of cold inertial ions and Tsallis distributed electrons.
- The ambient magnetic field is directed along z-axis, and the wave propagation vector lies in *x-z* plane
- Here we define electric field in terms of electrostatic potentials i.e., $E_x = -\frac{d\phi_\perp}{dx}$ and $E_z = -\frac{d\phi_\parallel}{dx}$, with $\phi_\perp$ and $\phi_\parallel$ are the corresponding electrostatic potentials.

M. Shamir, Imran A. Khan and G. Murtaza "Charged particles energization during magnetic reconnection in the Earth's magnetosphere by double layers: An analytical approach." MNRAS 509, 3703 (2022)

Theoretical Model

- To study the DLs associated with kinetic Alfvén waves, we introduce a frame $\xi = K_\perp X + K_\parallel Z - Mt$, where $M = u/c_s$ is the frame speed and $K_\perp$ and $K_\parallel$ are the direction cosines.
-
$$n_e = (1 + C_1\Phi_\parallel + C_2\Phi_\parallel^2 + C_3\Phi_\parallel^3) \qquad (1)$$

where $C_1 = \frac{q+1}{2}$, $C_2 = \frac{(q+1)(3-q)}{8}$ and $C_3 = \frac{(q+1)(q-3)(3q-5)}{8}$

$$-M\frac{\partial n_i}{\partial \xi} + K_\perp \frac{\partial}{\partial \xi}(n_i u_{ix}) = 0 \qquad (2)$$

-
$$u_{ix} = MK_\perp \frac{\partial^2 \Phi_\perp}{\partial \xi^2} \qquad (3)$$

Theoretical Model

- $$K_\perp^2 K_\shortparallel^2 \frac{\partial^4}{\partial \xi^4}(\Phi_\perp - \Phi_\shortparallel) = M_A^2 \frac{\partial^2 n_e}{\partial \xi^2}. \qquad (4)$$

- The following normalized variables have been used in the preceding equations:
  $n'_{e,i} = \frac{n_{e,i}}{n_{e0,i0}}$, $\Phi' = \frac{e\Phi}{T_e}$, $t' = \Omega_i t$, $l' = \frac{l}{\rho_s}$, $M = \frac{u}{c_s}$ where $\Omega_i (= eB_0/m_i)$ is the gyro-frequency, $\rho_s (= \frac{c_s}{\Omega_i})$ is the ion acoustic gyro-radius at electron temperature,
  $c_s = (T_e/m_i)^{1/2}$ is the sound speed and $M_A = \sqrt{\frac{\beta}{2}} M$ is the Alfvénic Mach number with $\beta = \frac{2\mu_0 n_0 T_e}{B_0^2}$.

Theoretical Model

$$K_\perp^2 \frac{\partial^2 \Phi_\perp}{\partial \xi^2} = \frac{n-1}{n} \tag{5}$$

$$K_\perp^2 \frac{\partial^2 \Phi_\perp}{\partial \xi^2} = K_\perp^2 \frac{\partial^2 \Phi_\parallel}{\partial \xi^2} + \frac{M_A^2}{K_\parallel^2}[n-1] \tag{6}$$

Now, substituting Eqs. (1) and (5) in Eq.(6) and then integrating with appropriate boundary conditions i.e., $\Phi_\parallel \rightarrow 0$, $\frac{\partial \Phi_\parallel}{\partial \xi} \rightarrow 0$ as $\xi \rightarrow \infty$ one can get

$$0 = V(\varphi) + \frac{1}{2}\left(\frac{\partial \varphi}{\partial \xi}\right)^2 \tag{7}$$

where the Sagdeev potential is

$$V(\varphi) = -\frac{S_1 \varphi^2}{2K_\perp^2} + \frac{S_2 \varphi^3}{3K_\perp^2} + \frac{S_3 \varphi^4}{4K_\perp^2} \tag{8}$$

Theoretical Model

with

$$S_1 = \left(C_1 - \frac{M_A^2}{K_{\parallel}^2} C_1 \right) \tag{9}$$

$$S_2 = \left(C_2 \frac{M_A^2}{K_{\parallel}^2} + C_1^2 \frac{M_A^2}{K_{\parallel}^2} - C_2 \right) \tag{10}$$

$$S_3 = \left(C_3 \frac{M_A^2}{K_{\parallel}^2} + 2 C_1 C_2 \frac{M_A^2}{K_{\parallel}^2} - C_3 \right) \tag{11}$$

In the above Eq. (7), we have used φ instead of $\Phi_{\parallel}$ for the sake of simplicity. For DL solution to occur, the Sagdeev potential $V(\varphi)$ must satisfy the following conditions: (1) $V(\varphi) = 0$ at $\varphi = (0, \varphi_m)$, (2) $\frac{dV(\varphi)}{d\varphi} = 0$ at $\varphi = (0, \varphi_m)$ and (3) $\frac{d^2 V(\varphi)}{d\varphi^2} < 0$ at $\varphi = (0, \varphi_m)$.

Theoretical Model

By using the first two conditions in Eq. (8), we get

$$V(\varphi) = \frac{S_3}{4K_\perp^2}(\varphi_m - \varphi)^2\varphi^2 \qquad (12)$$

where $\varphi_m = -\frac{2S_2}{3S_3}$.

$$\frac{1}{2}\left(\frac{\partial\varphi}{\partial\xi}\right)^2 + \frac{S_3}{4K_\perp^2}(\varphi_m - \varphi)^2\varphi^2 = 0 \qquad (13)$$

whose solution is

$$\varphi = \frac{\varphi_m}{2}\left[1 - tanh\sqrt{-\frac{S_3}{8K_\perp^2}}\varphi_m\xi\right] \qquad (14)$$

We can also calculate the parallel electric field associated with DL structure from the above Eq. (14) as

$$E_{\parallel} = -\nabla_{\xi}\varphi \qquad (15)$$

Theoretical Model

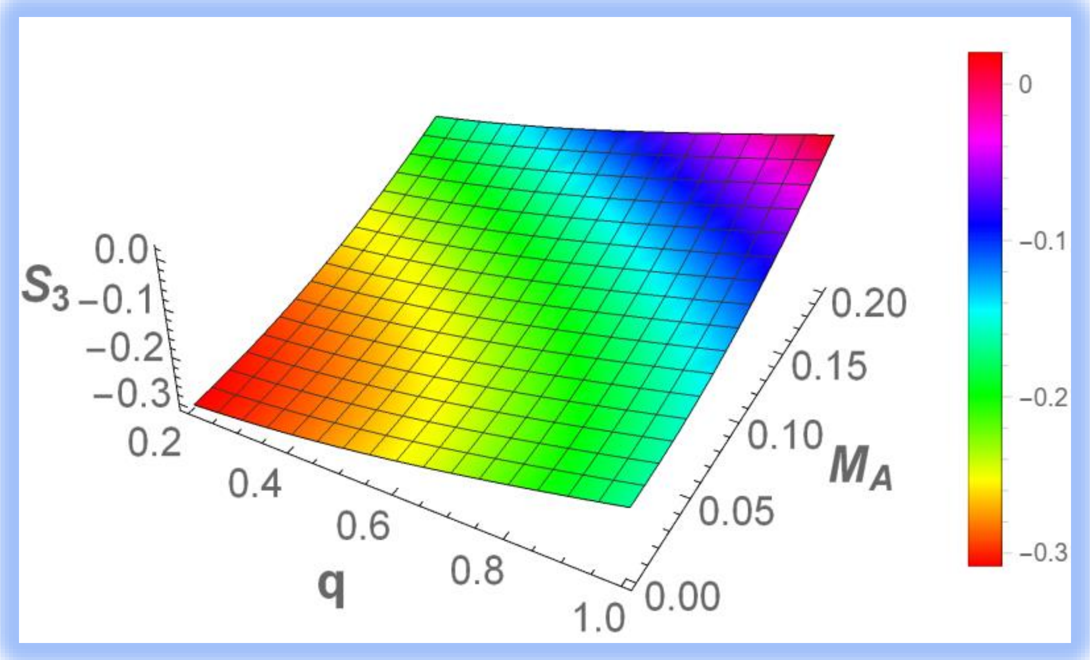


Fig. 2. Adapted from Shamir et al. (2022)

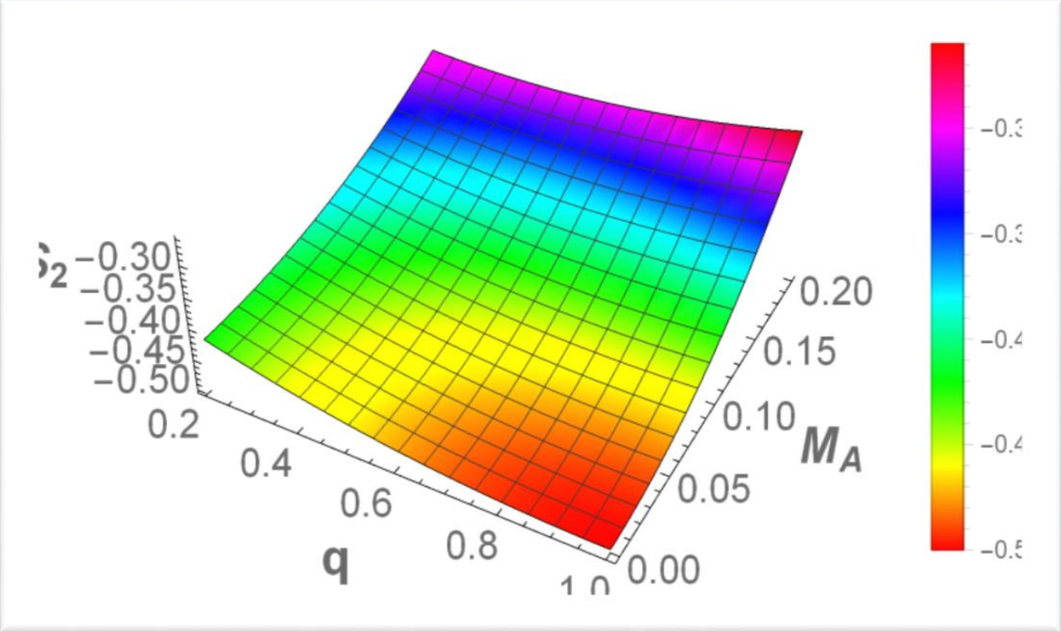


Fig. 3. Adapted from Shamir et al. (2022)

Theoretical Model

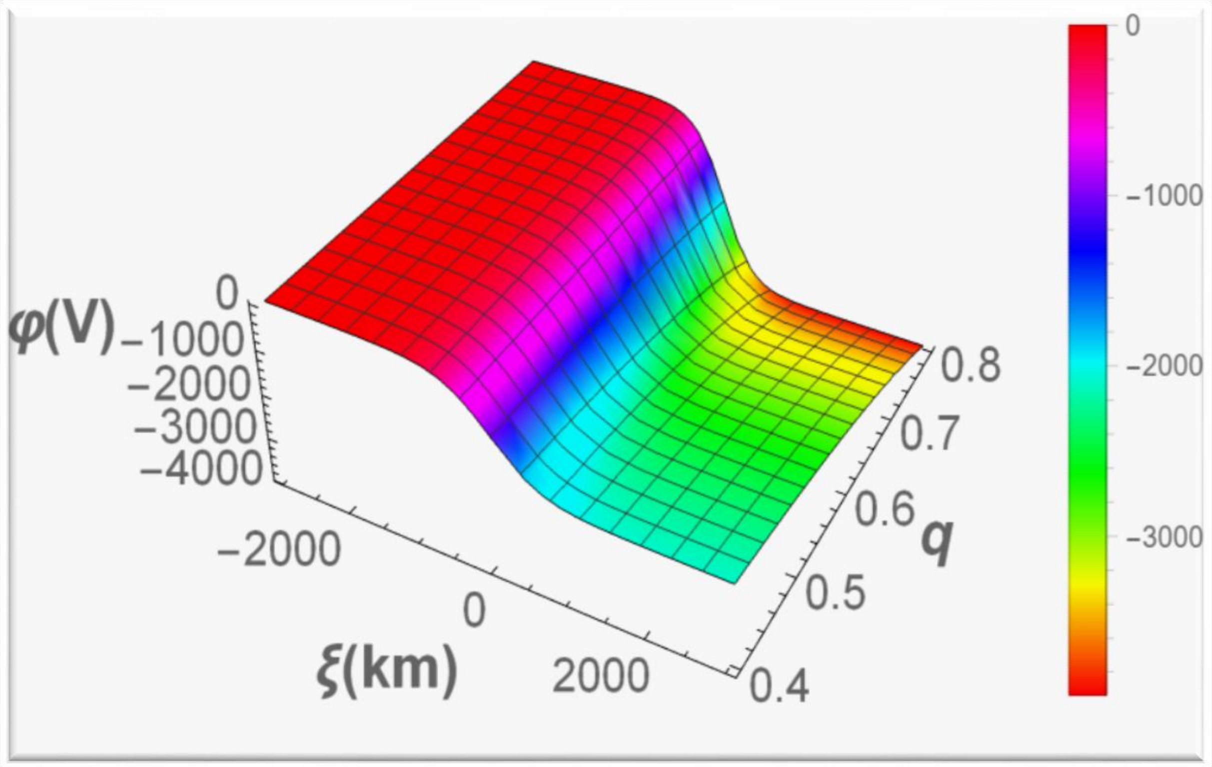


Fig. 4. Adapted from Shamir et al. (2022)

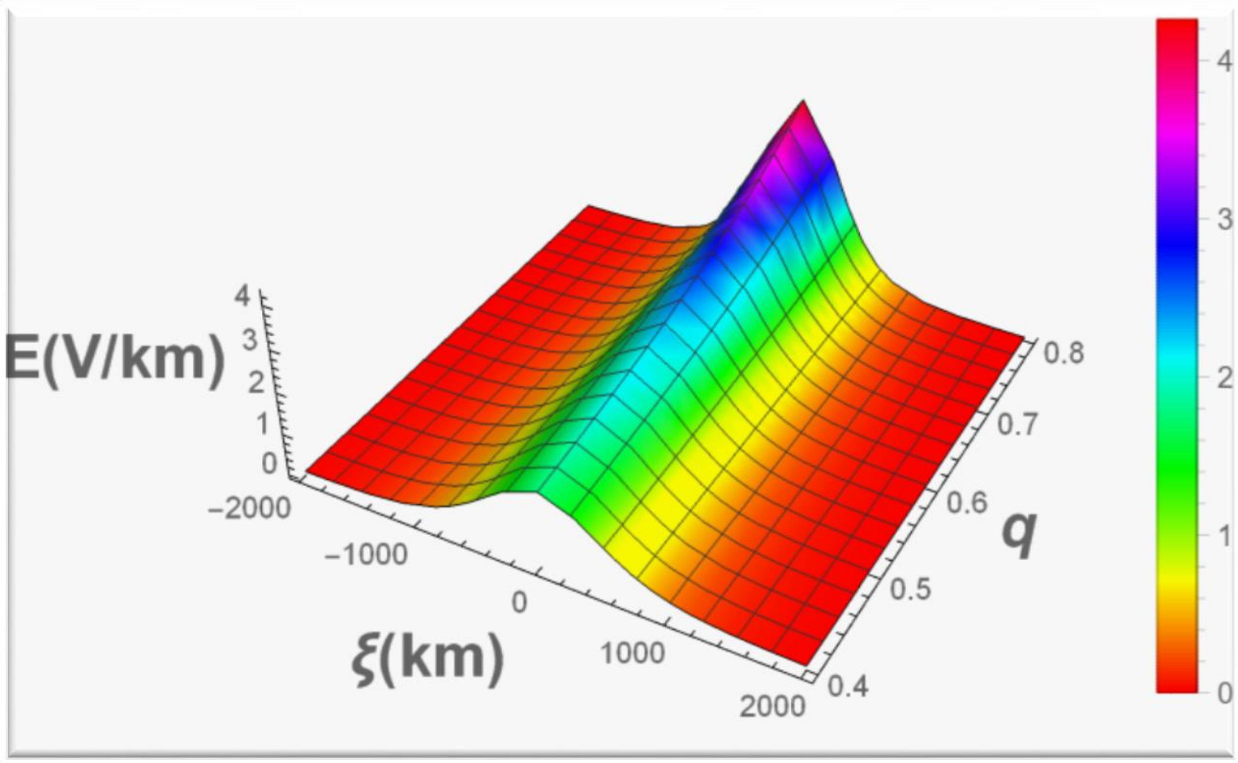


Fig. 5. Adapted from Shamir et al. (2022)

Results

- The amplitude of DL strongly depends on the non-extensive parameter.
- $e\varphi$ is the energy gained from the parallel electric fields by electrons entering the reconnection region in a straight shot along a magnetic-field line.
- In our case, the strength of the DL structure φ is of the order of kilo Volts (which may energize charged particles up to keV) which is comparable with the previously published research on the DLs in the separatrix region (Wang et al. 2014; Lindstedt et al.2009)
- Our estimated spatial scale size for the DL (is approximately equal to $3\rho_s \approx 500$ km) is consistent with the previous findings (Lindstedt et al. 2009).

Comparison with MMS Observation

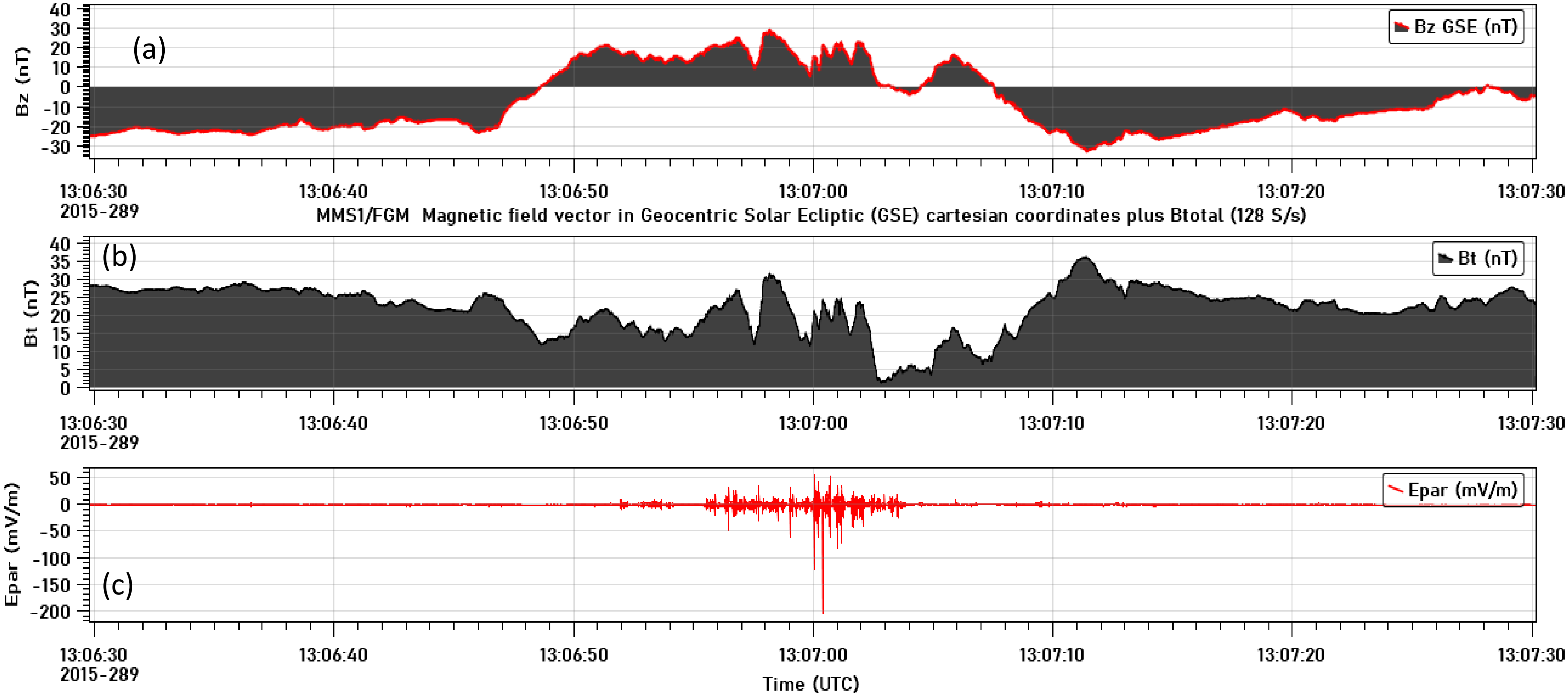
- Event#1: 16 October 2015 (Also reported by Ergun et al. [2016]
- Event#2: 11 September 2015 (Also reported by Lenouvel et al. [2021]

I use measurements taken by the following instruments on board MMS:

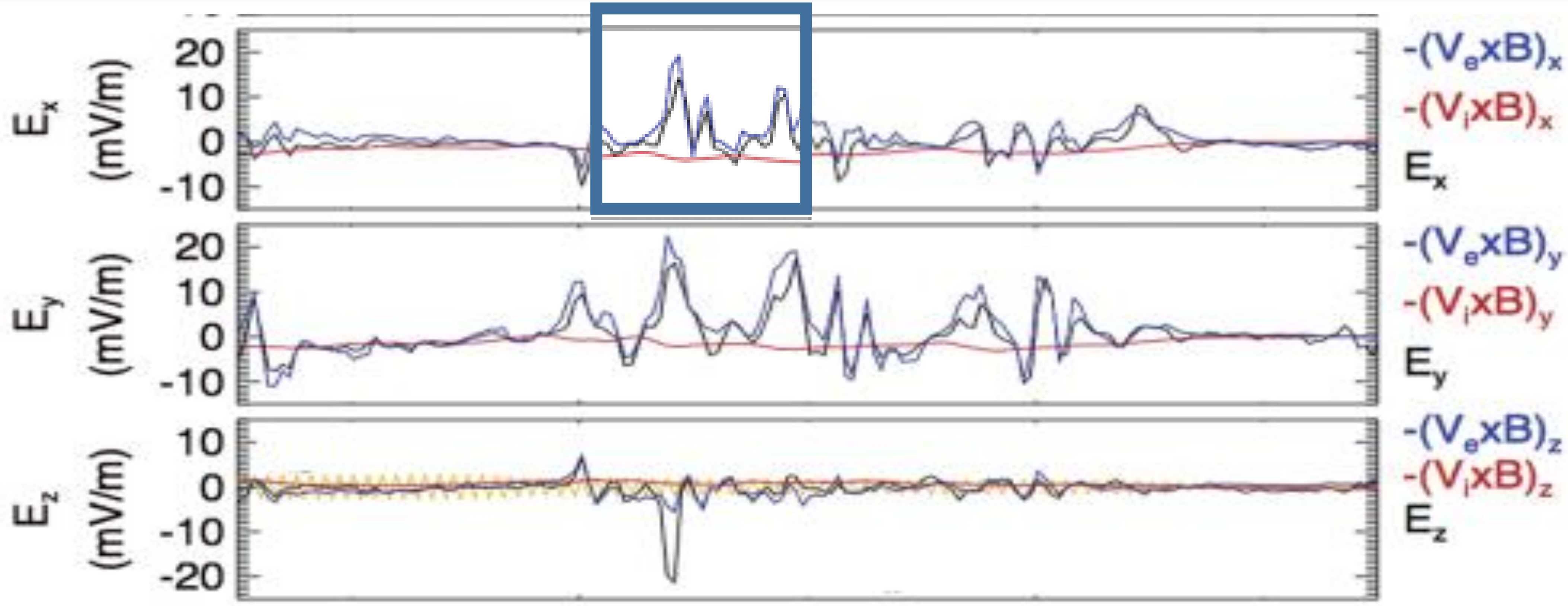
- The fluxgate magnetometer (FGM) [*Russell et al.*, 2014]
- Fast Plasma Investigation (FPI) [*Pollock et al.*, 2016]
- The Fly's Eye Energetic Particle Spectrometer (FEEPS) [*Blake et al. 2016*]
- Double probe electric field instrument [Lindqvist et al. 2016]

MMS Observations

Event#1 16 October 2015



MMS Observations
Event#1 16 October 2015



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Adapted from Ergun et al. [2016]

MMS Observations
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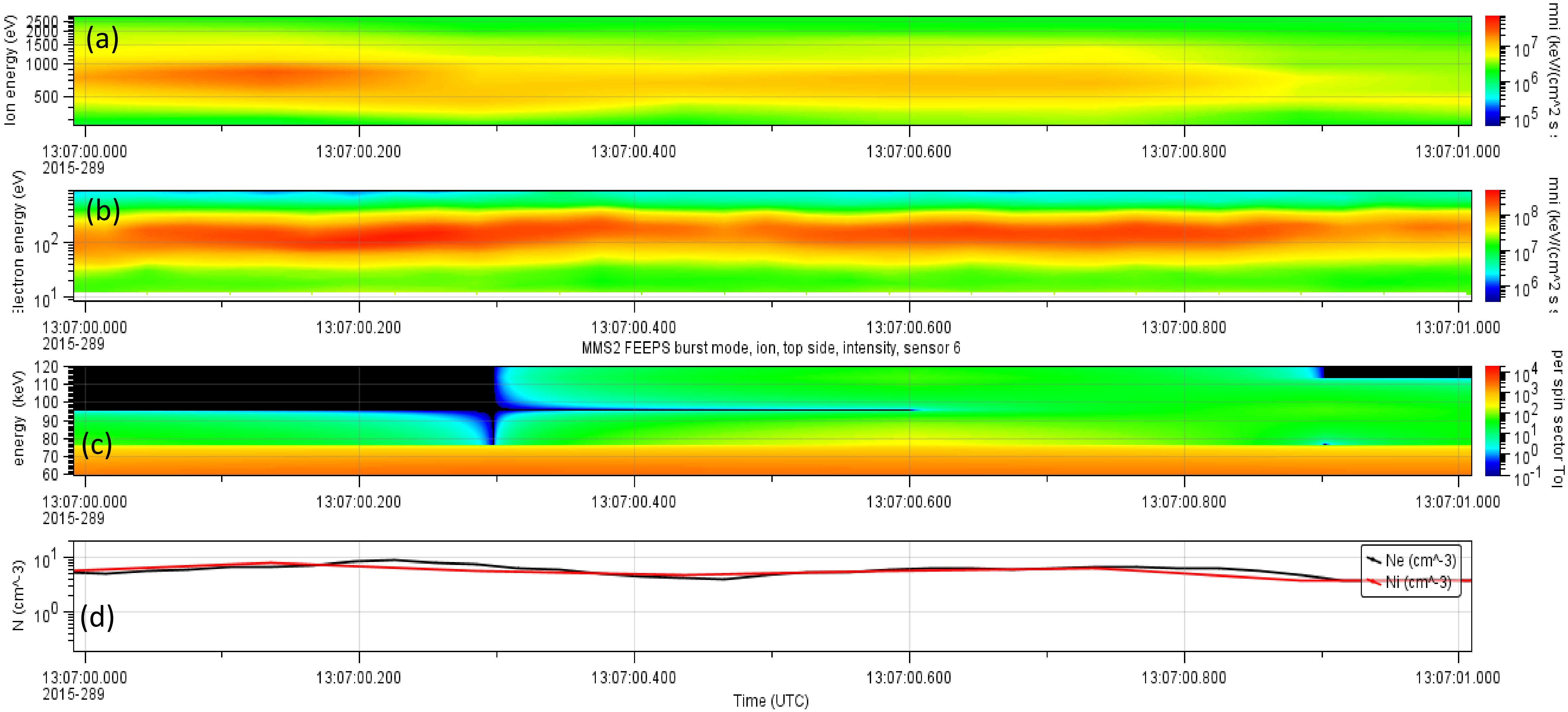
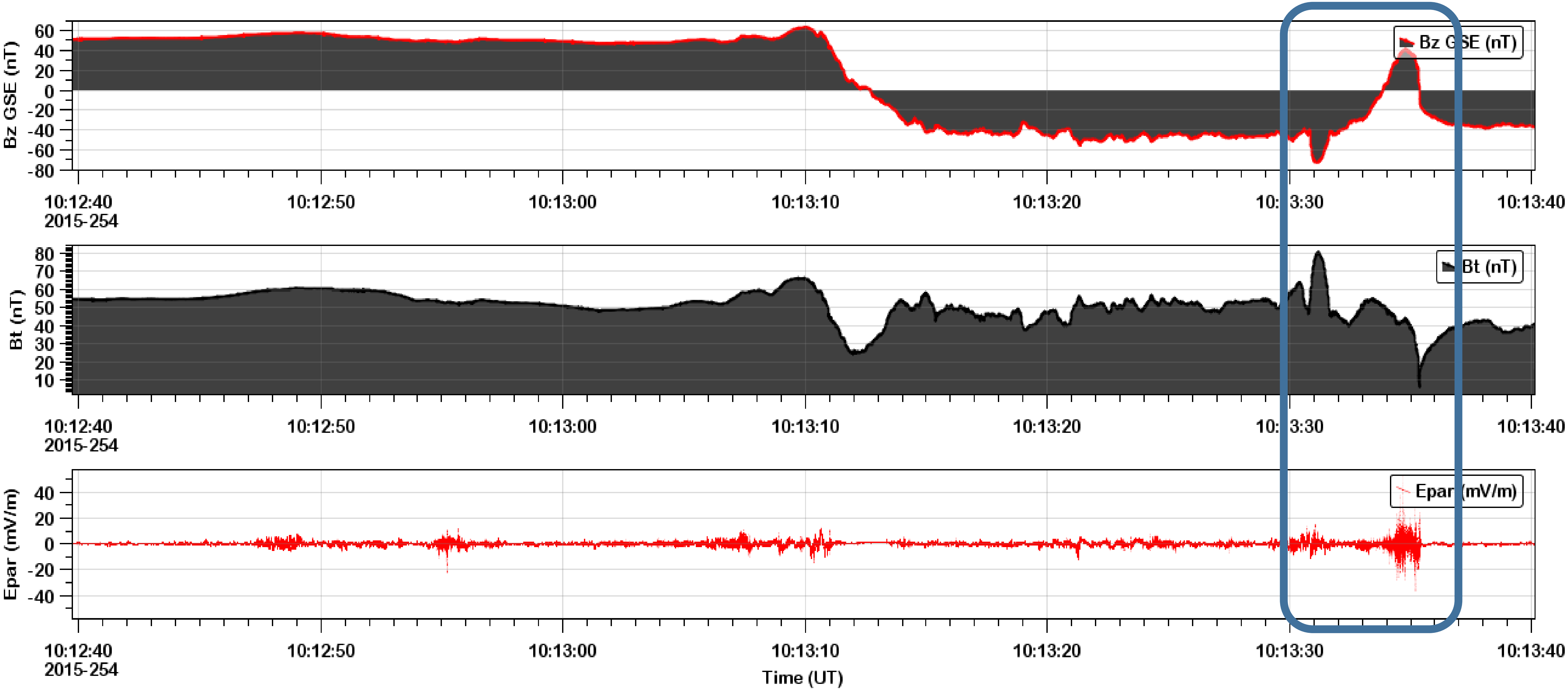
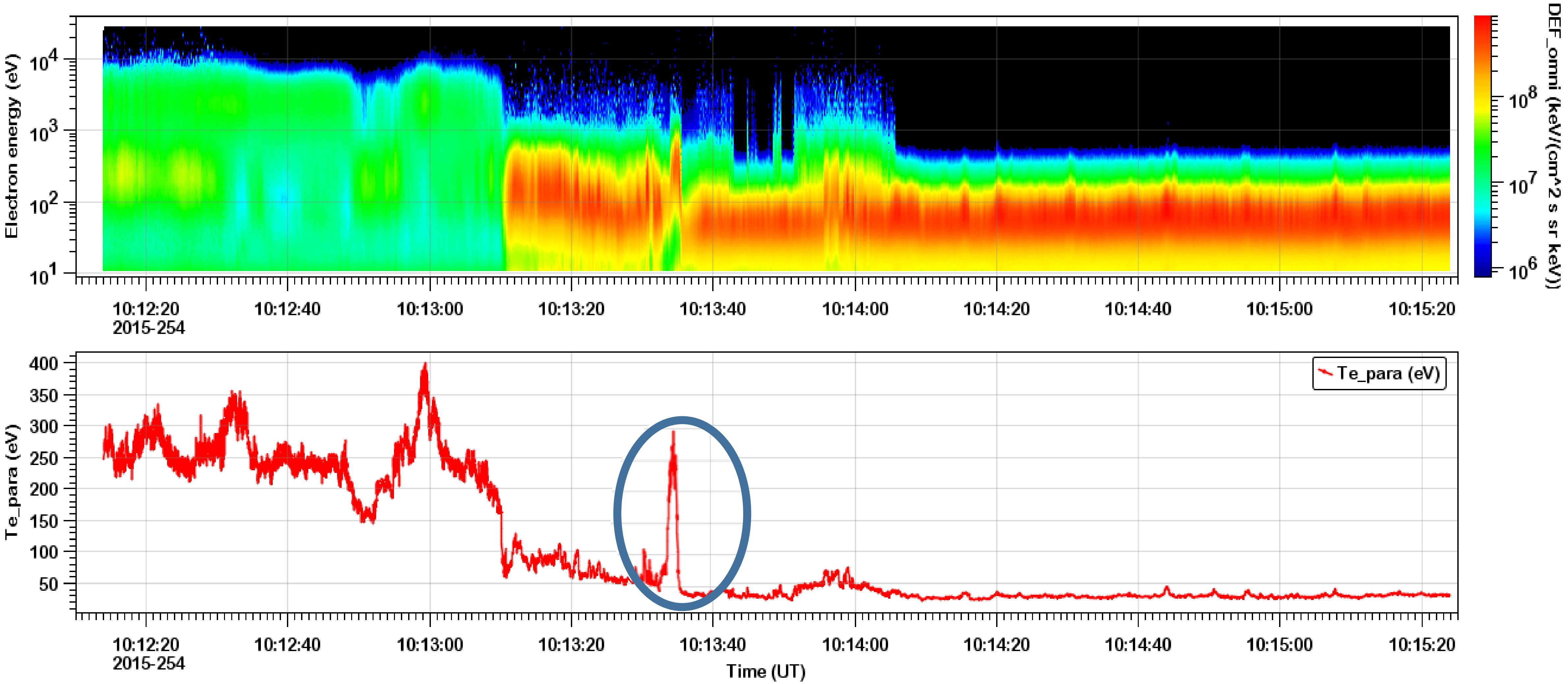


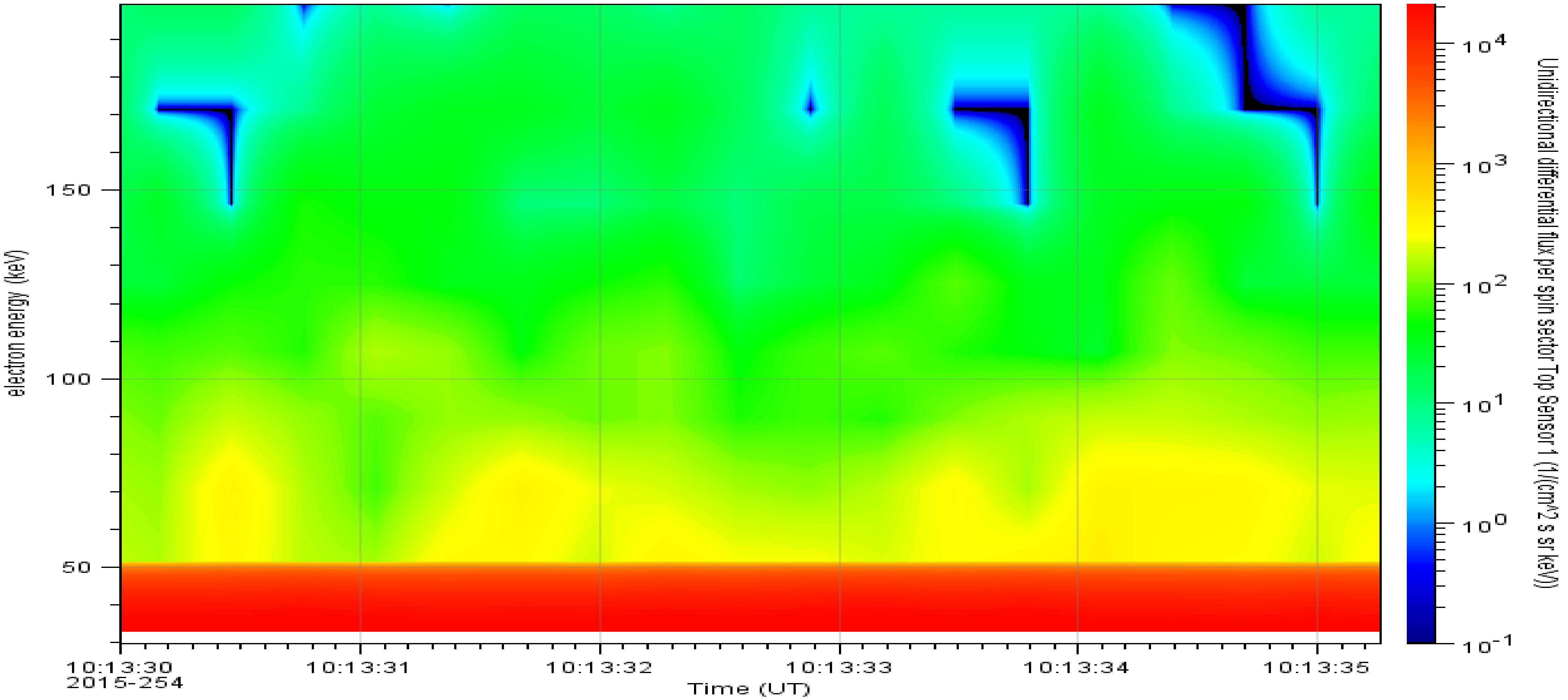
MMS Observations
Event#2 11 September 2015



MMS Observations
Event#2 11 September 2015



MMS Observations
Event#2 11 September 2015



Conclusion

- Using the observed data for the Earth's magnetopause, we have tried to explain particle energization during magnetic reconnection.

- **The effects of the spectral index q on DL structure and parallel electric field** have been investigated using Sagdeev potential technique. It has been found that the amplitude of DL strongly depends on the non-extensive parameter.

- Based on a comparison of our findings with the reported literature and MMS observations, we found that our findings are consistent with the observations and the reported literature (Ergun et al. 2016a,b; Wang et al. 2014; Lindstedt et al. 2009; Jaynes et al. 2016).

- **We claim that our analytical model has successfully explained the phenomenon of charged particle energization during magnetic reconnection.**

Data used in this talk

- **M. Shamir,** Imran A. Khan and G. Murtaza "Charged particles energization during magnetic reconnection in the Earth's magnetosphere by double layers: An analytical approach." MNRAS 509, 3703 (2022)
- All other data used in this talk are publicly available at MMS Science Data Center (https://lasp.colorado.edu/mms/sdc/public/)
- http://spedas.org/wiki/index.php?title=Main_Page
- http://spedas.org/wiki/index.php?title=Getting_Started_with_pySPEDAS