Electron acceleration in the separatrix region during magnetic reconnection

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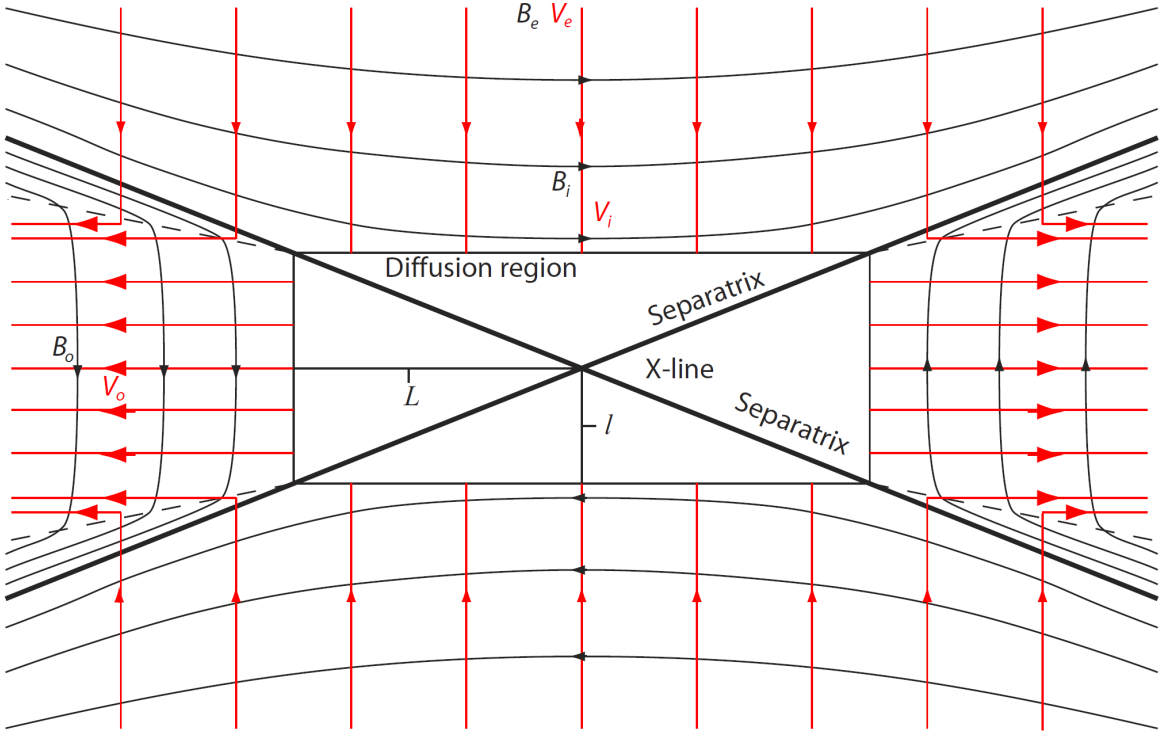
Outline

1. Introduction to the separatrix
2. Electron distribution in the separatrix region
3. Parallel electric field/Double Layers detected near the separatrices
4. Discussion & Conclusions

1. Introduction to the separatrix

The separatrix is the surfaces (lines in 2D) separating the plasma not yet entered into the reconnection region from the plasma already processed by reconnection.



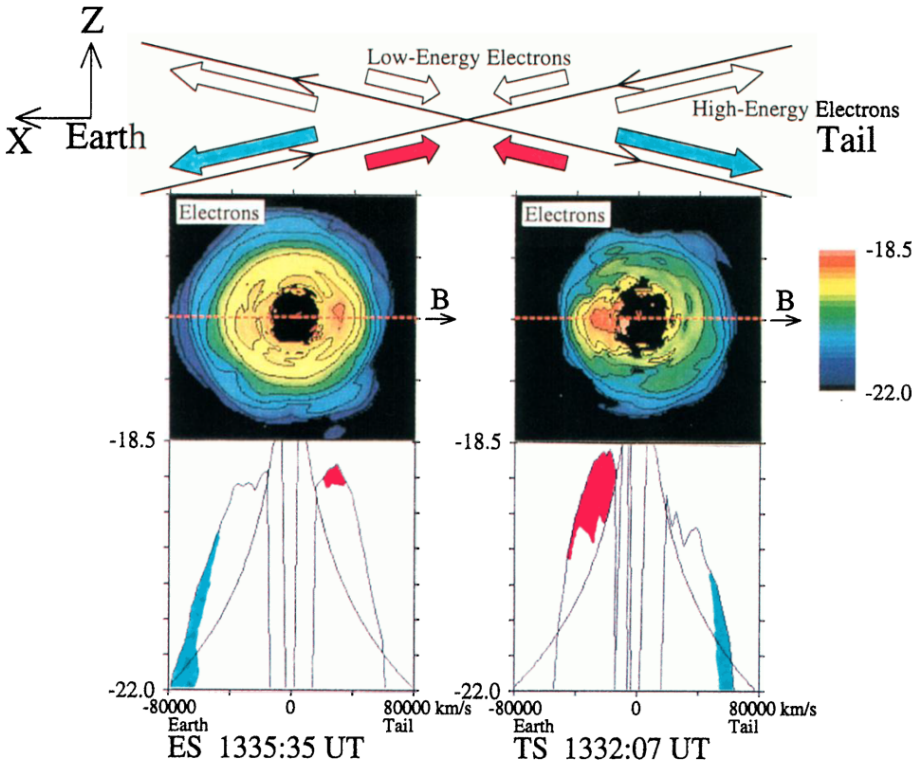
[Lindstedt et al., 2009]

Separatrices: the channels of inflowing electrons with low energy

1. Introduction to the separatrix

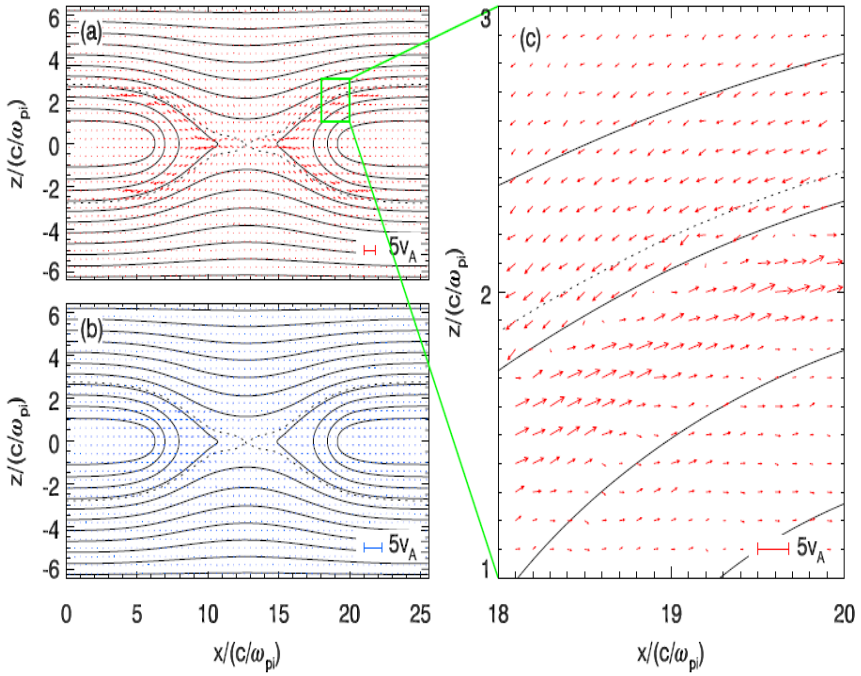
Inflowing electron beam

Magnetotail



[Nagai et al., 2001]

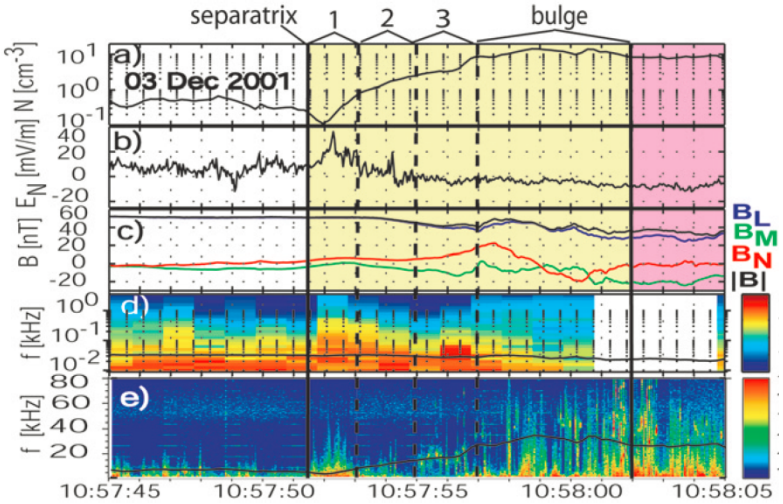
PIC Simulation



[Lu et al., 2006]

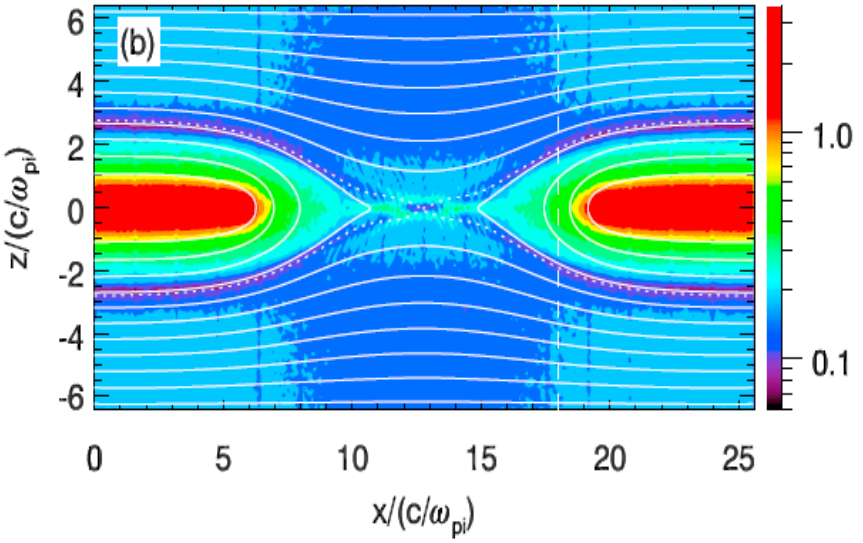
1. Introduction to the separatrix

Electron density cavity along the separatrix



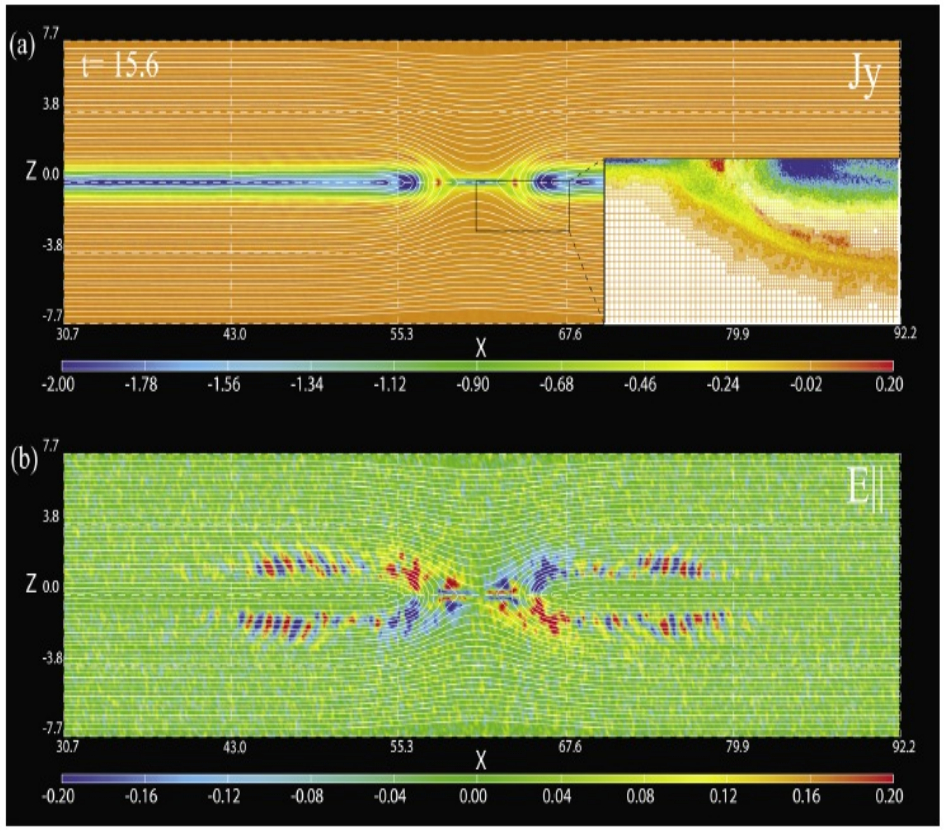
[Retino et al., 2006]

PIC Simulation

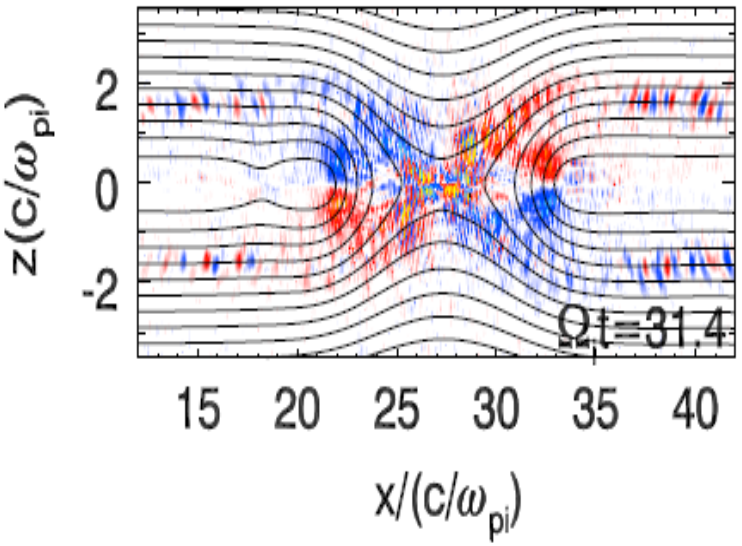


[Lu et al., 2010]

1. Introduction to the separatrix



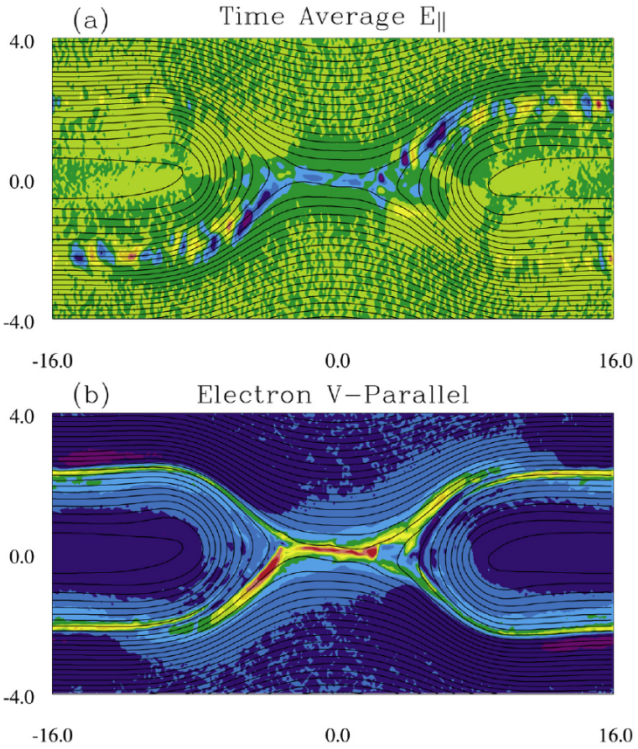
[Fujimoto et al., 2006]



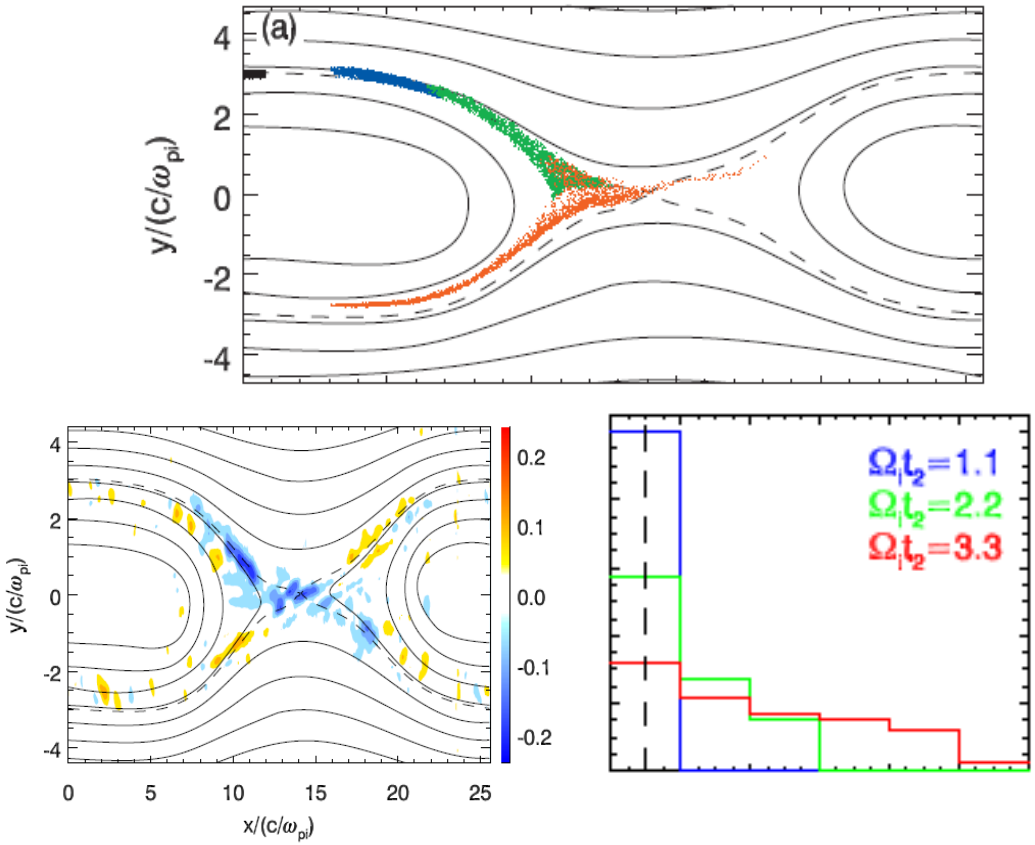
[Huang et al., 2014]

1. Introduction to the separatrix

"Electrons are accelerated in the acceleration cavities and are therefore capable of reaching **relativistic energies**."

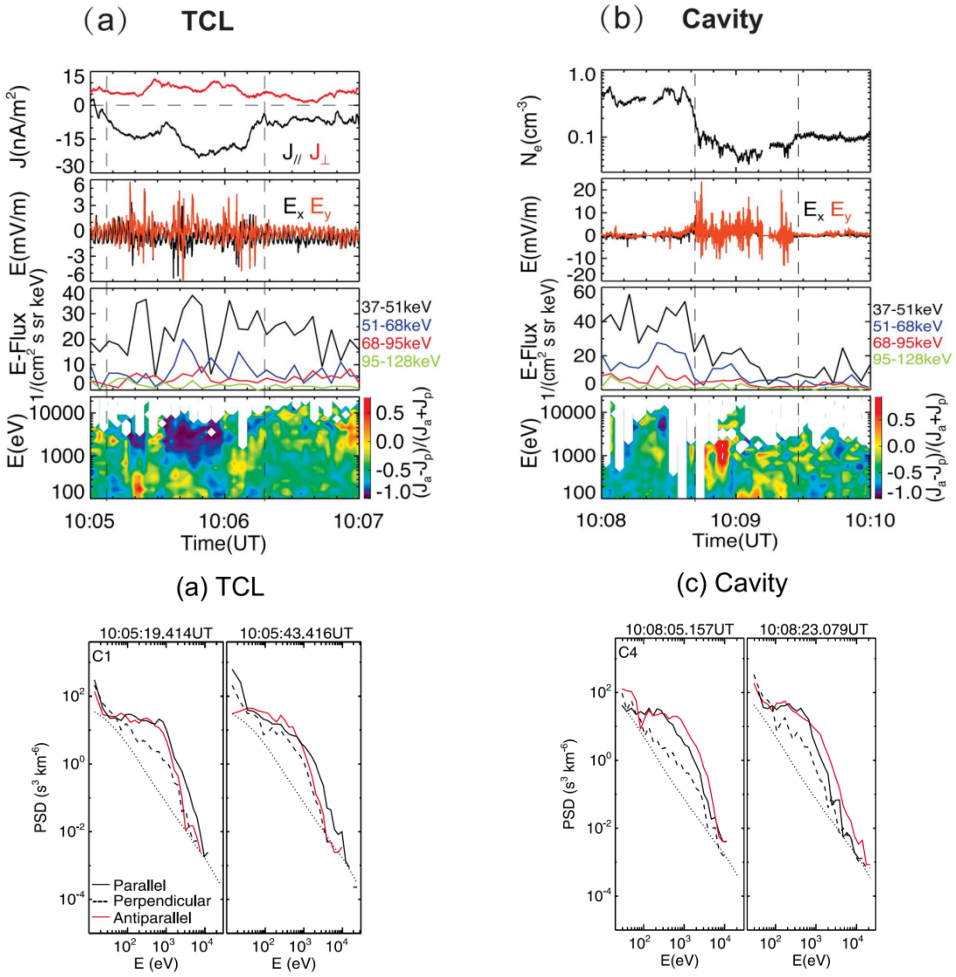


[Pritchett, 2001]

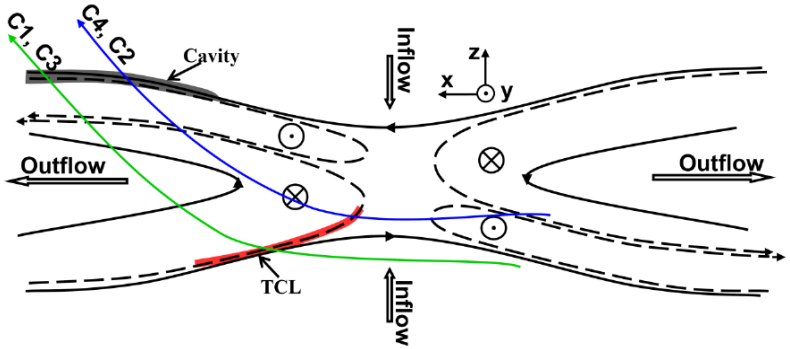


[Huang et al., 2010]

2. Electron distribution in the separatrix region



28/AUG/2002



The energy → 10 keV

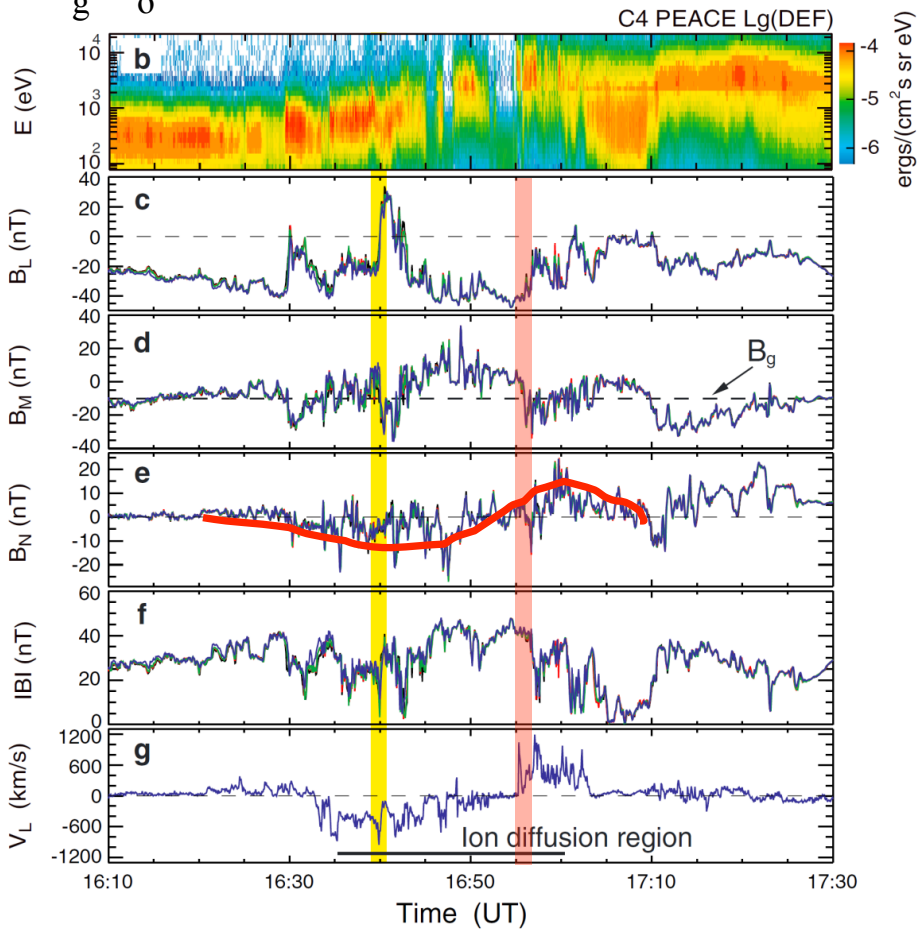
Inflowing electrons might have been accelerated in the separatrix region.

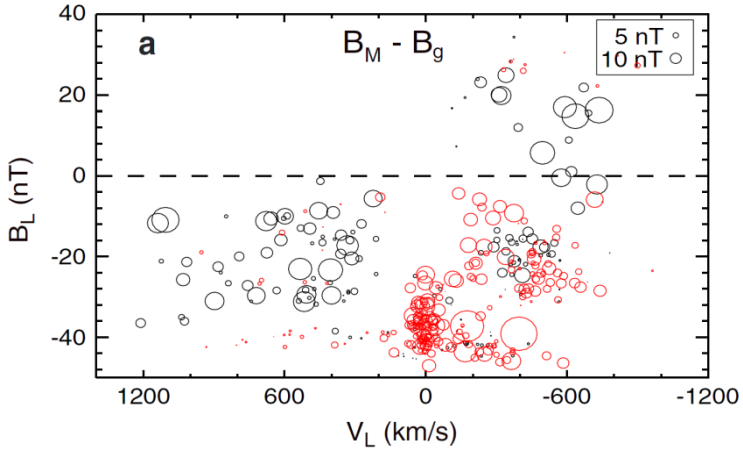
[Wang et al., 2012]

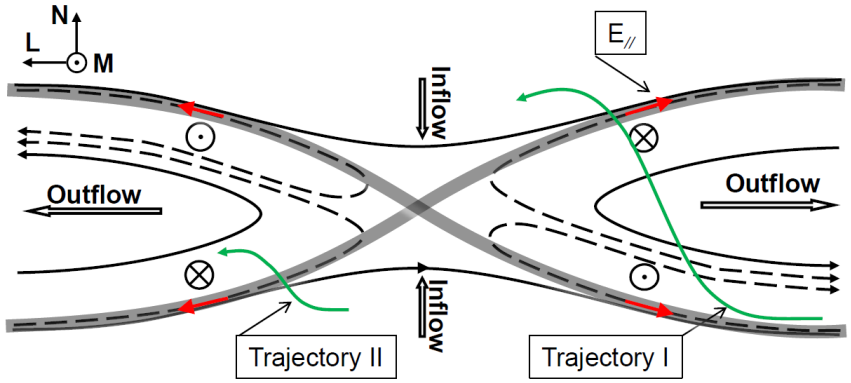
2. Electron distribution in the separatrix region

A guide field reconnection 17/AUG/2003

$B_g/B_o \sim 0.3$

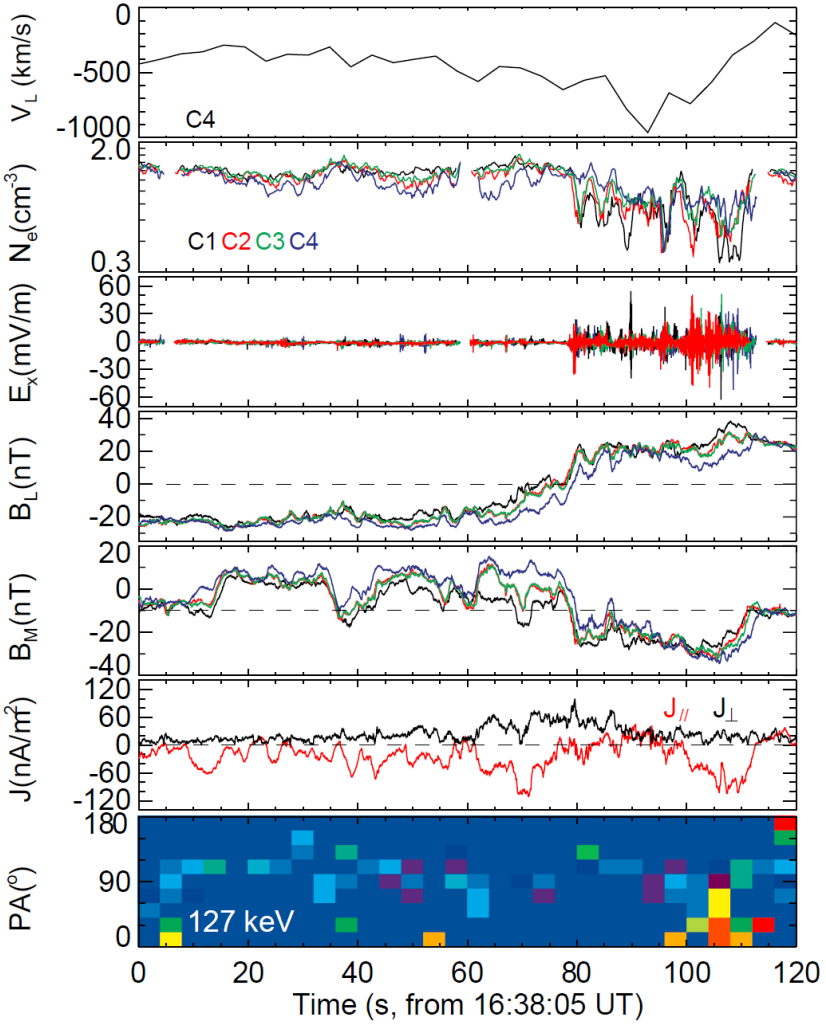


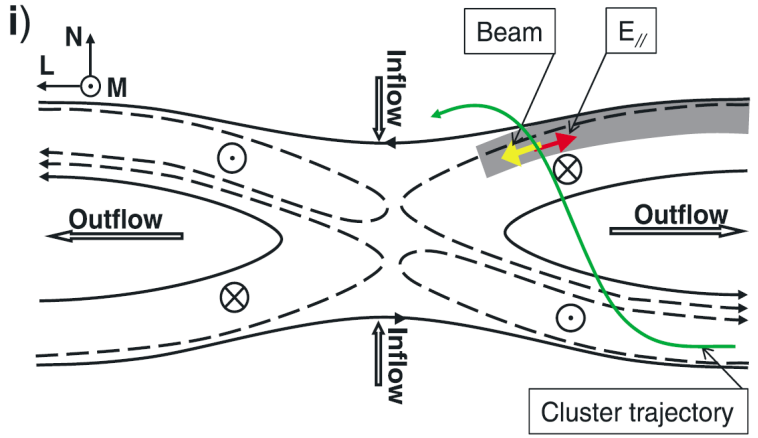




[Wang et al., 2013]

2. Electron distribution in the separatrix region: 1st crossing

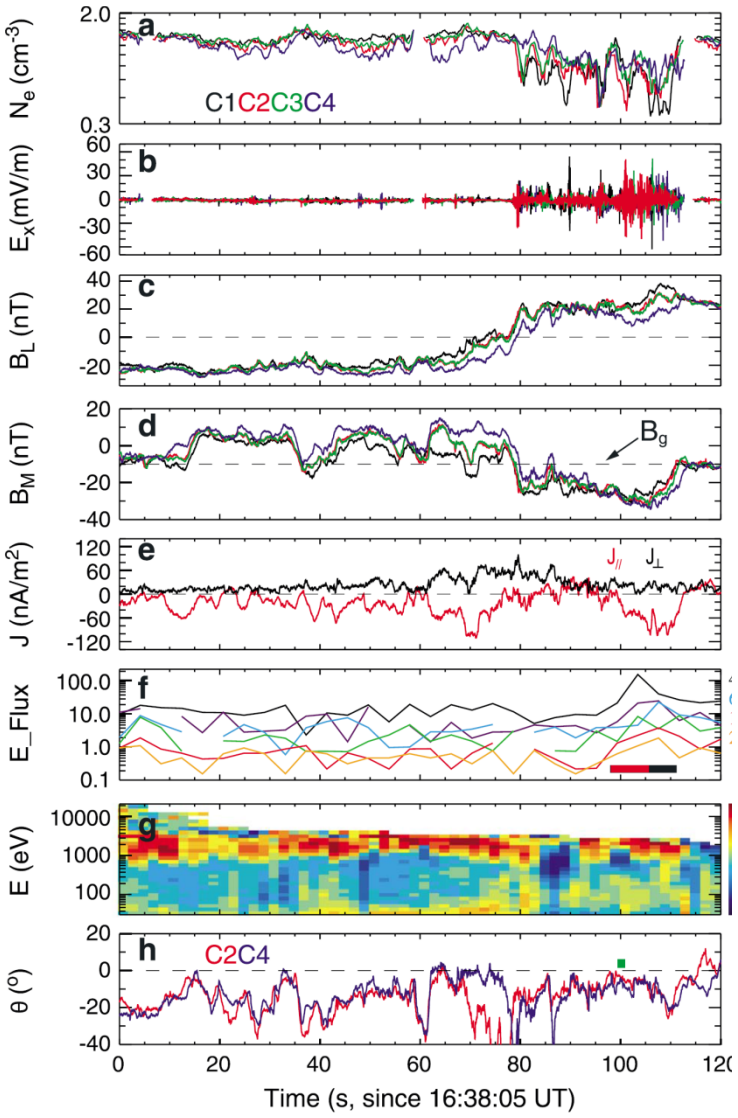


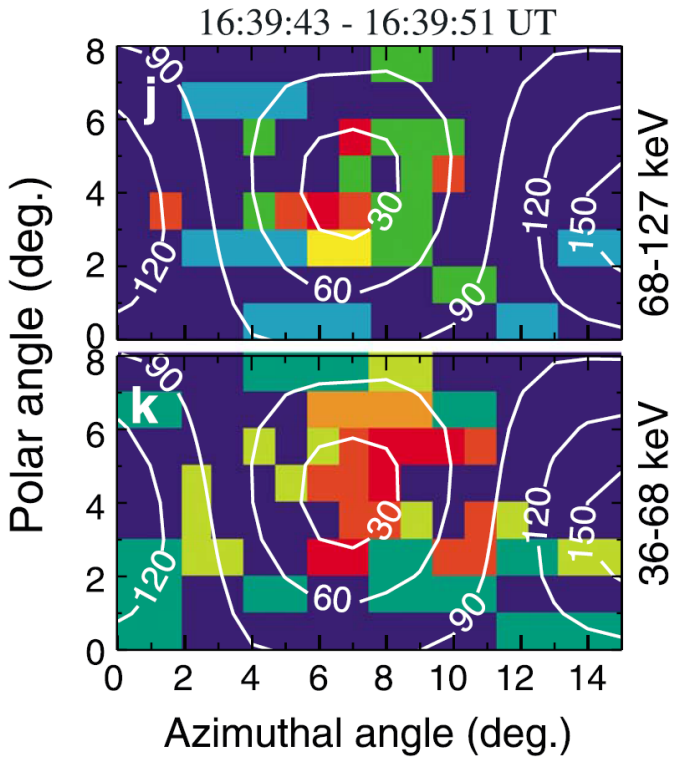


1. A thin current layer in the separatrix region
2. Inflowing electron beam with energy up to 200 keV
3. Multiple density sub-cavities along the separatrix
4. The strong electric field fluctuations

[Wang et al., GRL 2013]

2. Electron distribution in the separatrix region: 1st crossing

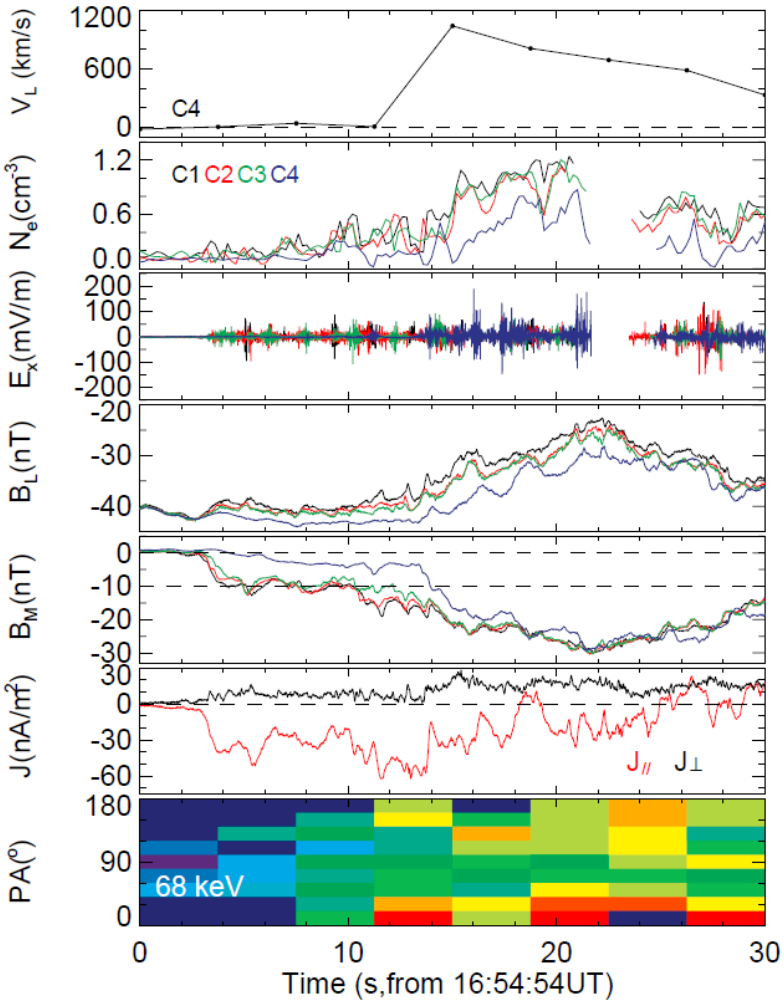




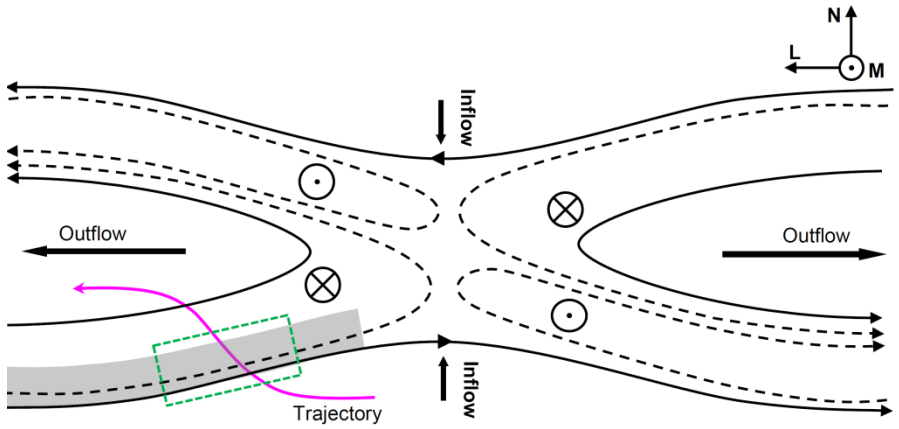
5. Fluxes of energetic electrons are enhanced in the separatrix region

[Wang et al., GRL 2013]

2. Electron distribution in the separatrix region: 2nd crossing



[Wang et al., 2014]

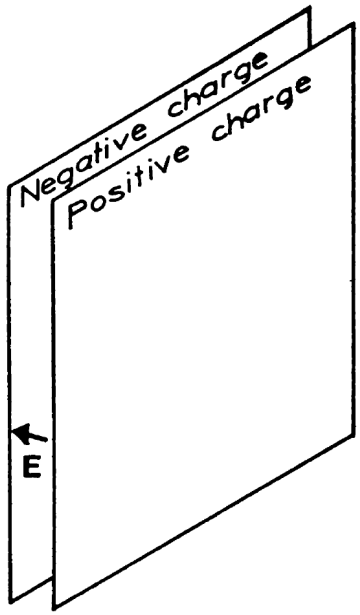


1. A thin current layer in the separatrix region
2. Inflowing electron beam with energy up to 100 keV
3. The strong electric field fluctuations

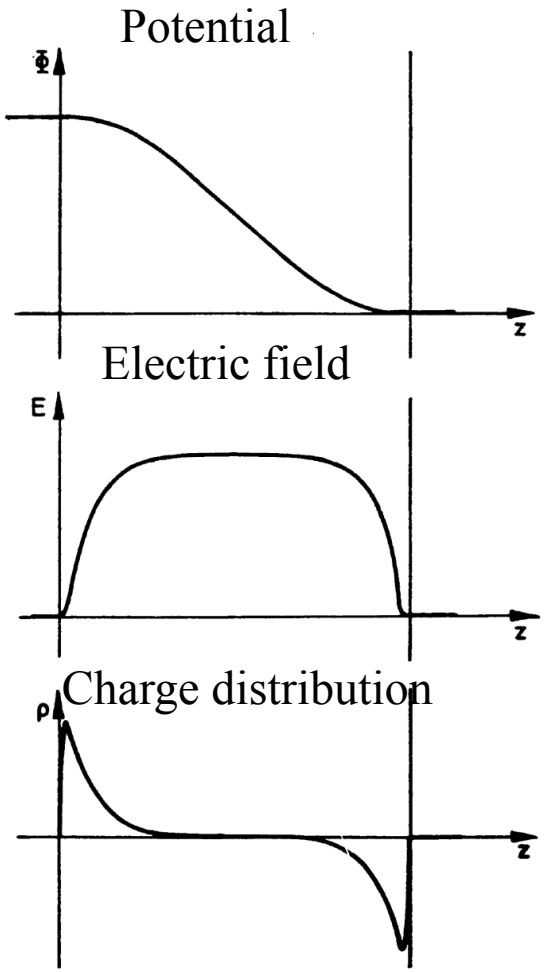
How the electrons are accelerated near the separatrix ?

3. Parallel electric field/Double Layers detected near the separatrices

Schematic picture of a double layer



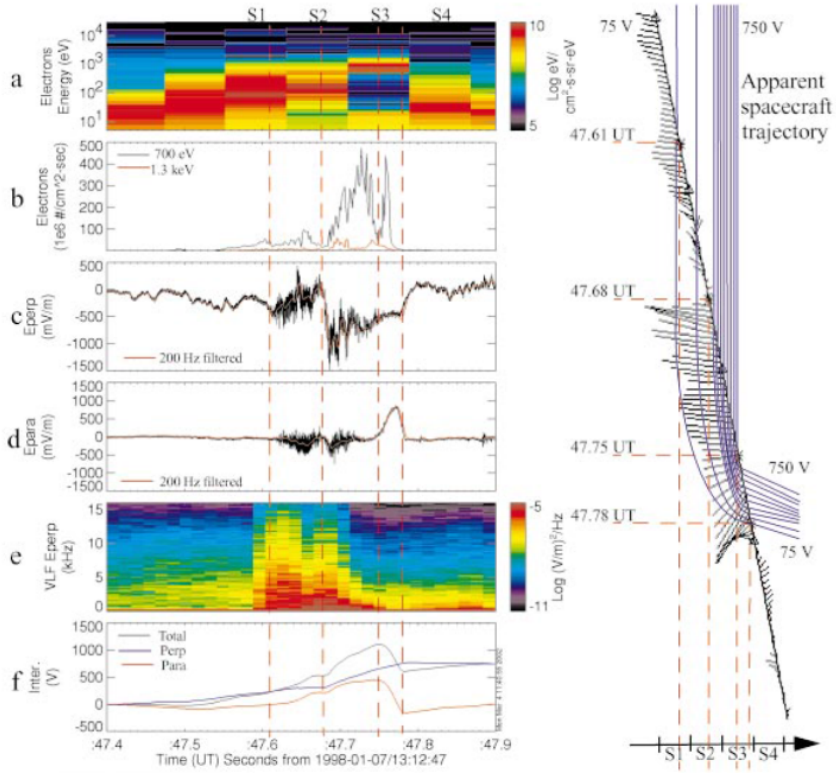
An electric double layer (DL): a narrow localized region in plasma which sustains a large potential jump , i.e. an electric field



[Block, 1977]

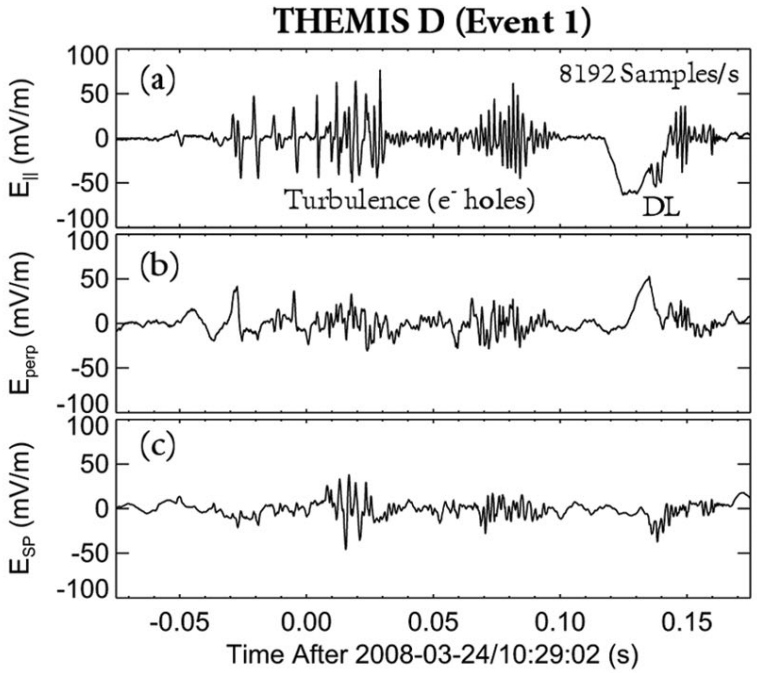
3. Parallel electric field/Double Layers detected near the separatrices

DL: downward current region of aurora



Andersson et al., POP 2002

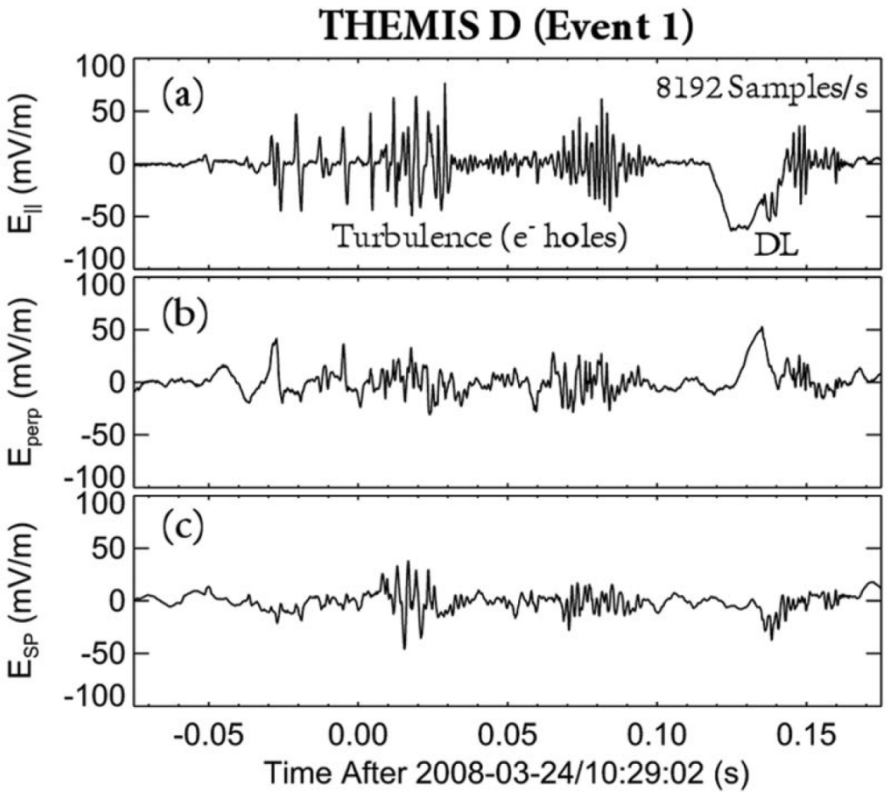
DL: Magnetotail



Ergun et al., PRL 2009

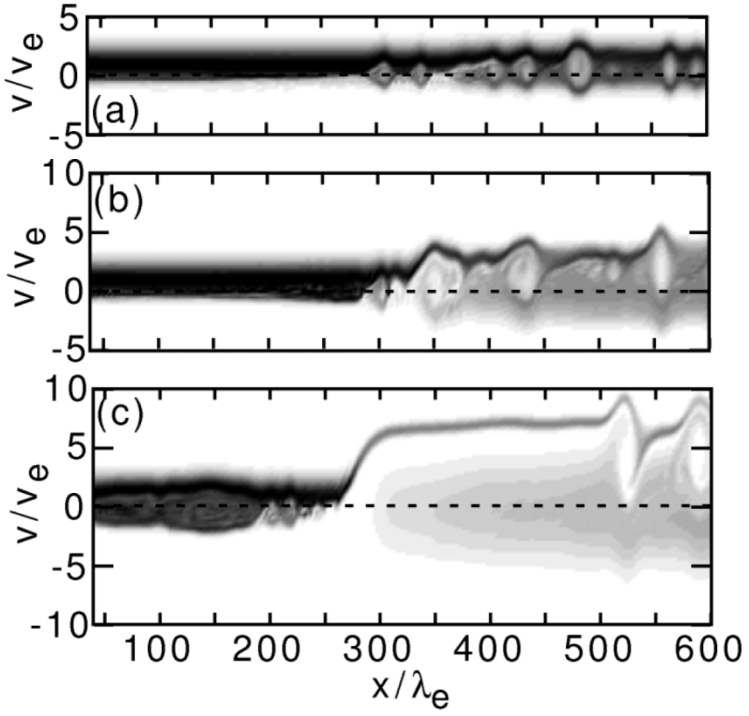
3. Parallel electric field/Double Layers detected near the separatrices

DLs observed in the plasma sheet



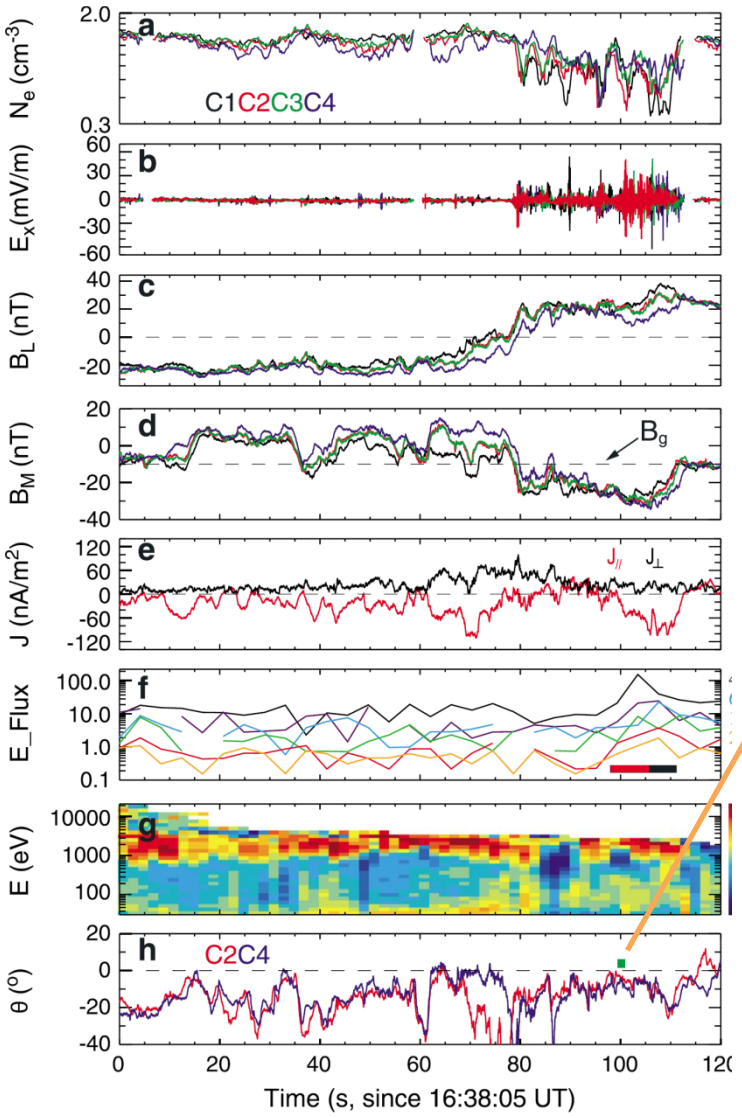
Ergun et al., PRL 2009

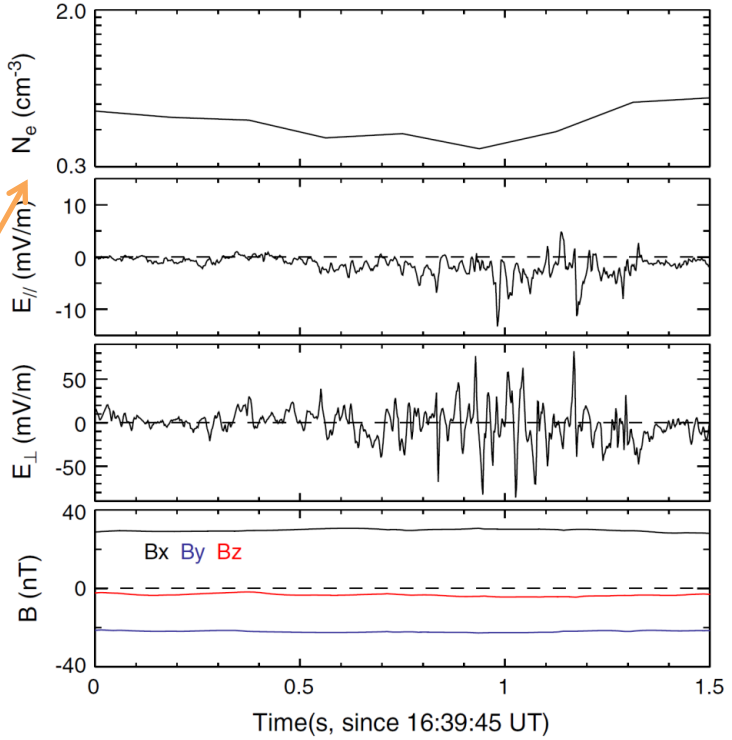
Ehs at the high potential side of DLs



Newman et al., PRL 2001

3. Parallel electric field/Double Layers detected near the separatrices: 1st crossing



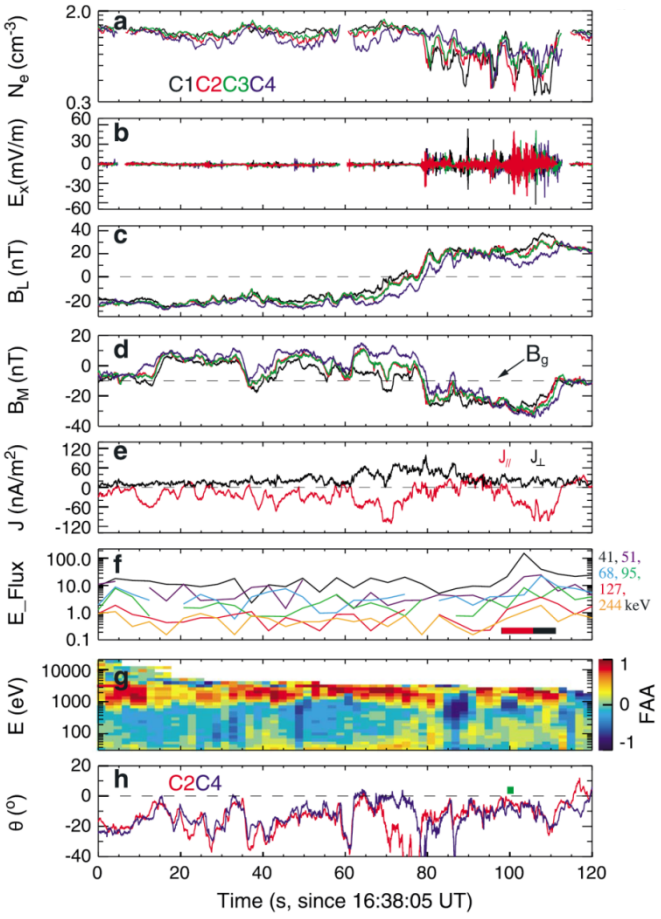


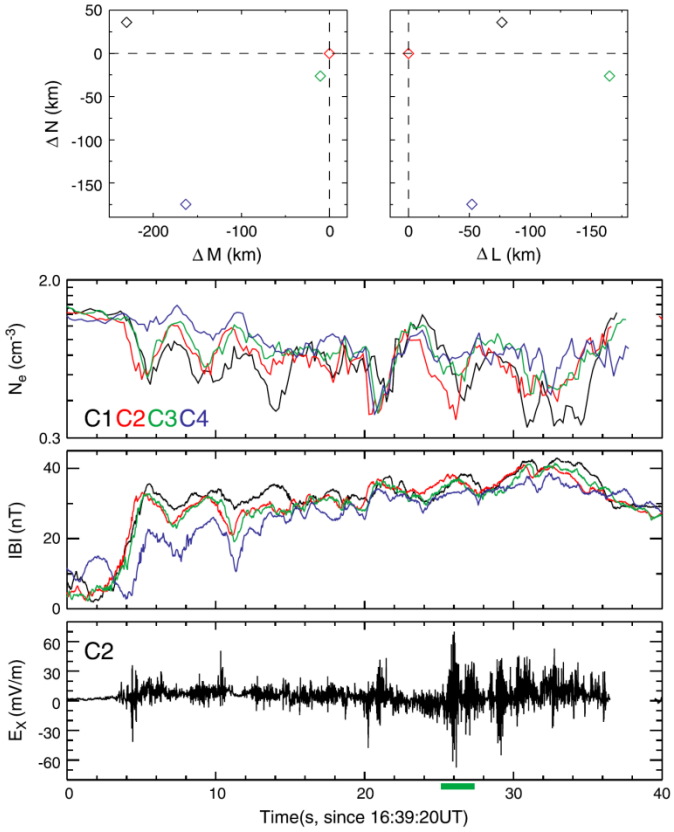
Parallel electric field directs away from the X-line, ~ -10 mV/m

[Wang et al., 2013]

3. Parallel electric field/Double Layers detected near the separatrices: 1st crossing

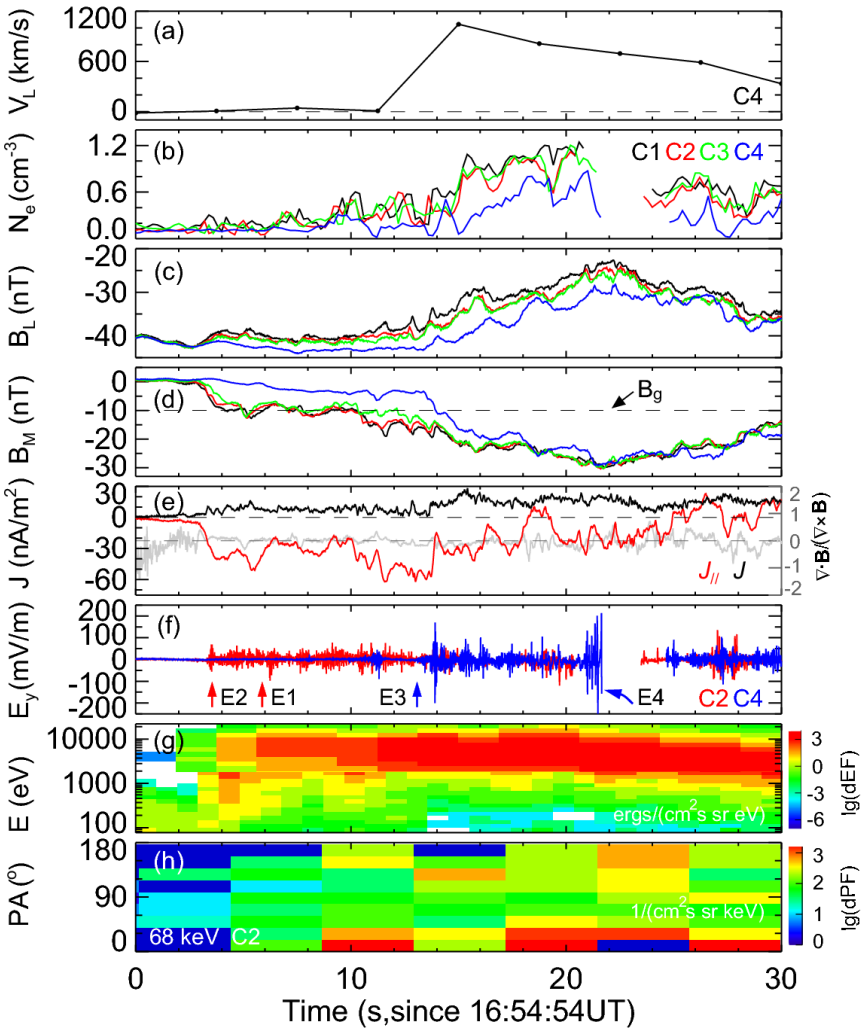
Multiple sub-cavities; The $E_{//}$ observed just within one of the sub-cavities





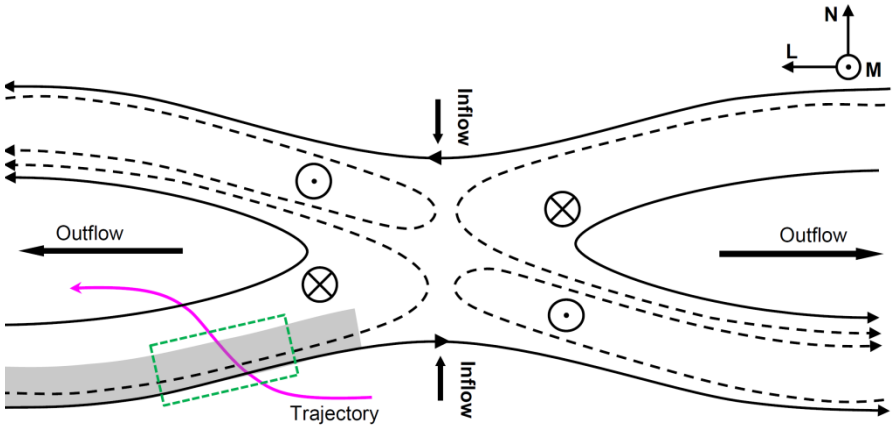
Wang et al., GRL 2013

3. Parallel electric field/Double Layers detected near the separatrices: 2nd crossing

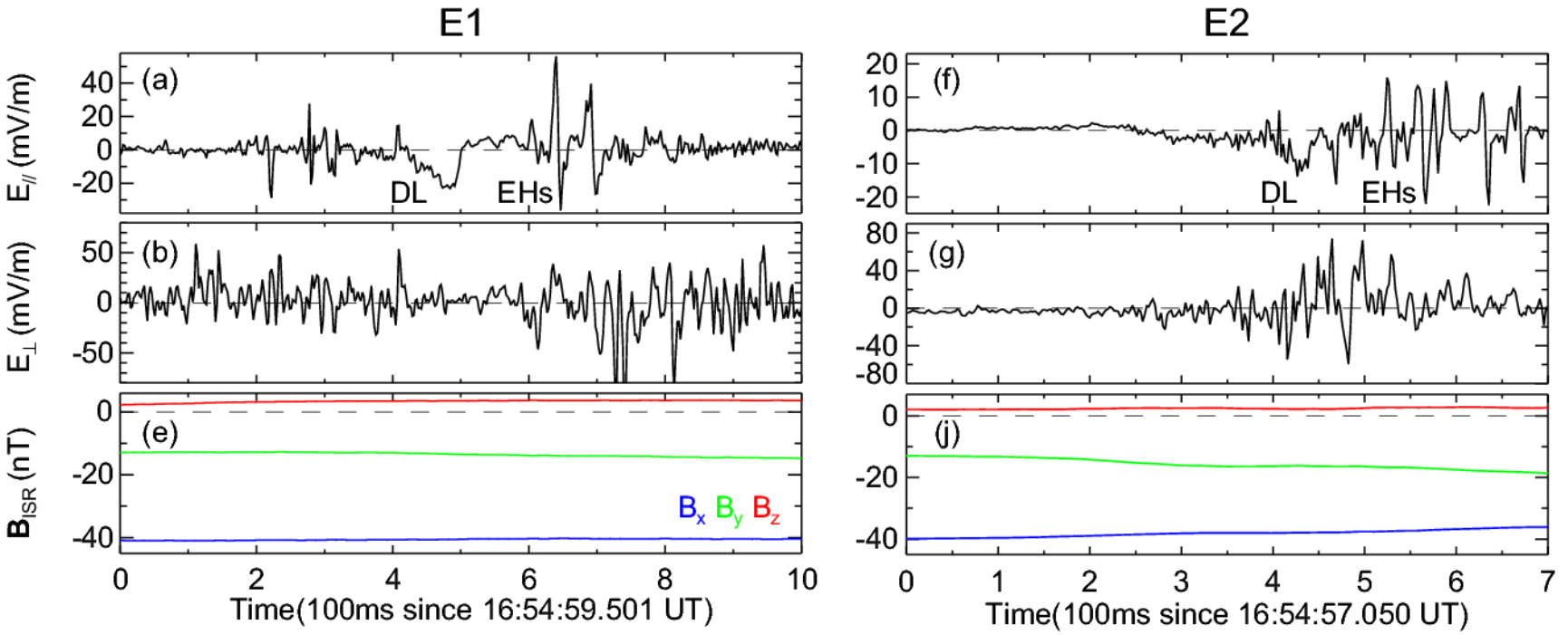


A short period of 15 sec when angles between the spacecraft spin plane and the magnetic field < 5° ; $E_{//}$ and one component of $E_{\perp}$ can be estimated.

Three **Double Layers** (E1-E3) are identified in the second crossing of the separatrix



3. Parallel electric field/Double Layers detected near the separatrices: 2nd crossing



Signature: a unipolar $E_{//}$ followed by a series of bipolar $E_{//}$
The unipolar $E_{//}$: Double Layer; the bipolar $E_{//}$: Electron hole

E1: DL ~ 100 ms
E2: DL~50ms

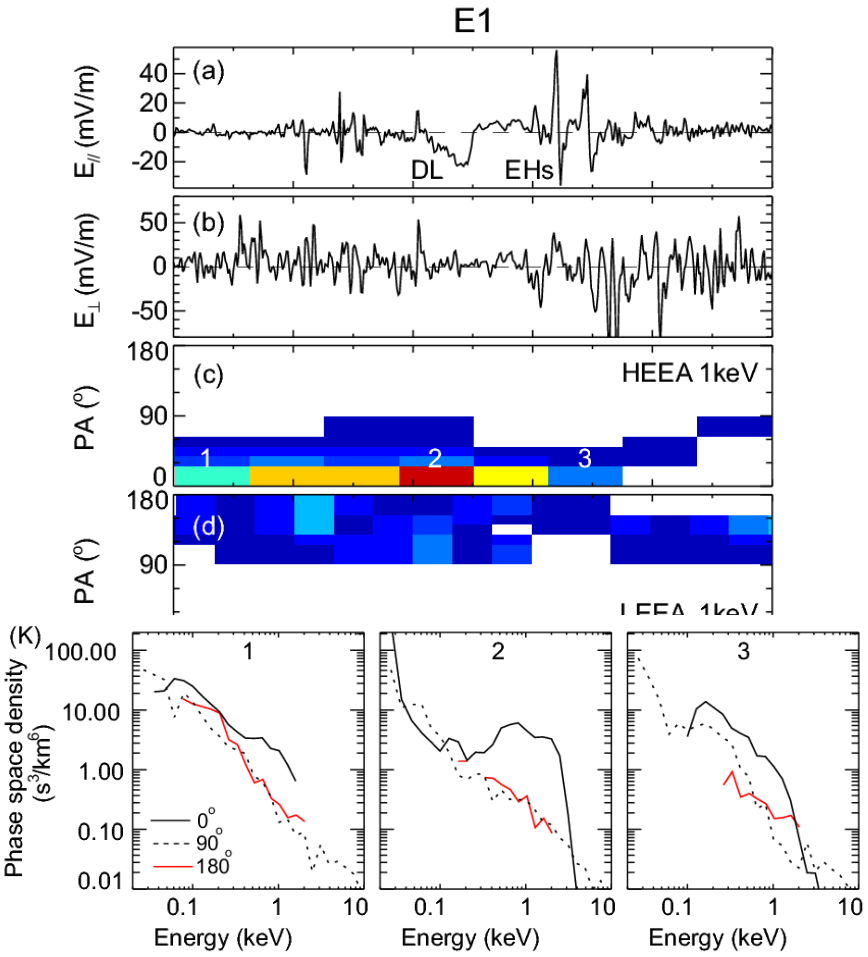
The DLs and Ehs velocity cannot be estimated by time delay of two probes

Polarity of Ehs: first positive then negative, moving parallel to magnetic field

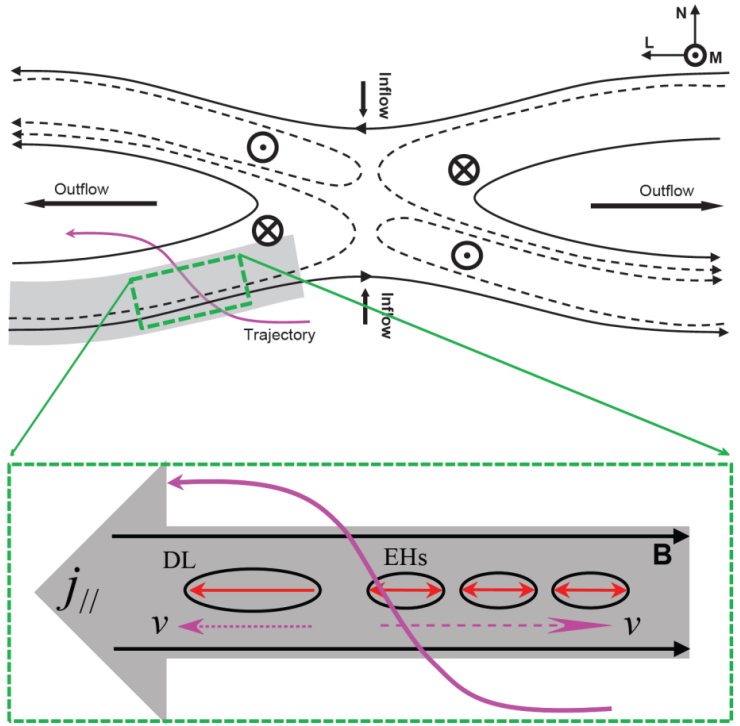
[Wang et al., GRL 2014]

3. Parallel electric field/Double Layers detected near the separatrices: 2nd crossing

An electron beam observed right within the DL

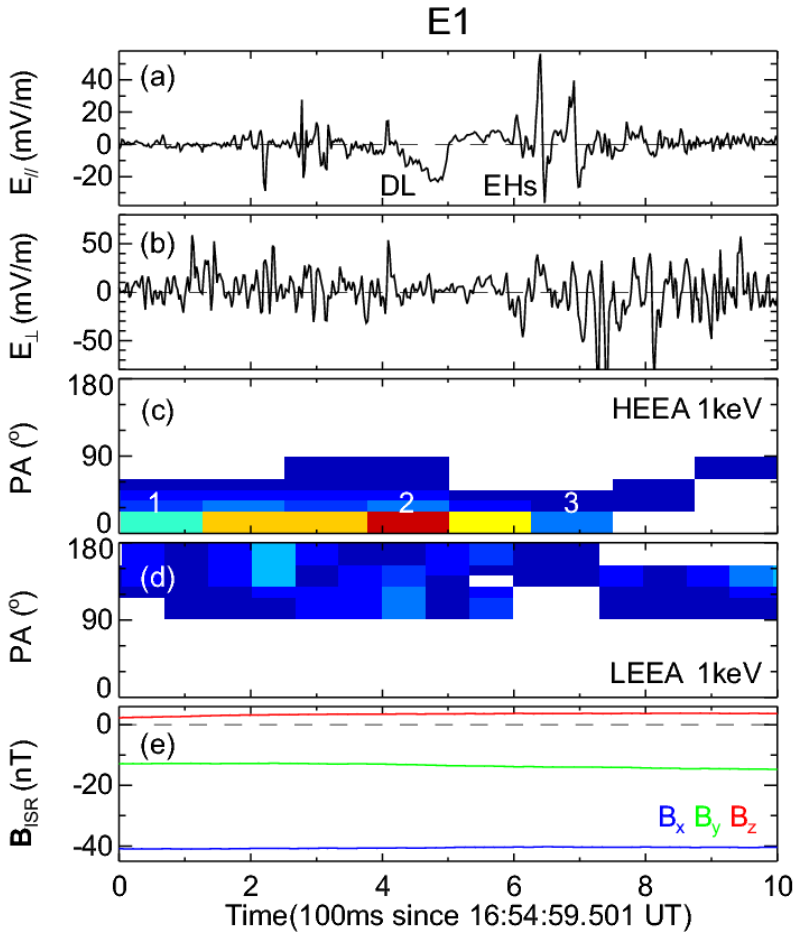


Assuming the DLs are moving towards X-line , EHs would be at the low potential side of DL, contrary to previous observation and theory. So, the DLs are moving away from the X-line



Wang et al., 2014

3. Parallel electric field/Double Layers detected near the separatrices: 2nd crossing

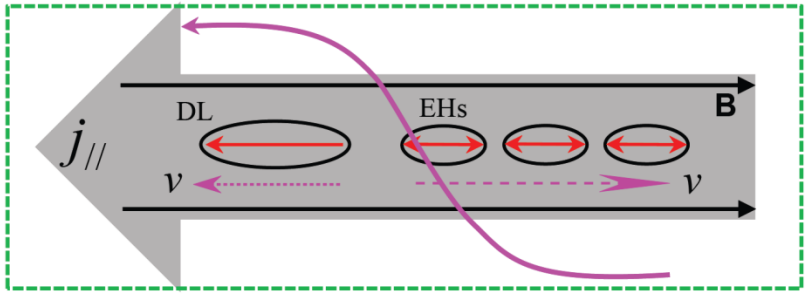


Wang et al., 2014

DL: $E_{//} \sim$ - 20 mV/m, $\Delta t \sim$ 100 ms

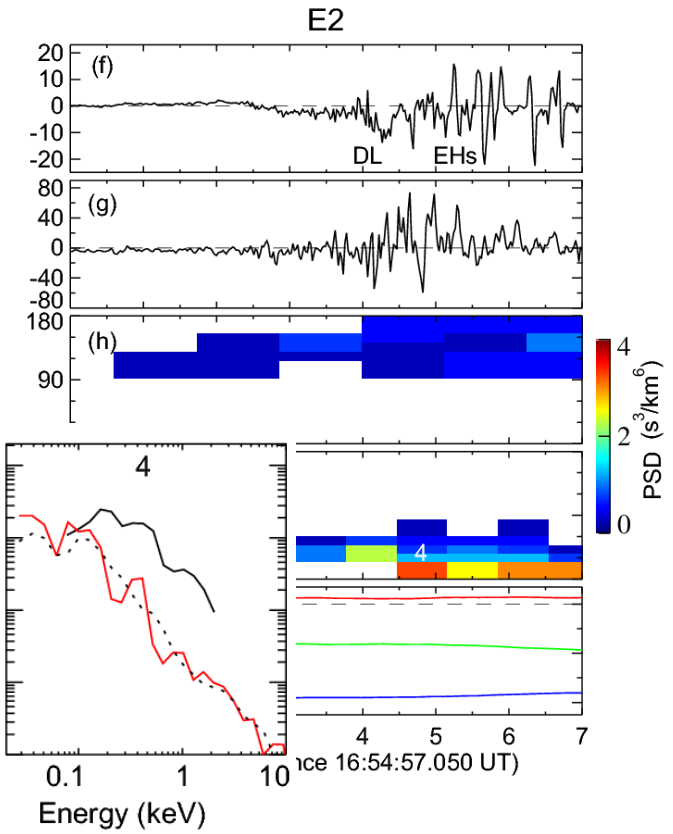
The velocity of the DL $v_{//} = \Delta U / (\Delta t \cdot E_{//}) \approx$ -150 - -1000 km/s (underestimated), comparable to the ion acoustic speed 800 km/s.

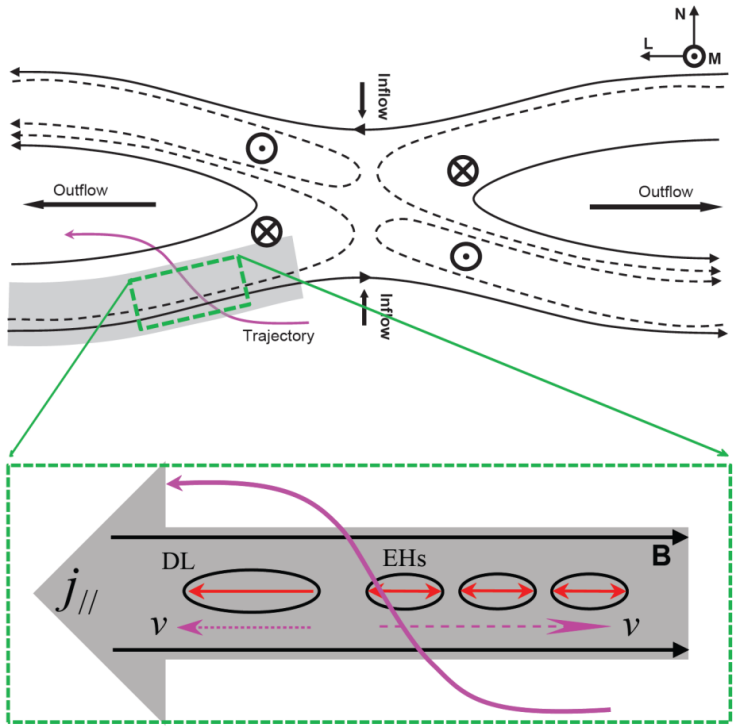
DL Size : 12.5 ~ 62.5 λ_D electron Debye length



3. Parallel electric field/Double Layers detected near the separatrices: 2nd crossing

Double Layers are created repeatedly during reconnection and propagate away from the X-line. Electrons could experience numerous DLs while they are moving towards the X-line, and accelerated to high energy.





Wang et al., 2014

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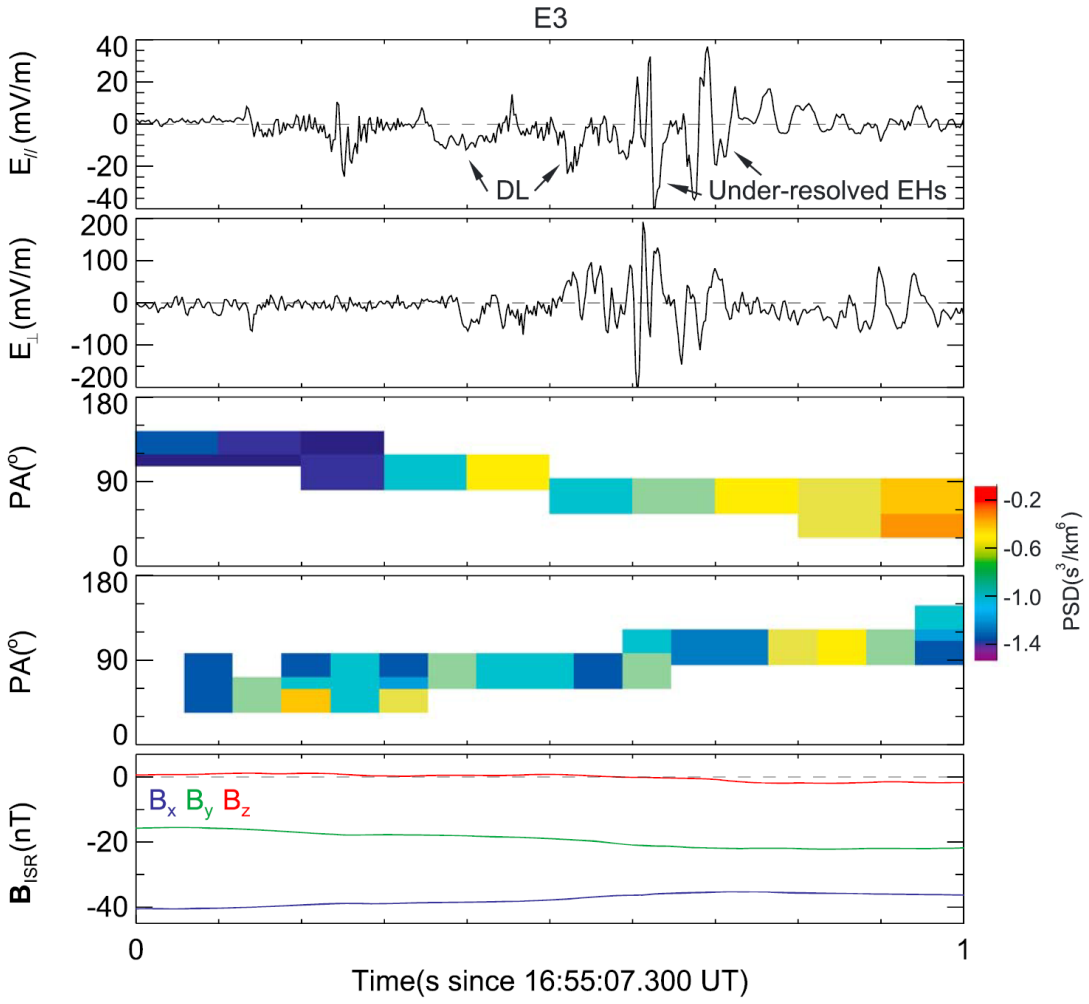

Wang et al., GRL 2014

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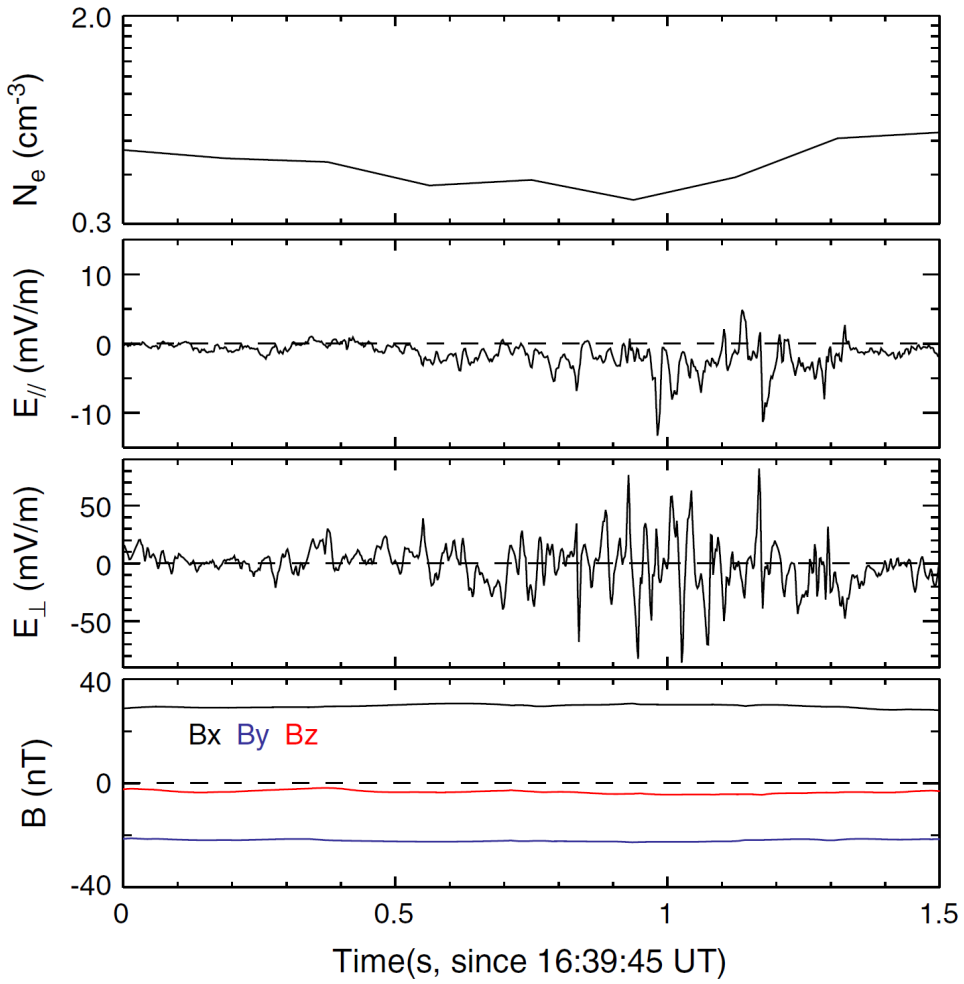

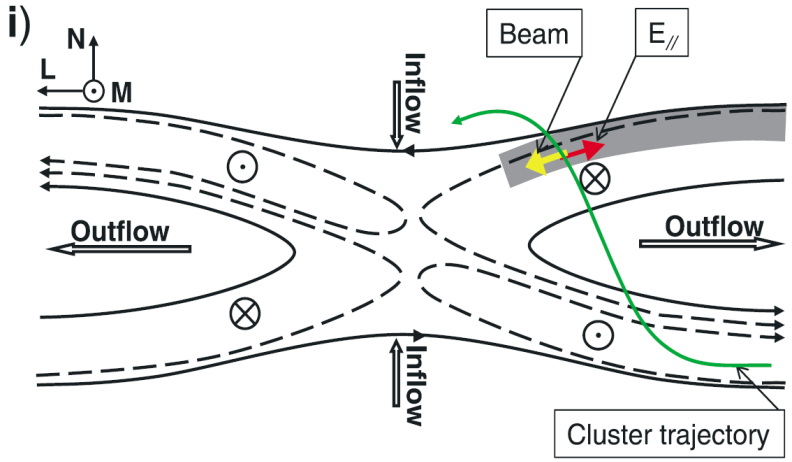

$E_{//}$ breaks up into DLs ??

Wang et al., GRL 2013

4. Discussion & Conclusion

By using several magnetic reconnection events in the magnetotail, we studied electron acceleration during reconnection. The main conclusions:

1.Electrons have already been accelerated (up to 100 keV) in the separatrix region, while they are flowing towards the X-line

2.There are multiple sub-cavities in the separatrix region. The electron acceleration might be closely associated with the sub-cavities.

4. Discussion & Conclusion

3. The parallel electric field directed away from the X-line could be responsible for the electron acceleration.

4. Double Layers are created repeatedly during reconnection and propagate away from the X-line. Electrons could experience numerous DLs while they are moving towards the X-line, and be accelerated to high energy.

5. EHs are gathering towards the X-line, might play a role in anomalous resistivity by scattering electrons in reconnection.

Thank you !