The role of O^+ in the near-earth magnetotail dynamics

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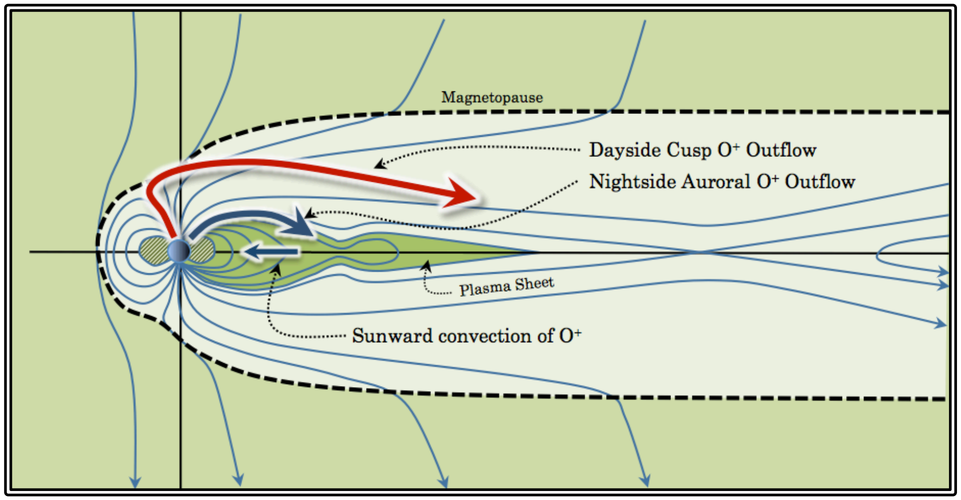
Outline

What is the effect of O^+ on the onset and energy release in the reconnecting magnetotail?

- Introduction
  - Ionospheric outflow feeding of the plasma sheet
- Three-scale diffusion region
  - 2.5D three-species kinetic simulation results
  - Comparisons with Cluster data
- Influence of O^+ on global dynamics
  - Effect on the stability of the thin current sheet
  - Effect on the unloading rate

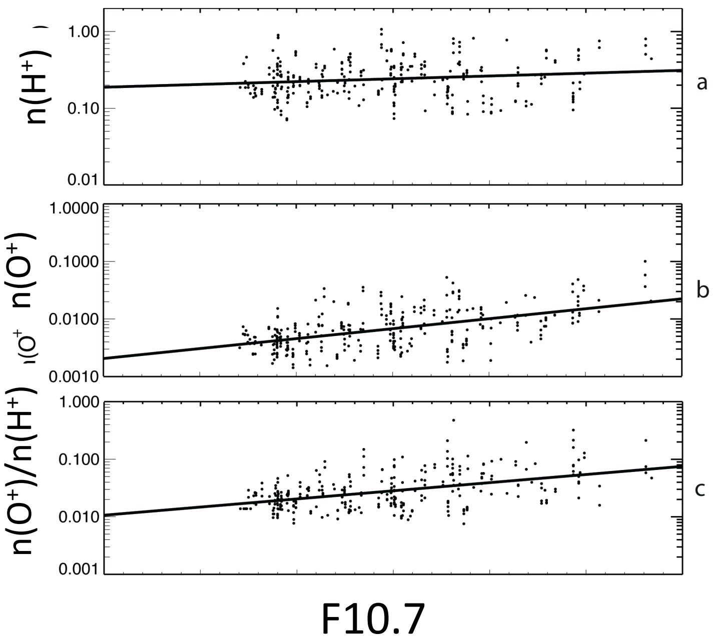
Pathways of energetic ionospheric outflow to the plasmasheet



(from Genestreti, 2012)

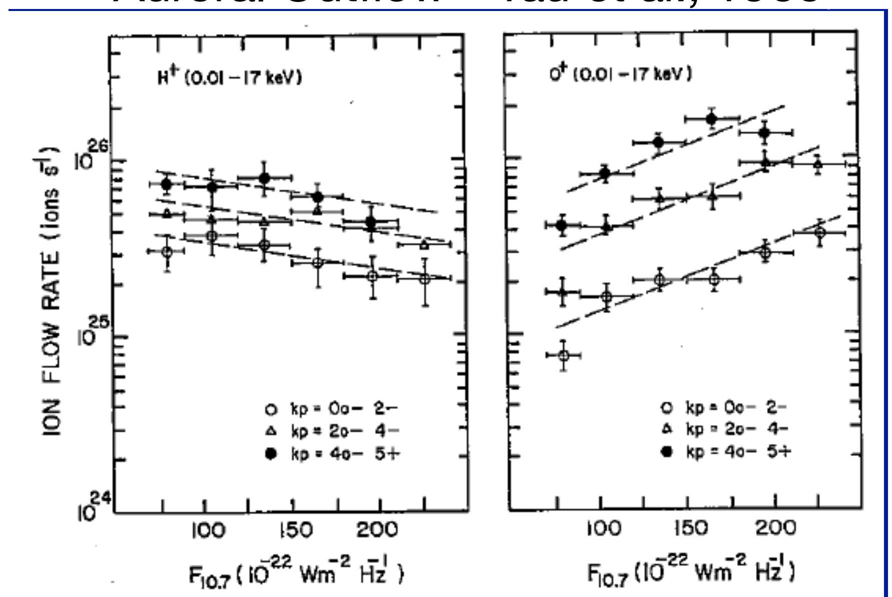
- The ionospheric outflow from the dayside cusp is convected through the lobes to the plasma sheet
- When reconnection occurs, the O^+ that was on a lobe open field line, is now on a plasma sheet closed field line
- Outflow from the nightside auroral region has direct access to the plasma sheet
- Convect earthward towards the inner magnetosphere

The solar EUV (F10.7) connection



Mouikis et al., 2010

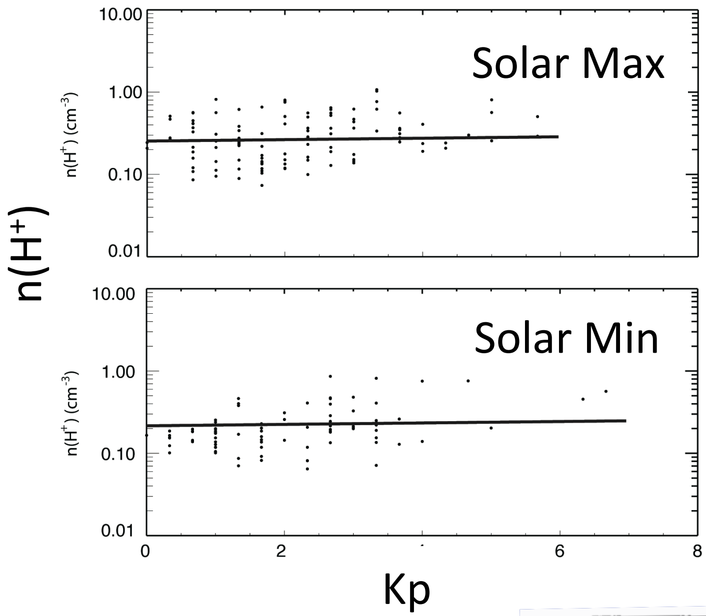
Auroral Outflow – *Yau et al., 1988*

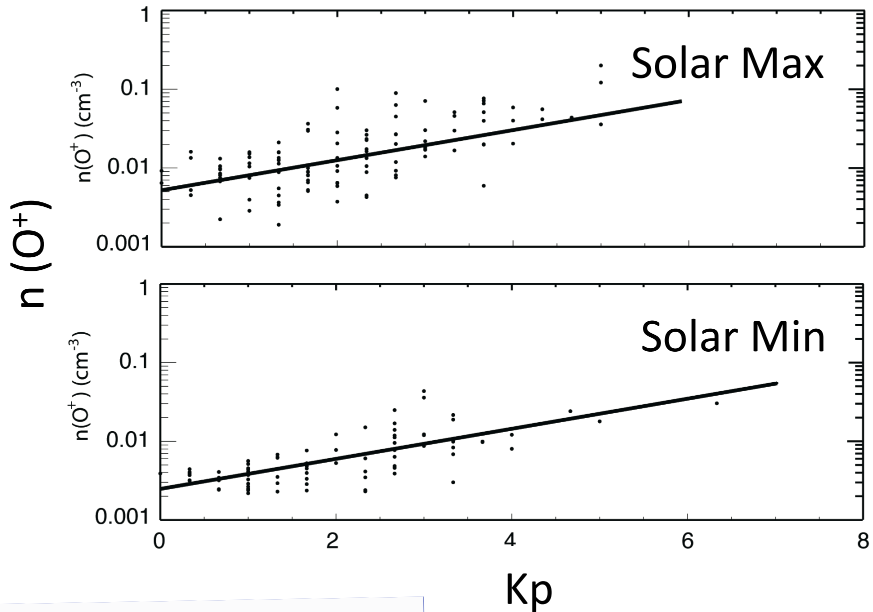


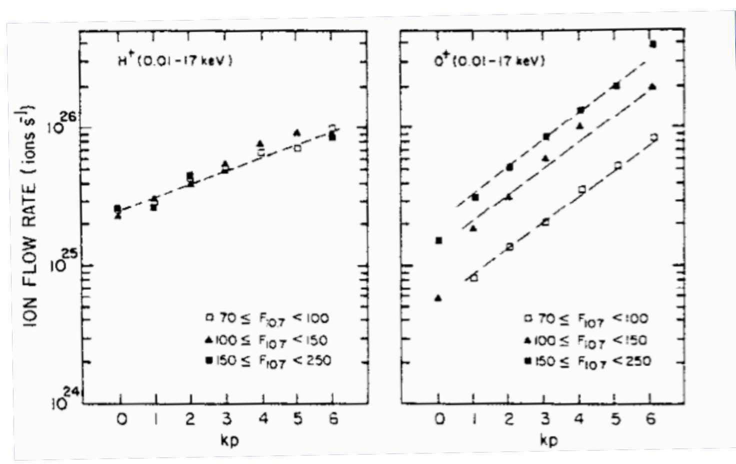
- ➢ While H^+ ionospheric outflow decreases with F10.7 the plasma sheet density remains the ~same due the the mixed source (solar wind) of plasma sheet H^+

- ➢ O^+ auroral outflow increases together with the density in the plasma sheet (~x8)

The Kp connection



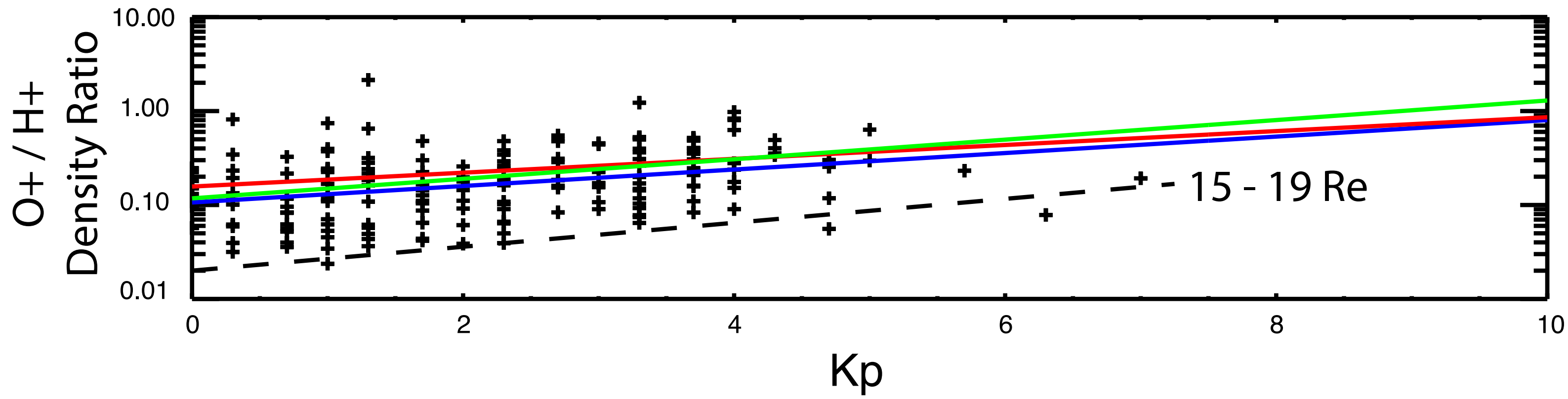




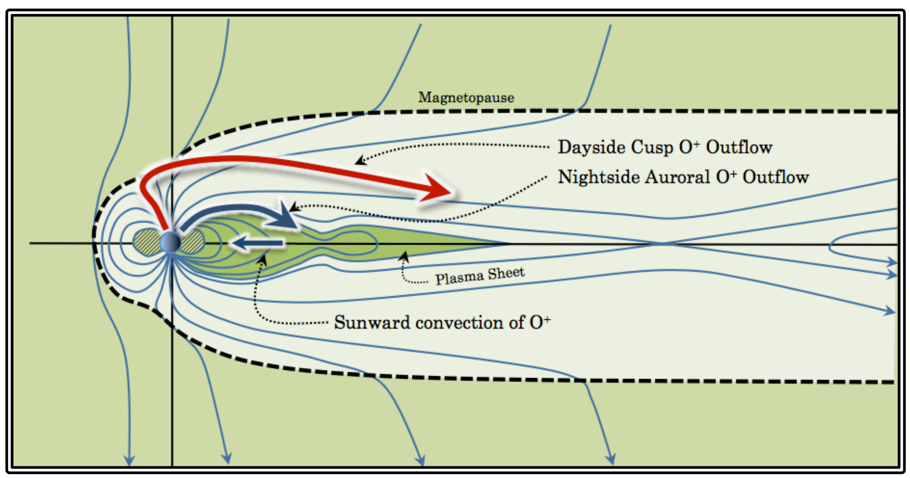
Auroral Outflow
Yau et al., 1988

- Ionospheric outflow and density in the plasma sheet increase by ~x15.
- O^+ increase with Kp is mainly a source effect

Additional entry of O^+ inside the 15 Re

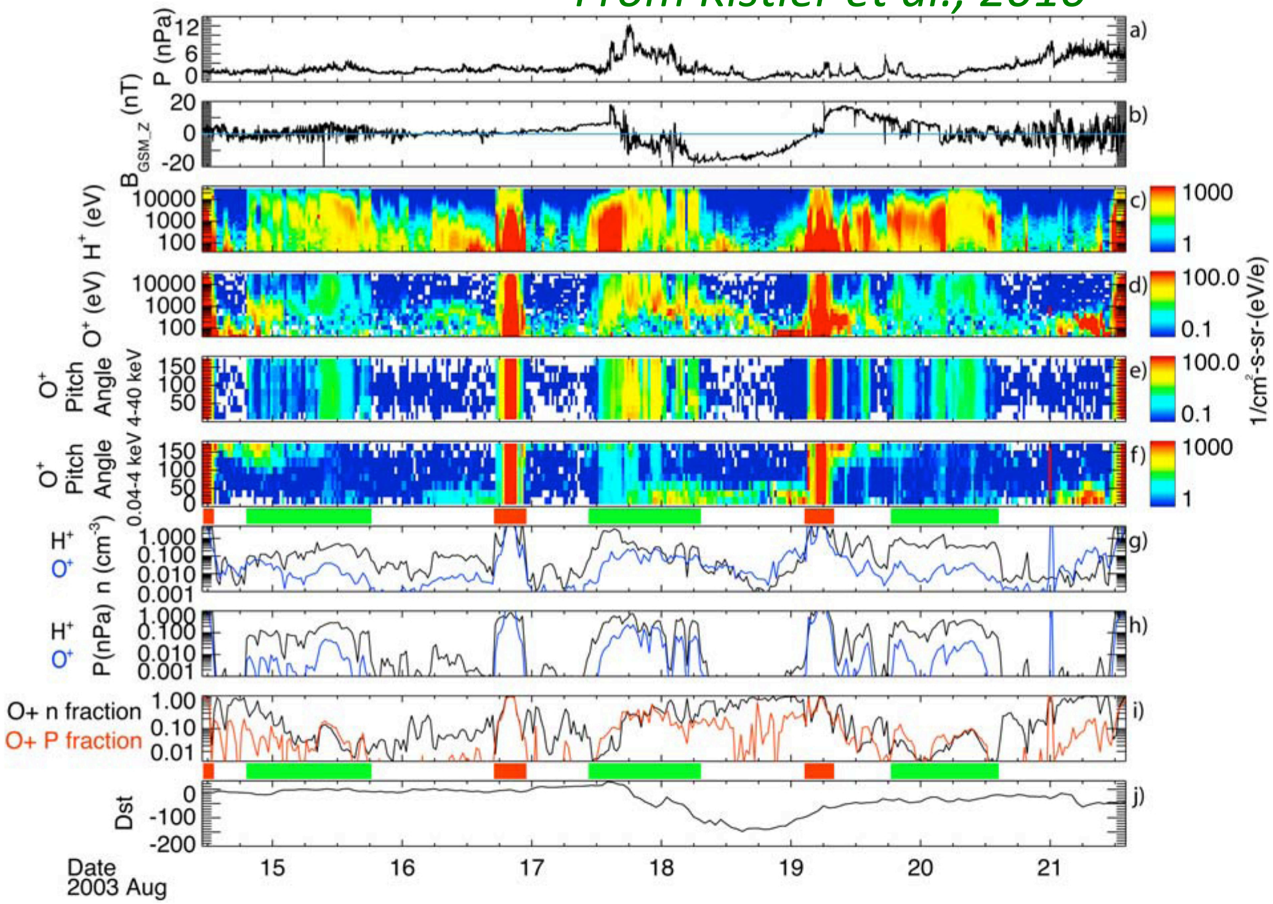


R: 15-20 Re - Mouikis et al., 2010 / L: 7-8 – Mouikis et al, 2014
L: 7-8 - Maggiolo and Kistler, 2013, / L: 6-7 - Young et al., 1982



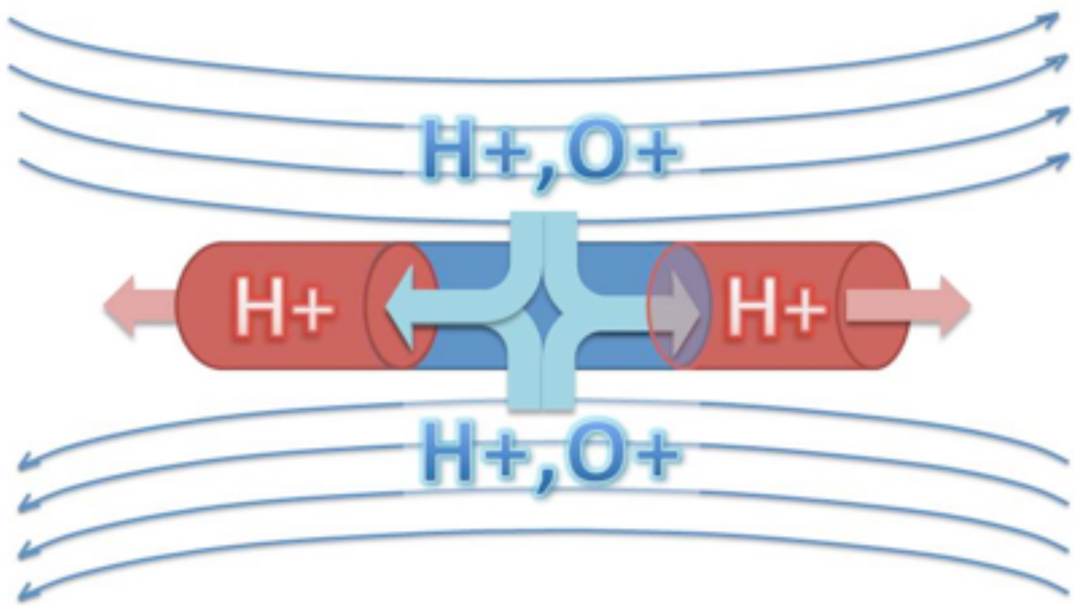
Storm time cusp outflow

From Kistler et al., 2010



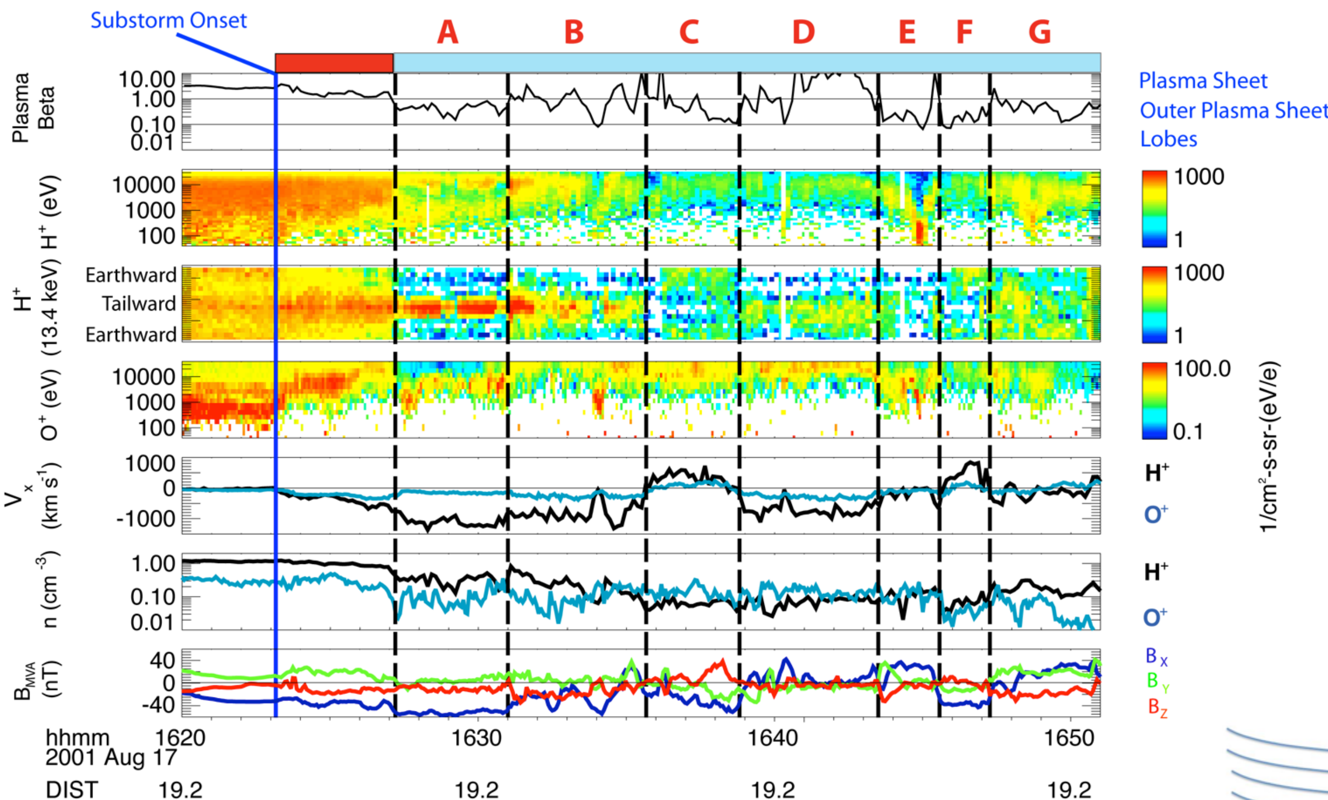
- During a storm, outflow from the cusp/cleft region increases due to higher solar wind pressure
- The cusp/cleft outflow is transported across the polar cap and into the lobes
- The lobe O+ enters the plasma sheet
- Storm-time substorms will further accelerate the O+

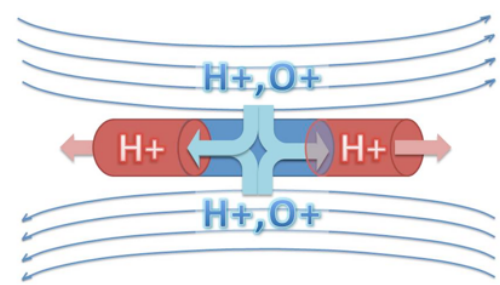
"Flushing" effect in near-Earth reconnection



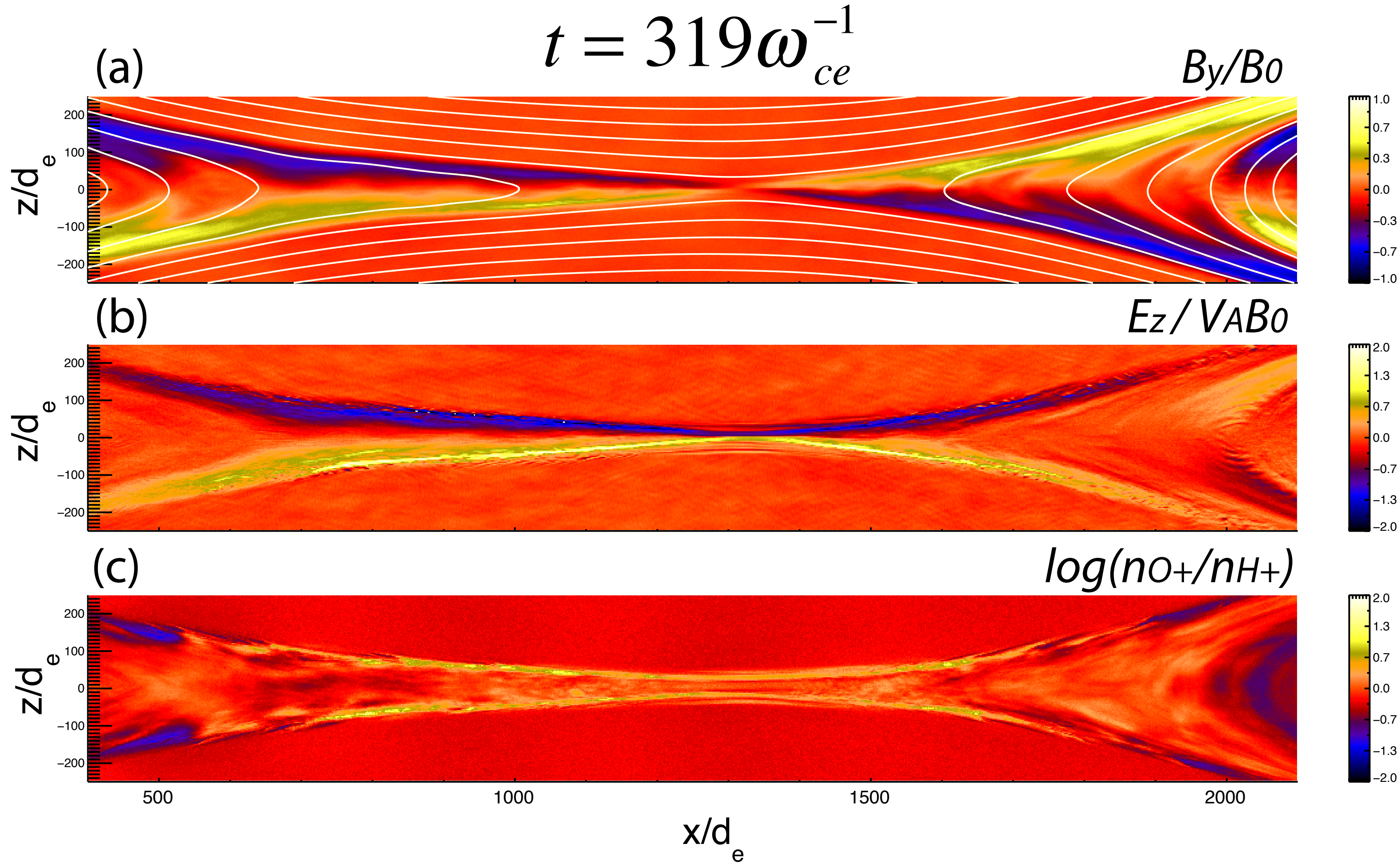
from Karimabadi et al., 2011

“Flushing” effect in near-Earth reconnection

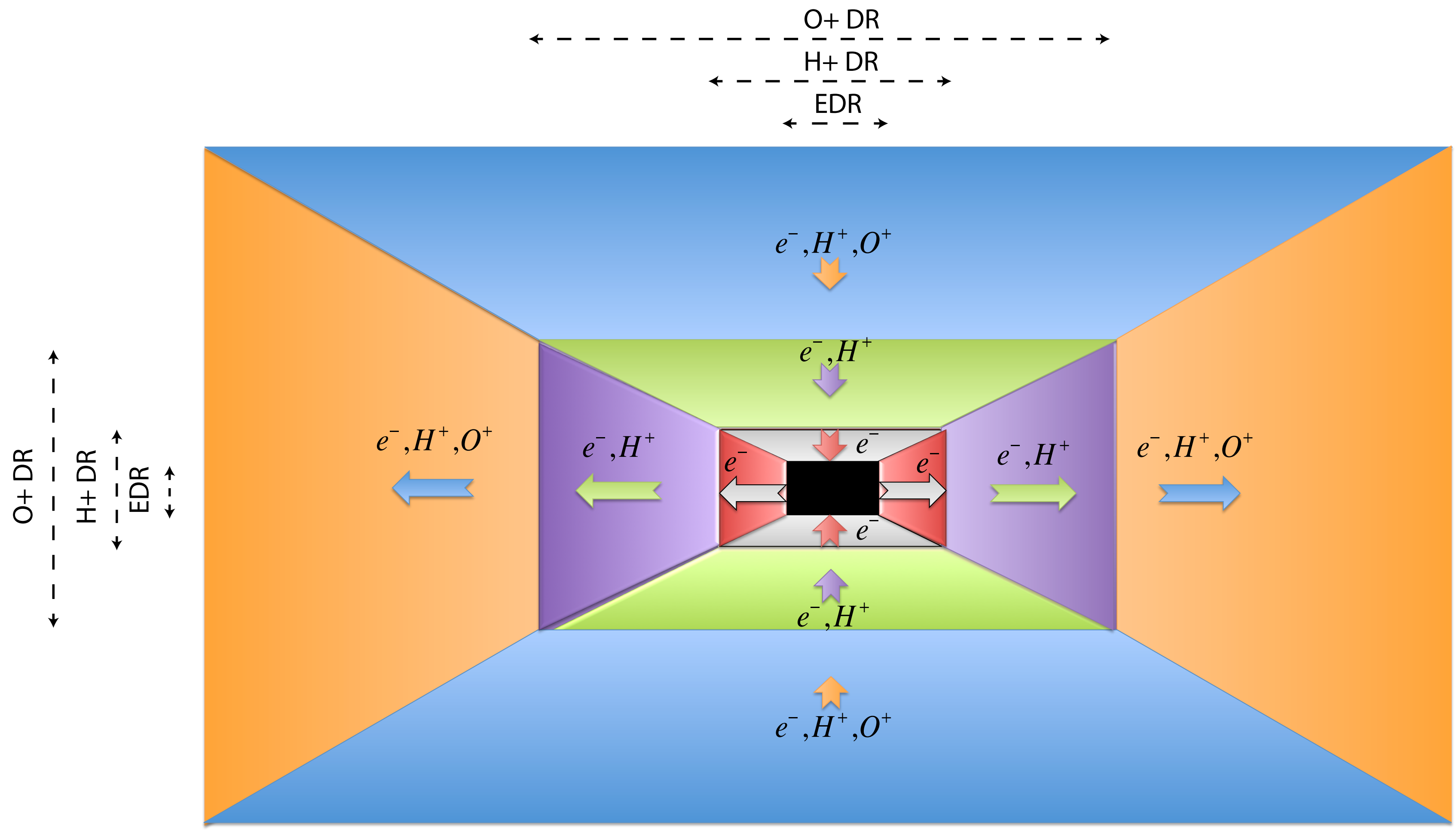




2.5D PIC three-species simulation

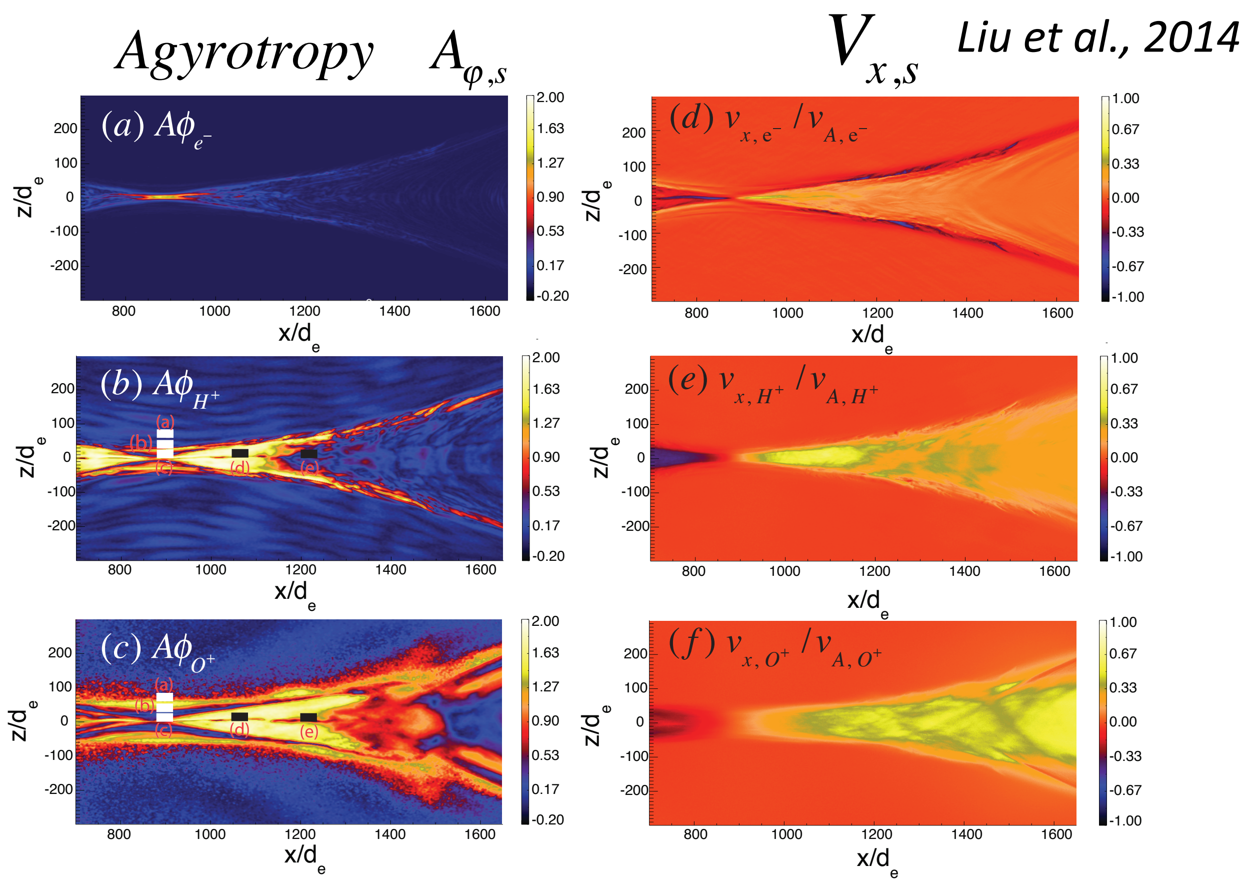


The nested three-scale diffusion region



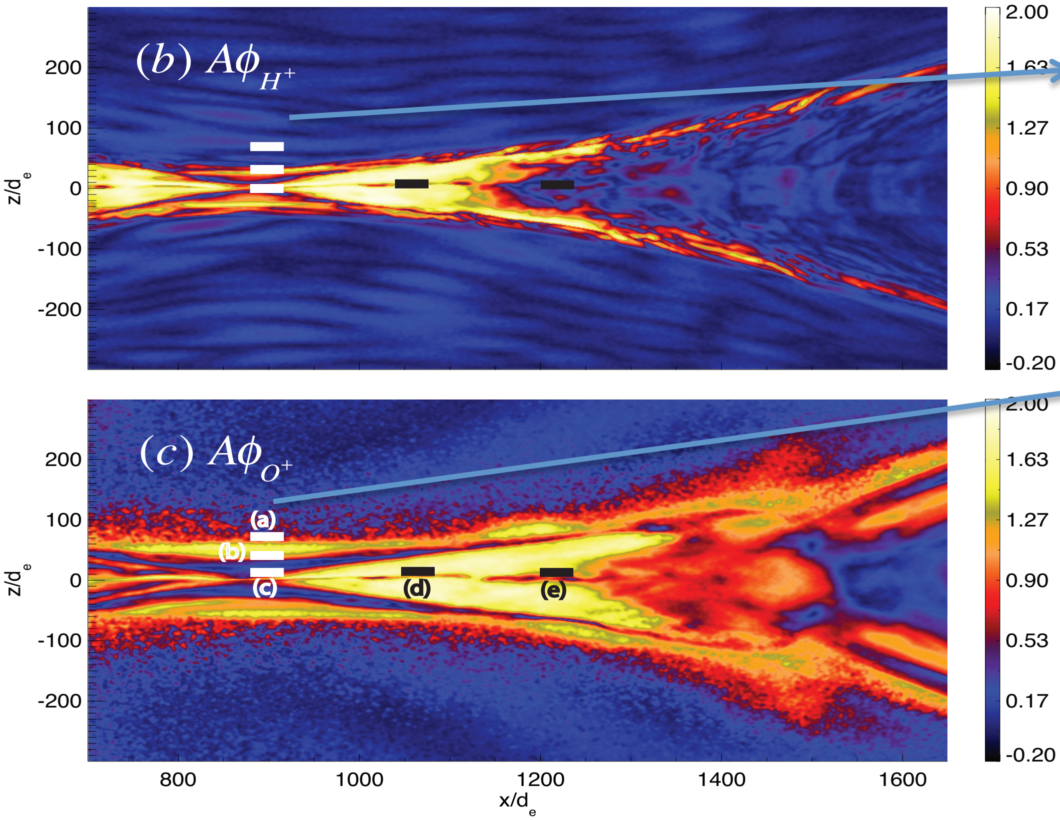
Liu et al., 2014

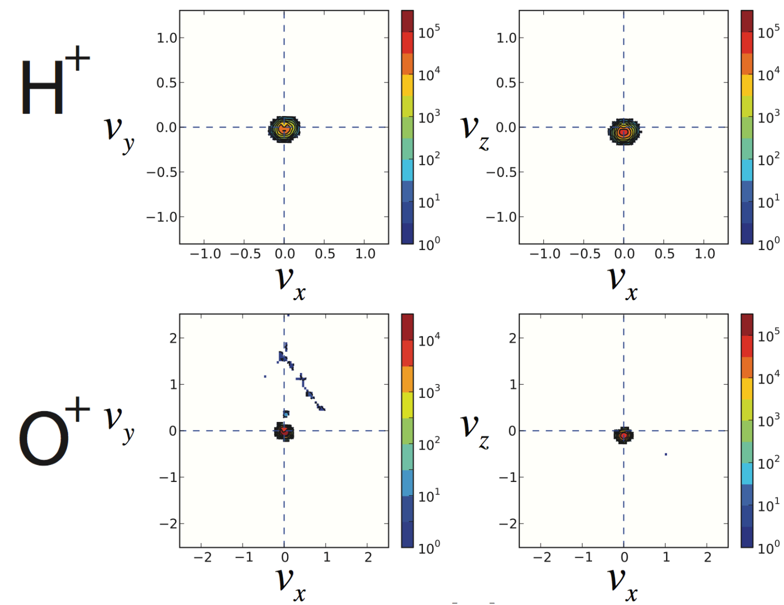
Three-scale diffusion region



$$A_{\phi,s} = \frac{2\left|P_{\perp 1,s} - P_{\perp 2,s}\right|}{P_{\perp 1,s} + P_{\perp 2,s}} \in [0,2]$$ *Scudder and Doughton, 2008*

Signature of demagnetization for H^+ and O^+ along the inflow direction



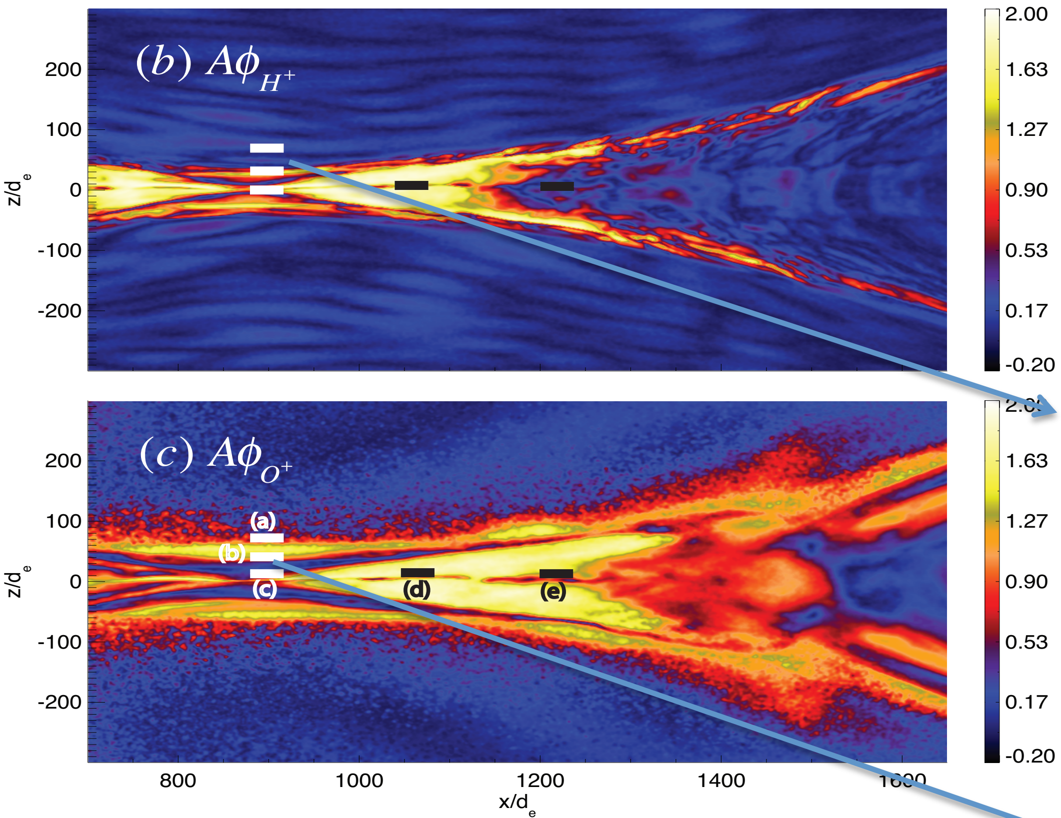


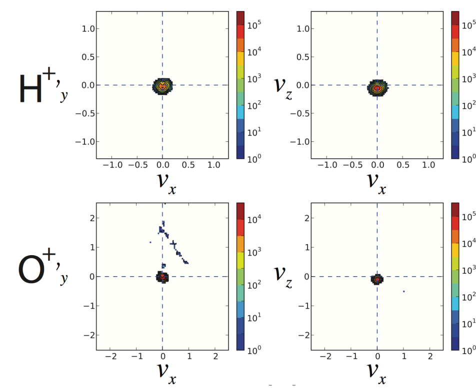
H^+ inflow region

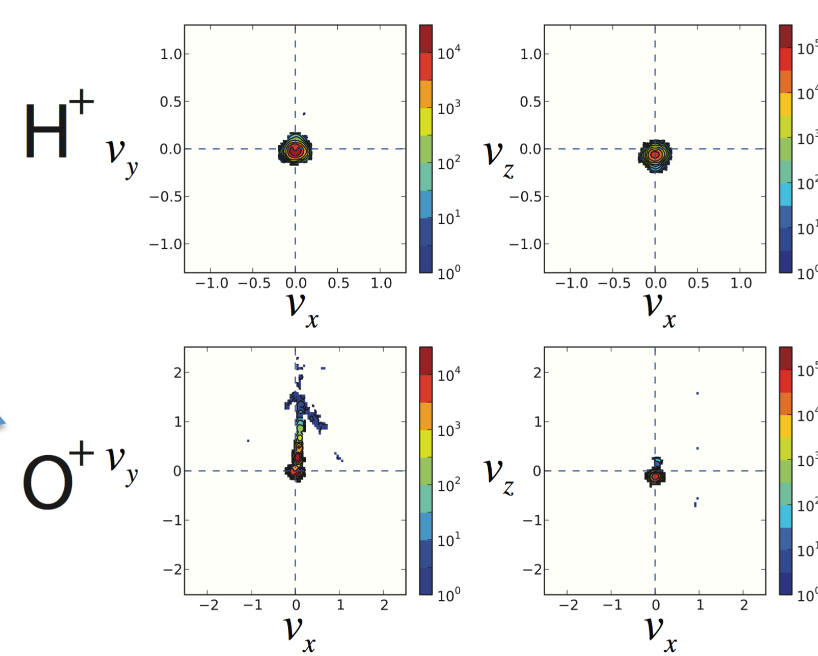
O^+ inflow region

Liu et al., 2014

Signature of demagnetization for H^+ and O^+ along the inflow direction





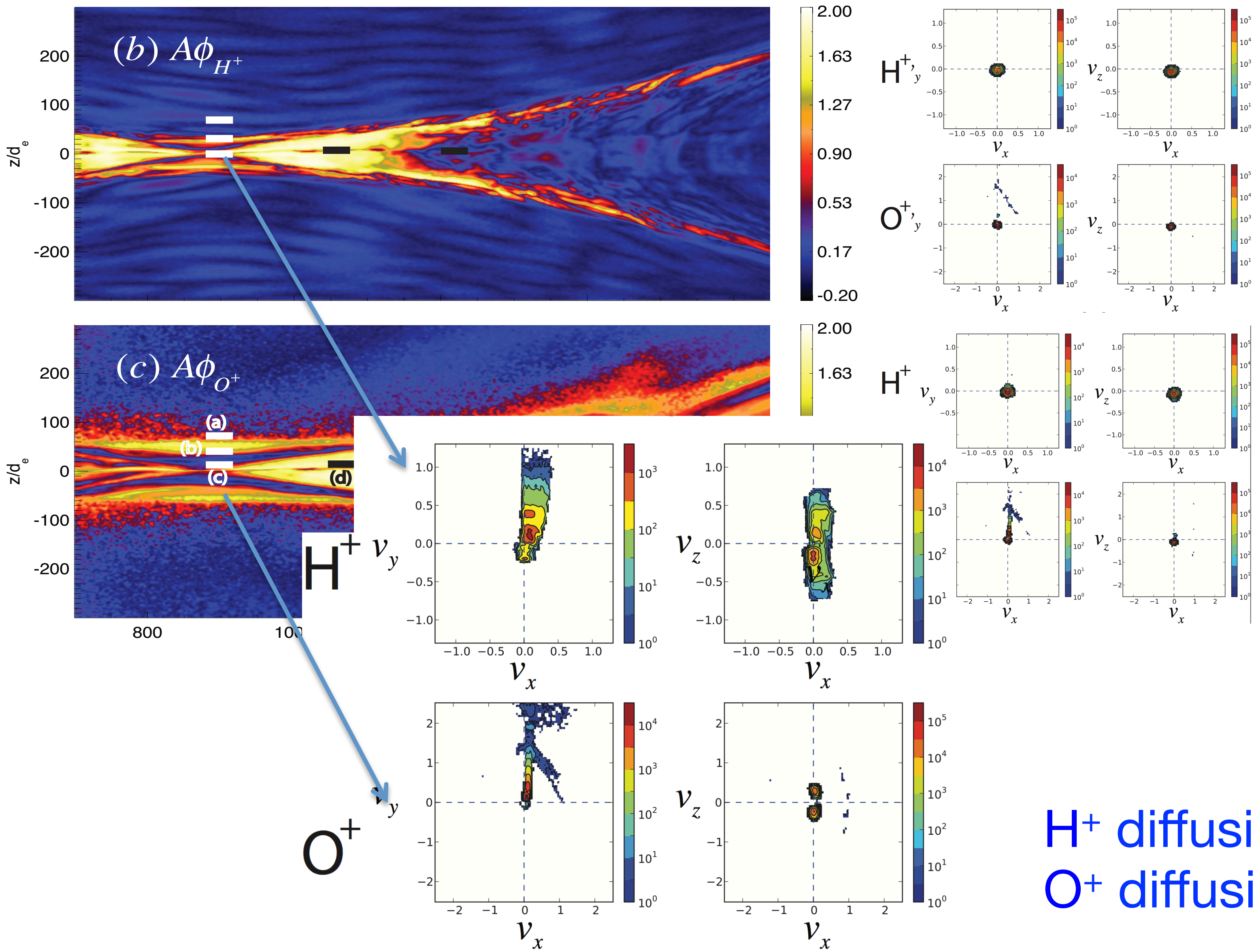


H^+ inflow region

O^+ diffusion region

Liu et al., 2014

Signature of demagnetization for H^+ and O^+ along the inflow direction

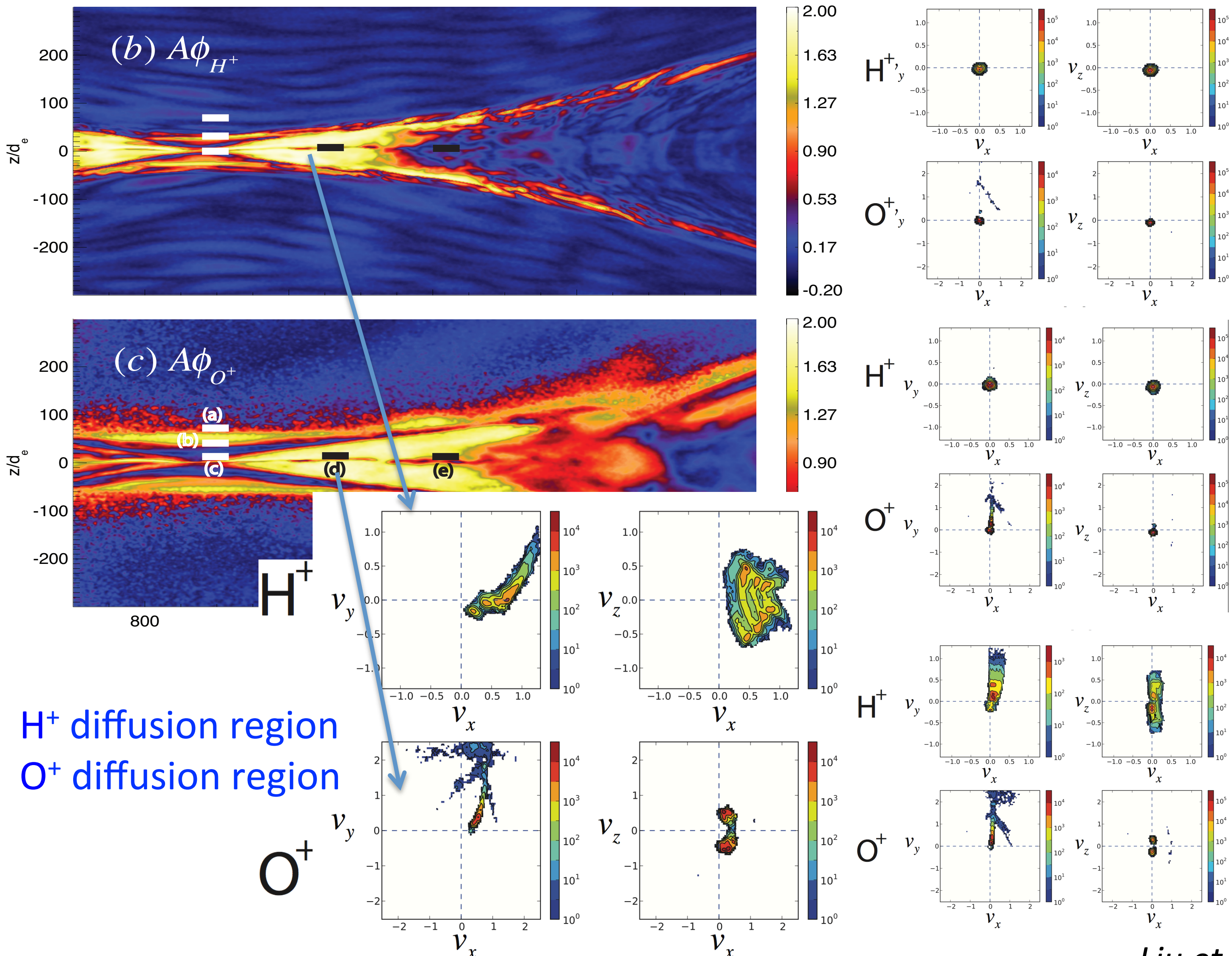


H^+ diffusion region

O^+ diffusion region

Liu et al., 2014

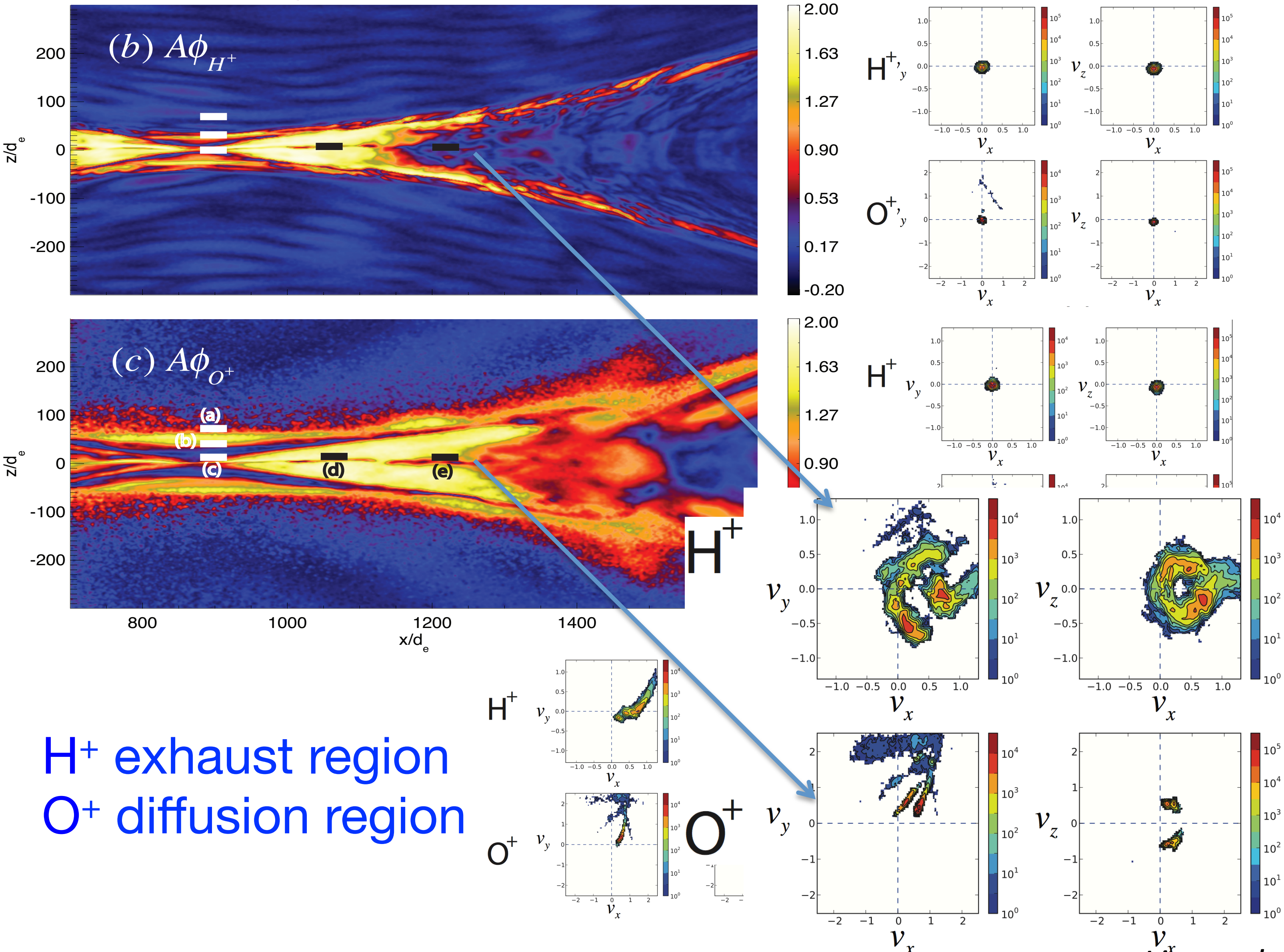
Signature of demagnetization for H⁺ and O⁺ along the outflow, 'jet', direction



H⁺ diffusion region
O⁺ diffusion region

Liu et al., 2014

Signature of demagnetization for H+ and O+ along the outflow, 'jet', direction

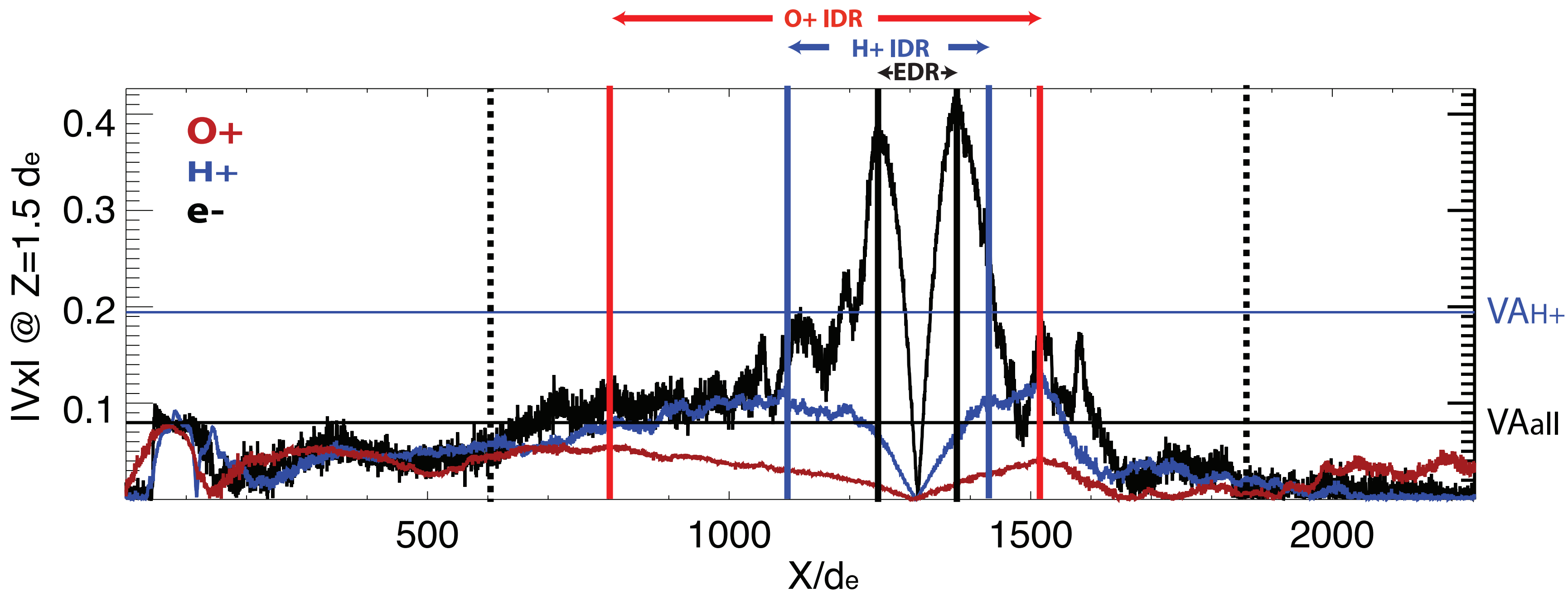


H^+ exhaust region

O^+ diffusion region

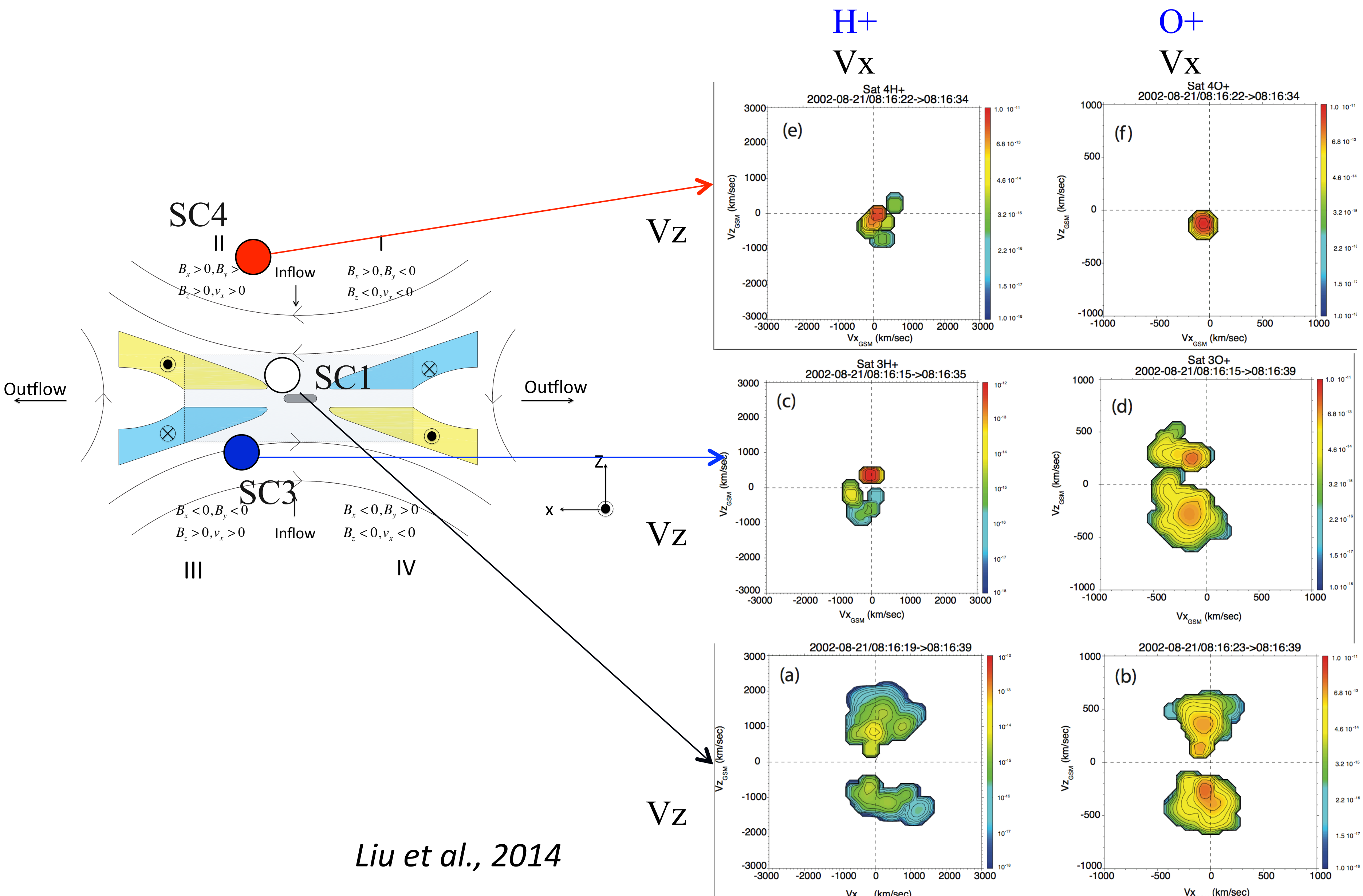
Liu et al., 2014

Acceleration in three-scale diffusion region



- Each species is accelerated to a fraction of its Alfven speed in its own diffusion region

Multi-layer structure along inflow direction (2002-08-21 event)



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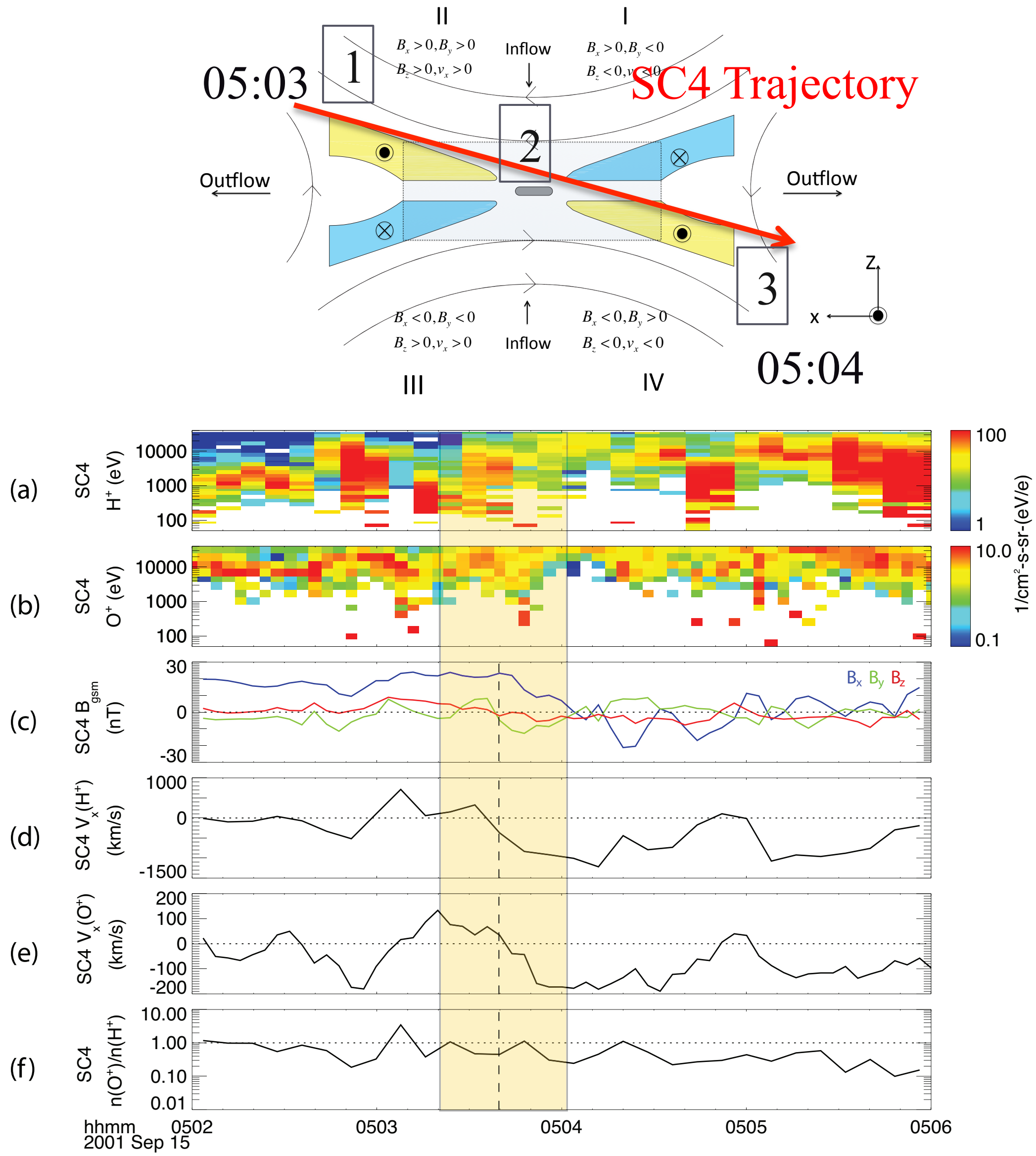
Multi-layer structure along outflow direction



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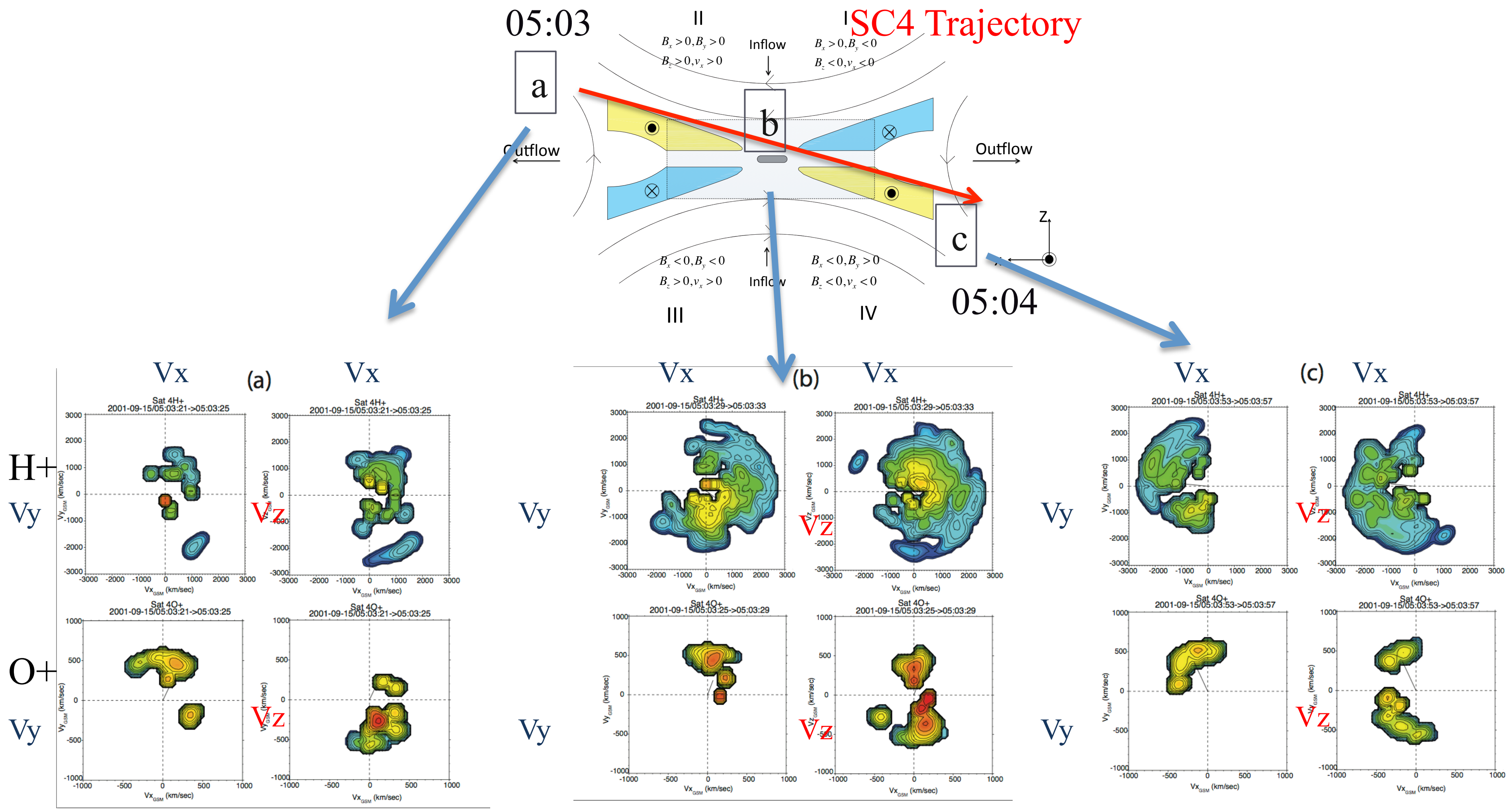
Multi-layer structure along outflow direction



- Both H^+ and O^+ observed the fast flow reversal.
- The clearer counter-streaming pattern is observed by O^+ for its longer diffusion region.

Liu et al., 2014

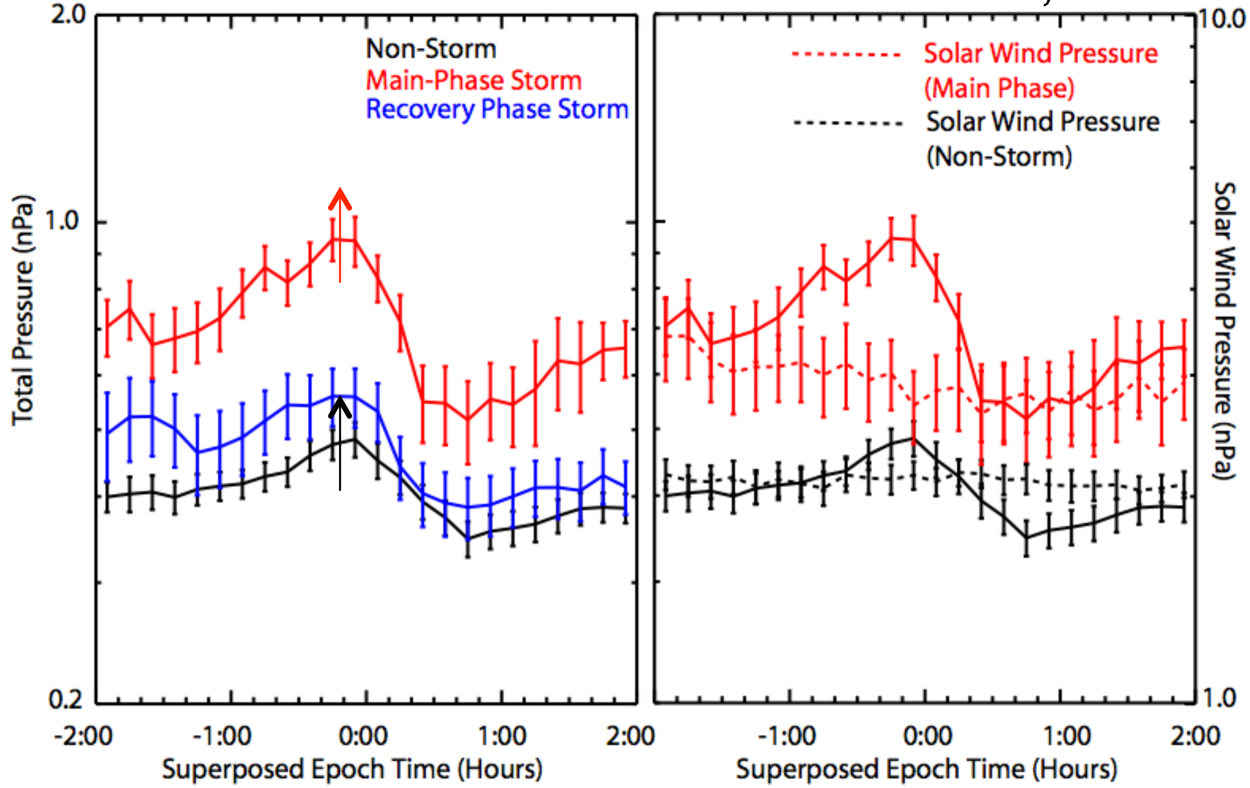
Implications of O^+ in reconnection from the simulation perspective

In the cases considered here, was found that O^+ can:

- reduce the number and repetition frequency of secondary islands,
- broaden and intensify the quadrupole magnetic structure,
- slow down the coalescence process and
- modify the composition of the ion current carriers.

Tail pressure around substorm onset

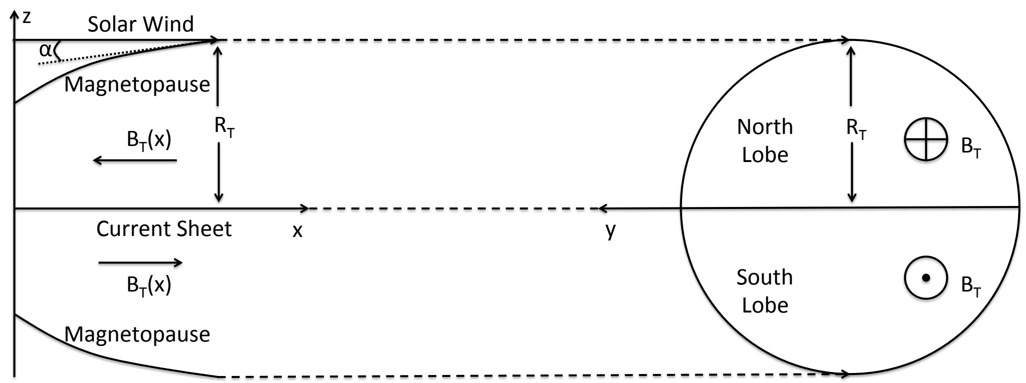
Kistler et al., 2006



Are the results

- due to Internal O^+ Effect or External Solar Wind Effect?

Normalizing the solar wind pressure



Pressure balance at the magnetopause is given by:

$$\rho u_{SW}^2 \sin^2 \alpha + p_{thermal} = p_{tot}$$

With $\rho u_{SW}^2 >> P_{thermal}$

Solving for the flaring angle function gives

$$\sin^2 \alpha = \frac{p_{tot}}{\rho u_{SW}^2}$$

However, the solar wind effect on tail flaring is nonlinear and the flaring angle also depends on the measurement location (Petrinec and Russell, 1996)

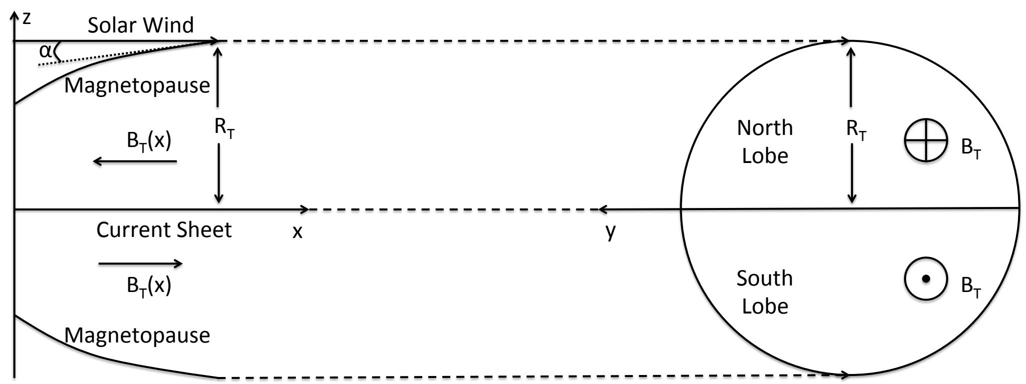
$$\sin^2 \alpha^* = \sin^2 \alpha \frac{0.19}{(\rho u_{sw}^2)^{-0.524} e^{0.085x}}$$

Normalization Removes:

- ✓ Solar wind pressure effect
- ✓ Difference due different measurement location

Liu et al., 2013

Tail magnetic flux estimation



Pressure balance at the magnetotail:

$$P_{tot} = P_{Lobe} = \frac{B_{Lobe}^2}{2\mu}$$

Solving for the lobe average field

$$B_{Lobe} = (2\mu P_{tot})^{1/2}$$

The magnetotail radius is calculated with our modified PR96 model by using the in-situ measured flaring angle:

$$R_T(t, \alpha_x)$$

magnetic flux in one semicircular cross section :

$$F_T = \frac{1}{2} B_{Lobe} \pi R_T^2(t, \alpha_x)$$

Liu et al., 2013

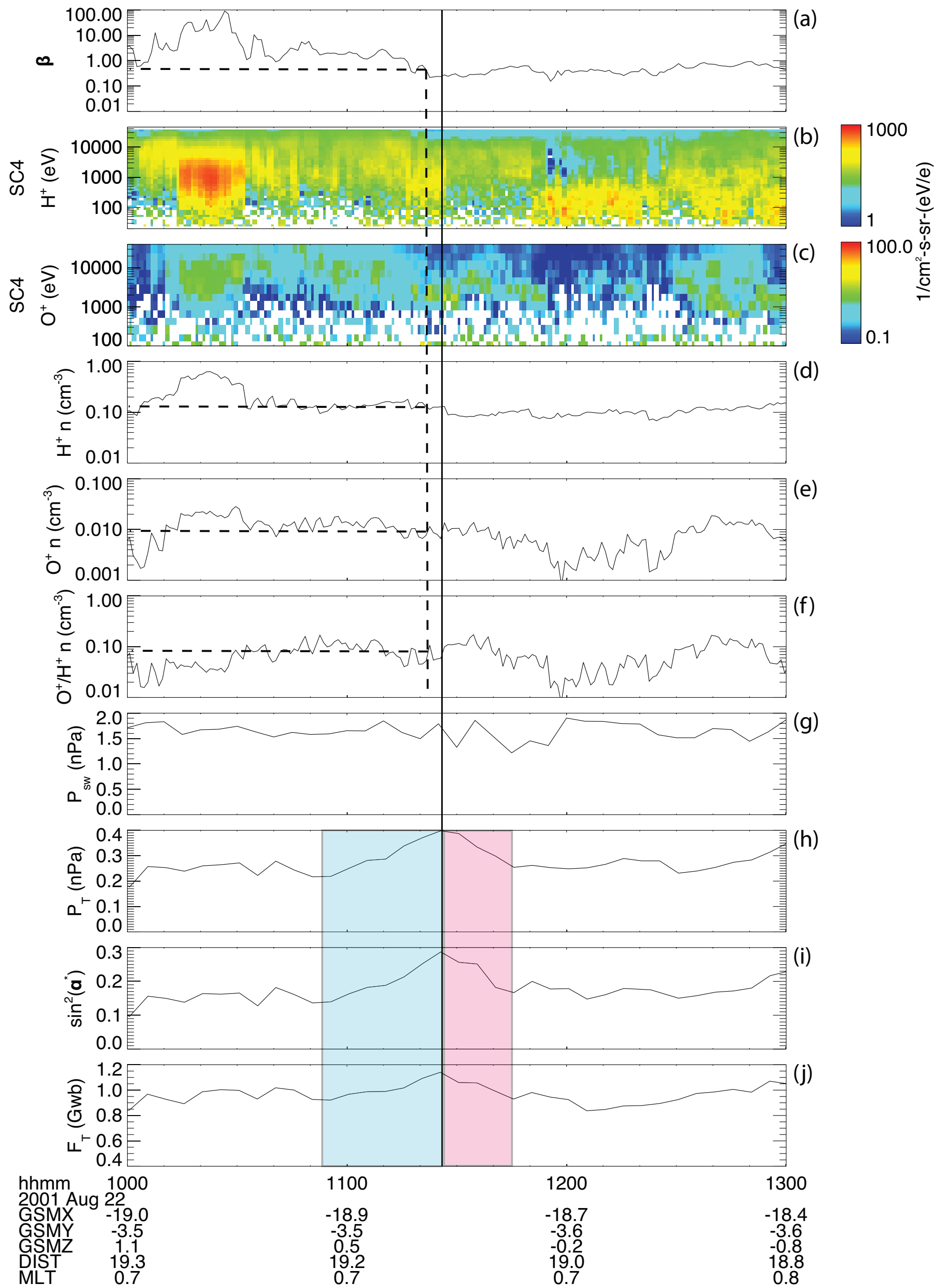
Statistical study example event

- **Data Selection:**
  - Identify the substorm onset
  - Identify the growth phase and expansion phase
  - Identify the nearest plasma sheet encountering in pre-onset time
    - Search back time until the criterion is satisfied.
  - Record the plasma sheet pre-existing ions density and density ratio.
- **Statistical Parameters:**
  - Tail stability threshold:

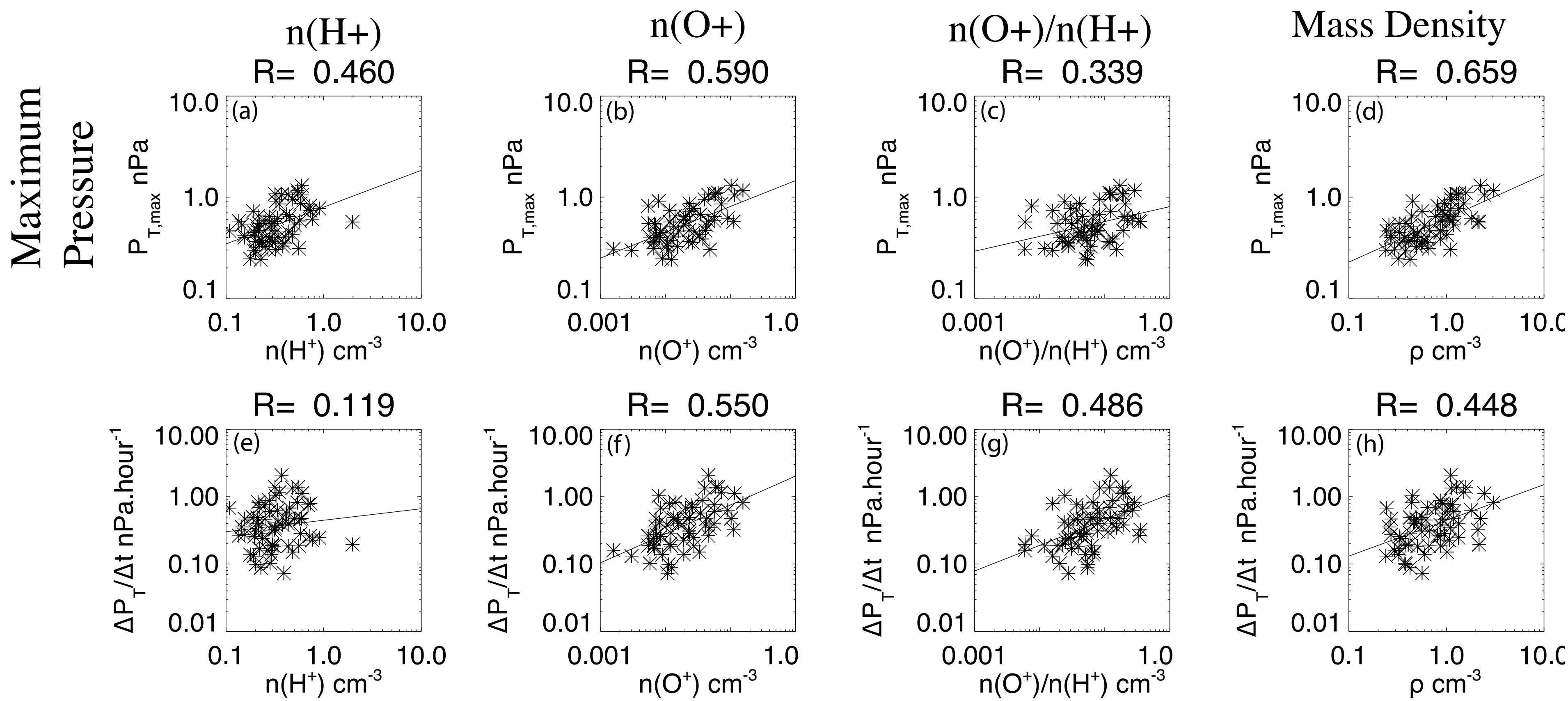
    $P_{\max}$ $\sin^2 \alpha^*_{\max}$ $F_{T,\max}$
  - Unloading rate:

    $\frac{\Delta P}{\Delta T}$ $\frac{\Delta \sin^2 \alpha^*}{\Delta T}$ $\frac{\Delta F_T}{\Delta T}$
  - Plasma sheet ion parameters:

    $n(H^+)$, $n(O^+)$, $n(O^+)/n(H^+)$ and mass density $n(H^+)+16*n(O^+)$



Pressure correlations



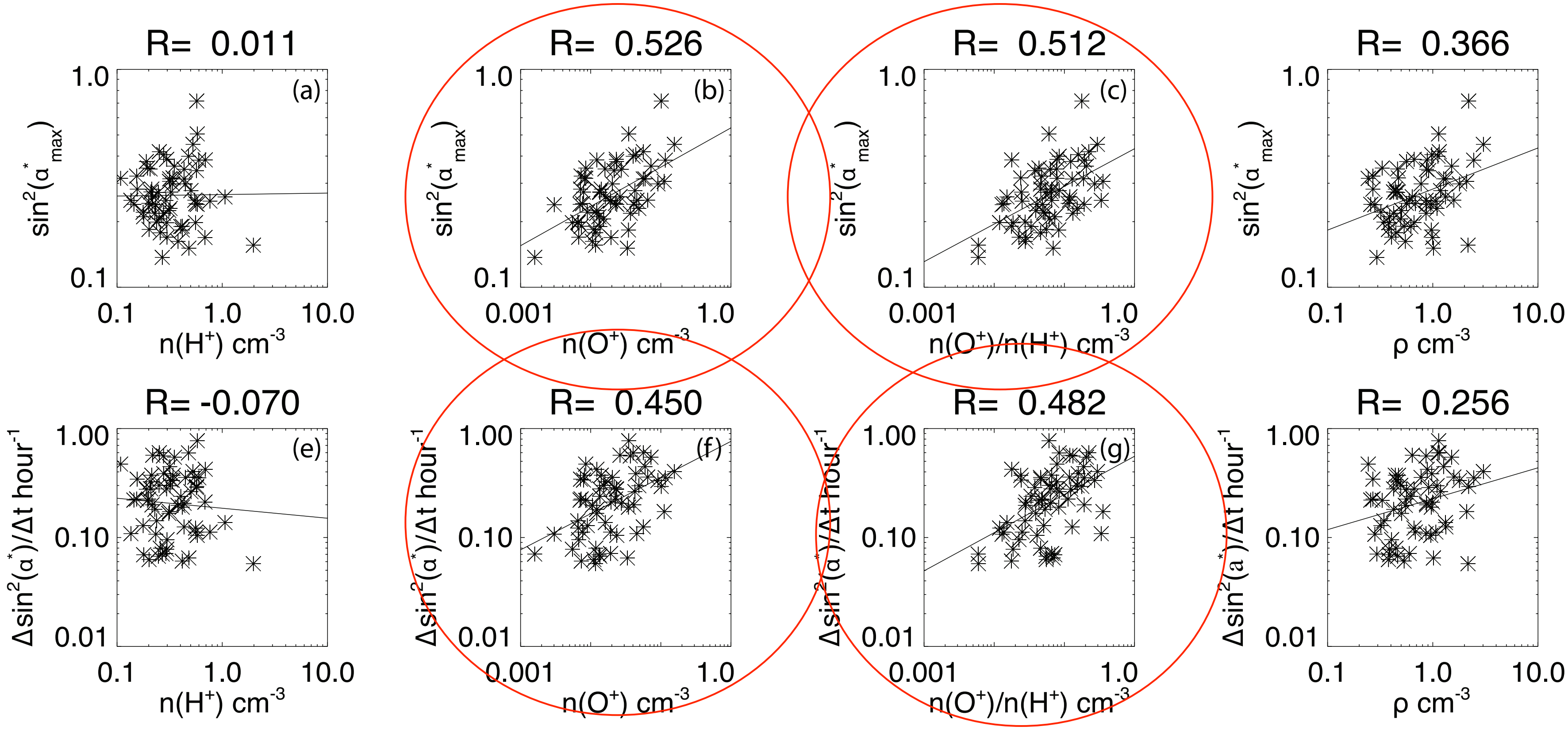
- n(O+) ↑
- n(O+)/n(H+)
- Mass density

➡

- Maximum Pressure ↑
- Pressure Decrease Rate

Liu et al., 2013

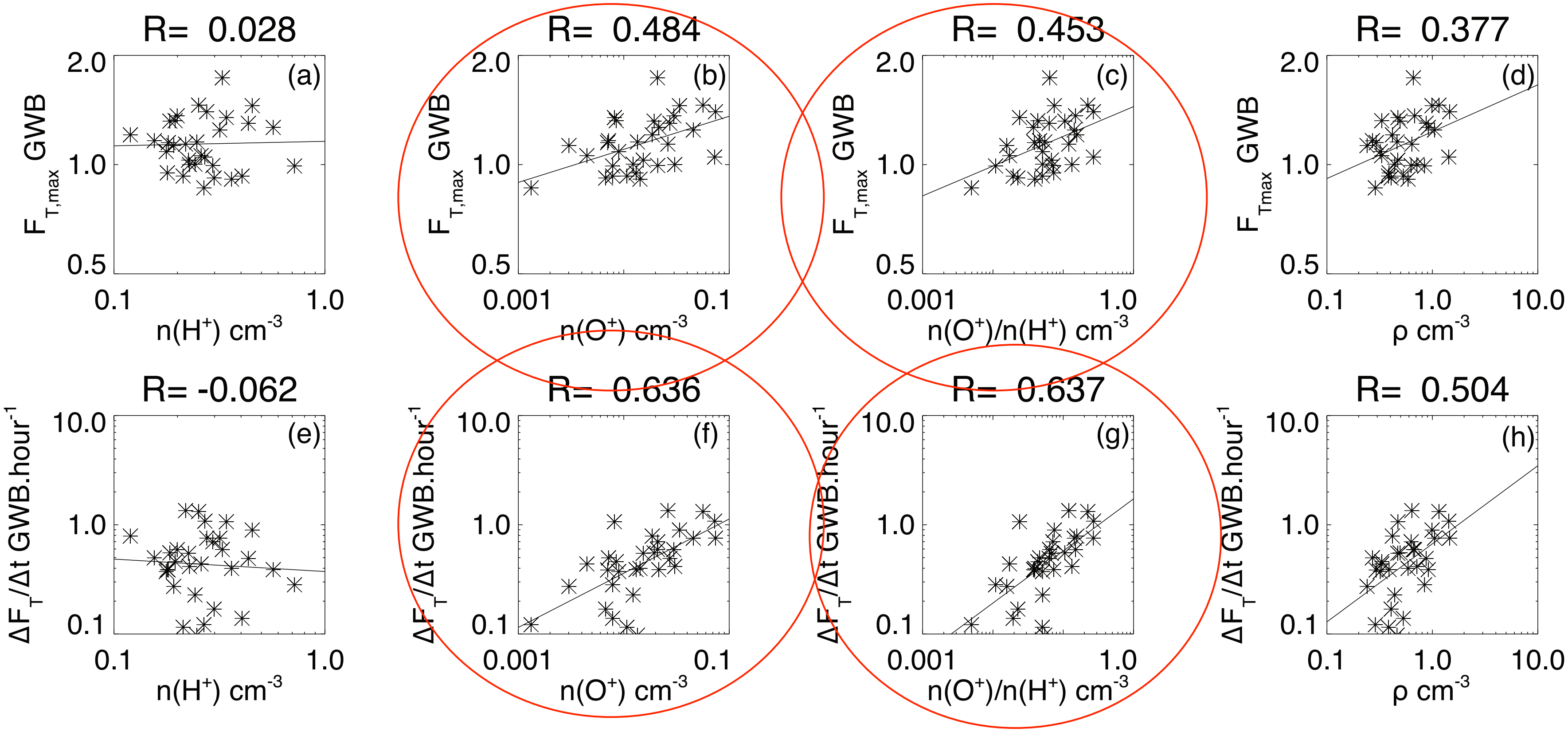
Flaring angle – Normalized tail pressure



- There is still a positive correlation in the stability threshold and the rate of unloading with
  - O+ density
  - O+/H+ density ratio

Liu et al., 2013

Magnetic flux



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Liu et al., 2013

Global scale summary

- After normalization for the effects of the solar wind pressure and the different locations in the tail, we find that both the maximum accumulated flux and the unloading rate are positively correlated with the O+ density and the O+/H+ density ratio.

- These results suggest that the higher O^+ content of the plasma sheet makes it harder to trigger a substorm onset. However, once it is triggered, the unloading proceeds faster if the O^+ content is higher.

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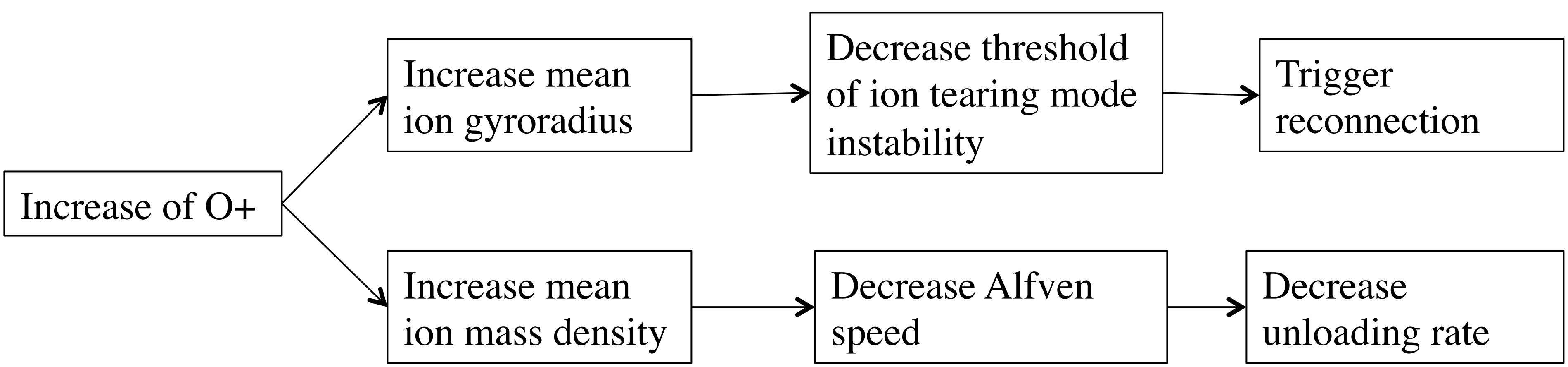

Summary

- The reconnection process in the Earth's magnetotail should be approached as a three-species plasma which introduces an additional larger scale length

- Yet, the effect on the reconnection rate and especially on the global dynamics is still unclear

- Statistical study showed that higher pre-onset O+ density in the plasma sheet correlates with a higher pressure build up before substorm onset and with a faster unloading rate during the substorm expansion phase

- However, it is not clear if this is the result of the mere presence of O+ or of the driving of the system or of reconnection over a broader region as in the case of "Sawtooth" events (Liao et al., [2014]).

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