Comparison of methods to determine the reconnection rate and the application on Magnetopause reconnection

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Abstract

It is still an open question whether and how the heavy ions may affect the reconnection rate. We first analyse data from a symmetric anti-parallel 3-species (e^-, H^+ and O^+) PIC simulation, and we clarify that each species is accelerated to the same ratio of its own VA, while the reconnection rate normalized by the combined VA represents the property of the system. Next we compare the reconnection rate in the simulation calculated with different methods to find out the spatial validity of each method. Using the conclusions from the simulation analysis, we apply the different methods to three dayside high latitude (GSE(2.8, 9.9, 6.3) R_E) magnetopause crossings observed by Cluster, though the presence of the asymmetry and the guiding field have not been considered. Results from the different methods can be comparable, however, the temporal magnetopause motions, etc. still provide much uncertainty to the reconnection rate estimation.

Introduction

Simulation *(units are normalized by: length-d_e , speed-c)*

- Fully kinetic PIC simulation with open boundaries[1];
- Domain: X[0, 2236] x Z[-1118, 1118], last step $t*\Omega_{ci}$ ~319, X-line ~(1310, 1);
- Three species with the mass ratios of m_H/m_e=50, m_O/m_e=500;
- Start from a Harris equilibrium, pure H+ current sheet, n_O/n_H=0.6 background;
- Flushing effect[2]: As reconnection proceeds, the initial current carriers are ejected out and the system is dominant with the background particles;

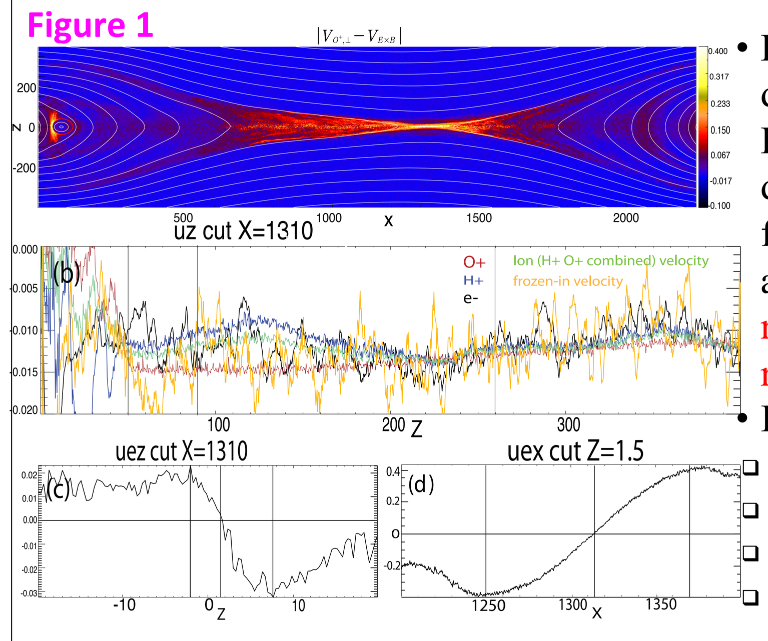
Methods to determine the reconnection rate (R)

- Definition: $\frac{d\Phi_B}{dt} \rightarrow \frac{\partial}{\partial y}=0$ assumption: $-E_y \sim V_{in}B_{in} \sim V_{out}B_{out}$
- Dimensionless R: with Lundquist number S
  - Sweet-Parker model: $\frac{V_{in}}{V_A}=\frac{1}{\sqrt{S}}$
  - Petschek model: $\frac{V_{in}}{V_A} \approx \frac{\pi}{8\ln S}$
  - R turns out to be around 0.1
- Continuity of Ey: $R \sim \frac{E_y}{V_A B_{in}} = \frac{B_{out}}{B_{in}} \cdot \frac{V_{out}}{V_A} = \frac{B_{out}}{B_{in}}$ only when $V_{out} \sim V_A$

Reconnection rate calculation from simulation

Inflow and diffusion region

Figure 1

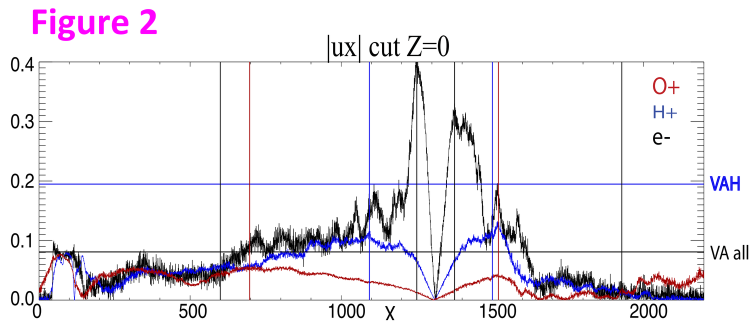


- High energy particles can be demagnetized first (Z~90 (260)) for H^+ (O^+)) without significantly deviating the bulk velocity from the frozen-in speed (Z~50 for both H^+ and O^+). V_{bulk} within the diffusion region up to ~10 *di* might still represent inflow velocity.
- Electron diffusion region
  - upstream edge: sudden decrease of uz
  - downstream edge: ux peaks
  - around [1250, 1370] x [-2, 8].
  - Upstream edge for inflow V_{bulk}: Z~20

Table 1	e^-	H^+	O^+	all
VA	0.7443	0.1944	0.0812	0.0804
V_{max}/VA	0.5204	0.5715	0.6121	Vo-ion/VA
V_{out}/VA_{all}	0.5261	0.6667	0.4863	0.5871

- Alfven velocity: upstream edge of species-dependent diffusion region.
- Each species is accelerated to the same ratio (~0.6) of its own upstream Alfven speed; The ratio might be dependent on the simulation model[3];
- Outside the whole diffusion region, all species approach to the same ratio (~0.6) of the combined Alfven speed;

Figure 2



Reconnection rate results in the simulation

Table 2

Methods (combined VA & diffusion region)	R
Vin/VA (normalized V)	0.144
$\frac{B_{out}}{B_{in}} \cdot \frac{V_{out}}{V_A}$ (normalized B)	0.163
Upstream Ey/VA/B_{in} (normalized Ey)	0.146
EDR Ey/VA/B_{in}	0.117

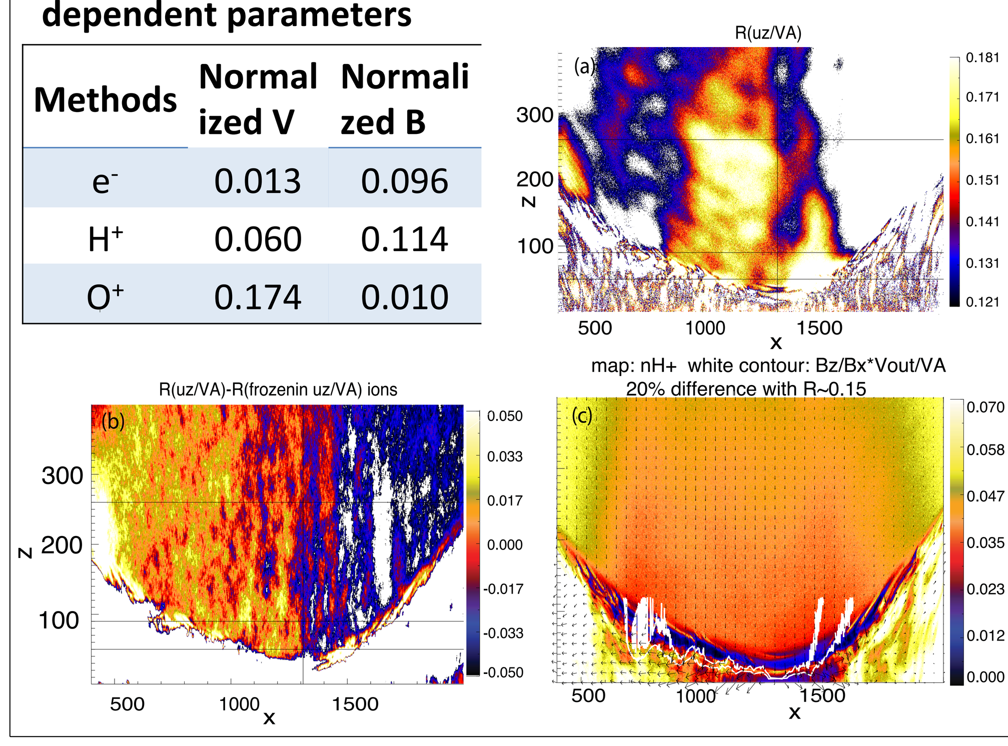
- R~0.15
- With VA and diffusion regions determined from combined species, three methods match well;
- 'Normalized Ey' in the electron diffusion region (EDR) matches species-dependent 'normalized B', however, they do not match 'normalized V' (compared with Table 3).

Reconnection rate spatial distribution

Table 3
R determined with species-dependent parameters

Methods	Normalized V	Normalized B
e^-	0.013	0.096
H^+	0.060	0.114
O^+	0.174	0.010

Figure 3

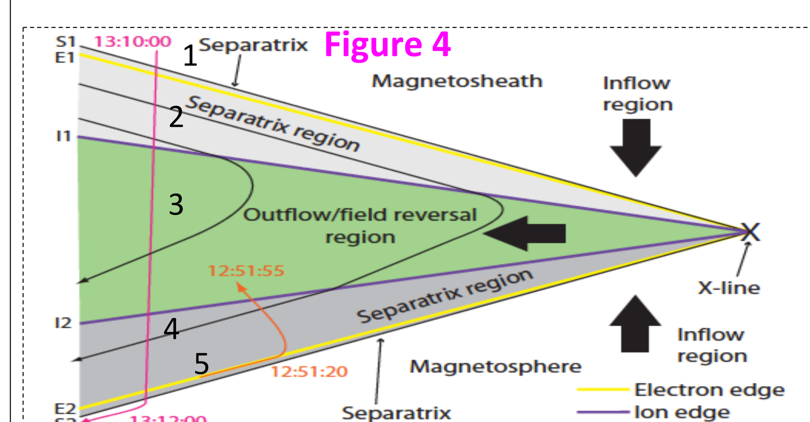


Comparison among methods

- Ideal
  - Bz/Bx along the inner side of the separatrix region;
  - *Vin/VA_{H+}, combined ion velocity or frozen-in velocity* as Vin, along the horizontal center further than ~10 *di*
- Comparable
  - *Vin/VA_{H+}* upstream to separatrix – larger
  - *Vin/VA_{H+}* H^+/O^+*Vin*, between O^+/H^+ diffusion region edges – minor deviation
  - *Vin/VA_{H+}* diffusion region without the density cavity – comparable

Cluster observation: dayside Magnetopause reconnection on January 4, 2004

Figure 4



Configuration[4]
Numbered intervals in Fig. 5a are superimposed on Fig. 4, where the separatrix (S) region on the Magnetosphere (Msp) side is divided into the regions with/without (4/5) magnetic field enhancement.

Identification of regions (Fig. 4)

- **Separatrix region, Msh side:**
  1. anti-parallel electrons (Fig. 6a);
- **Ion edges (solid vertical lines in Fig. 5):**
  1. B reversal; 2. ion jet;
  3. Mixed ions of both sides;
- **Separatrix region, Msp side:**
  1. density gradient; 2. density cavity (Fig. 5e);
  3. Electron anisotropy (Fig. 6c).

  Mixed electrons on both sides exist within all the regions between separatrices.
- **Note**

  Msh ions are also present in S region on Msp side (Fig. 7b), which might be due to multiple X lines[4].

Figure 5

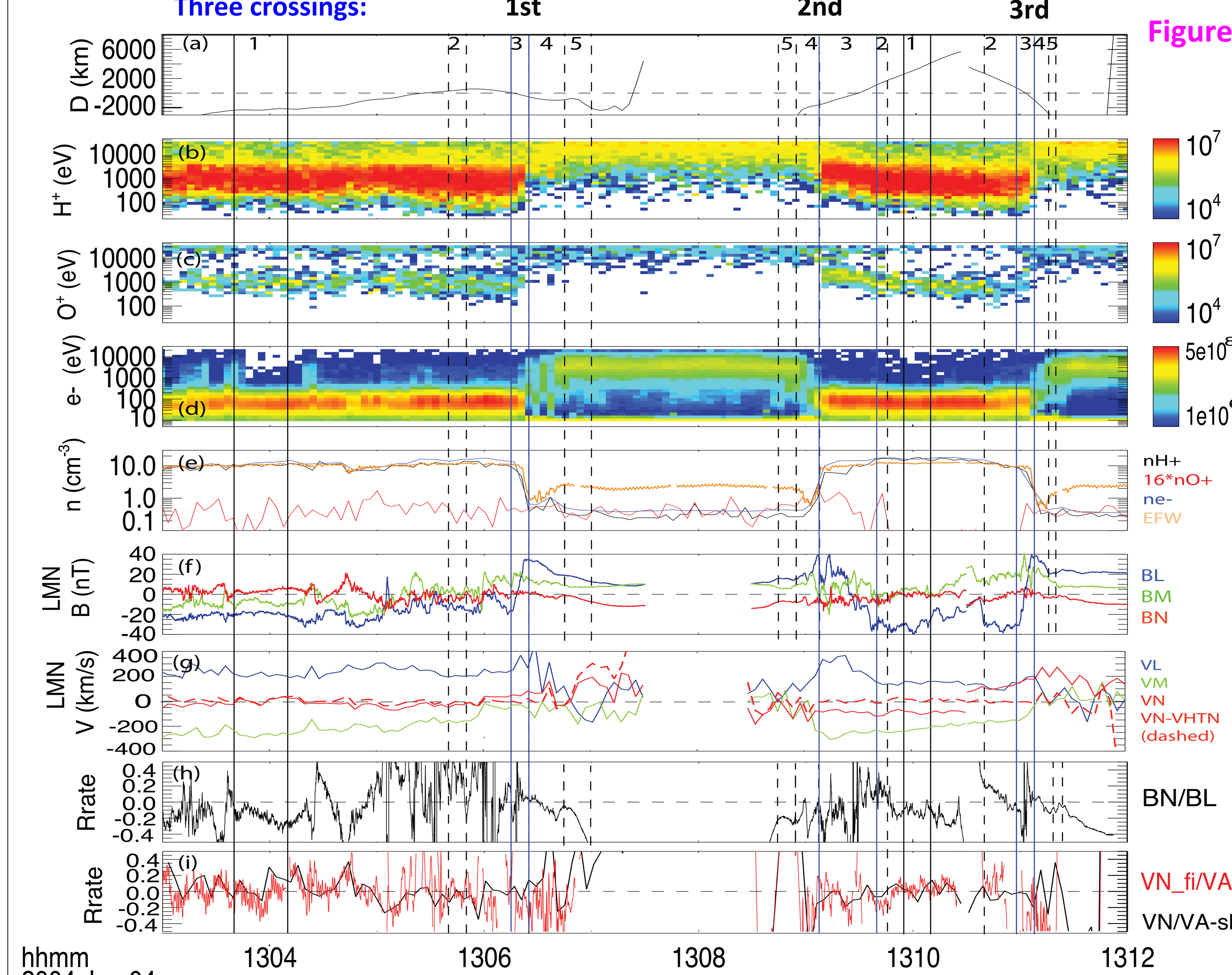


Figure 6

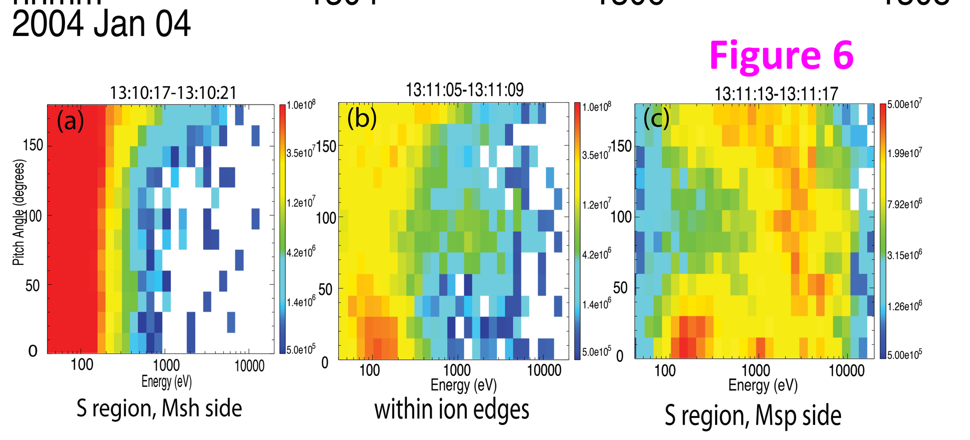
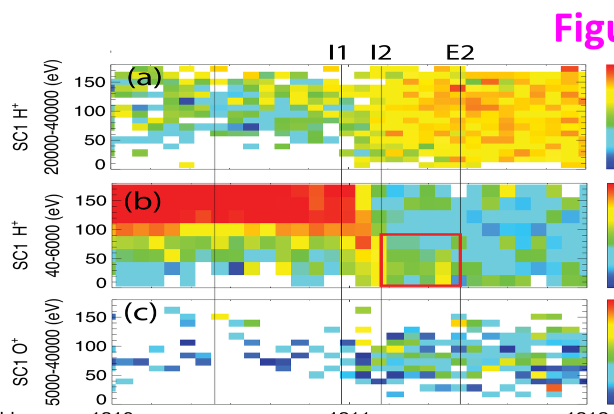
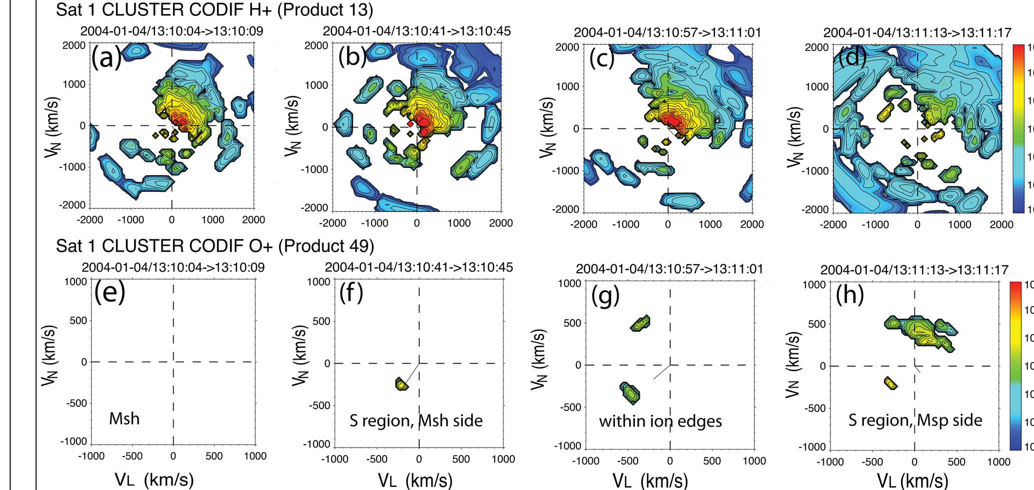


Figure 7



Possible involvement of O^+

Figure 8



VDF of O^+ (Fig. 8e-8h)

- inflow from the Msp side: evidence of the of heavy ions involvement;
- Different VDF structure: indication for different regions.

Reconnection rate estimation

Calculation of reconnection rates

- **Determine LMN coordinates**
  - Change due to temporal motion of MP: $\widehat{n_3}$ is 30 (60) degrees different with $\widehat{n_2}$ ($\widehat{n_1}$)
- **Calculate VA:** use the mass of H^+, averaged over Msh interval (labeled with '1')
- **Calculate Magnetopause motion**
  - Local normal V_{HT}, check with integrated distance to the reconnection site (Fig. 5a)
- **Obtain inflow velocity (Vin) (Fig. 5g):**
  - V_N-V_{HTN}
  - Inflow signatures extend to S region on Msh side (Fig. 8b): asymmetry, no density cavity on Msh side.
- **Obtain frozen-in inflow velocity (Vfi)** $(\frac{E\times B}{B^2}+V_{\parallel})_N - V_{HTN}$
- **Calculate R: B_N/B_L, Vin/VA, Vfi/VA (Fig. 5h-5i), take the average in the chosen intervals**

Table 4: Results for three crossings, good for Msh side, for Msp side

Methods	B_N/B_L			Vin/VA		Vfi/VA
T interval	S, Msh (2)	S, Msp, Bp (4)	S, Msp (5)	Msh (1)	S, Msh (2)	Msh (1)
1st	0.2636	-0.0637	-0.2628	0.0873	-0.0699	-0.0533
2nd	0.1334	-0.1707	-0.2127	-0.0066	-0.1002	0.0364
3rd	0.0709	-0.0034	-0.1094	0.0543	-0.0654	0.0414
Eval. Methds	Ideal	For Msp side	Not good	Ideal	Comparable	Ideal
Eval. Results	Good	Good for Msp	Not good	Not good	Reasonable	Not good

Ways to Evaluate values

- B_N/B_L should be positive & higher (negative & lower) on Msh (Msp) side;
- Vin/VA should be negative on Msh side.

Summary

- Considering only the contribution of Msh side inflow, R for these events is around **0.07-0.26**;
- B_N/B_L , assuming V_{out}~VA, is more reliable when crossing the separatrix;
- *Vin/VA* can be comparable;
- *Magnetic field enhancement* on the Msp side might be a good representation of S region;
- Vin/VA & Vfi/VA in Msh intervals
  - Expected to be comparable or slightly higher than real values;
  - Possible reason for the failure: LMN coordinates might be only locally valid.

Summary & Discussion

- Symmetric simulation shows that in the diffusion region, each species is accelerated to the same ratio of its own Alfven speed. The reconnection rate (R) normalized by the combined VA represents the reconnection efficiency of the system, while R normalized by species-dependent VA represents the behavior of each species.
- The accuracy of each method to determine R has spatial dependence. B_N/B_L is reliable along the separatrix region, but there might be an extra scaled factor of V_{out}/VA if V_{out} does not approach to VA; Vin/VA and Vfi/VA are good near the center along the direction perpendicular to the current sheet further than ~10 d_i, higher in upstream of the separatrix.
- In dayside Magnetopause reconnection, the temporary motion of the Magnetopause might have much effect on the estimation of R. The velocity in S region on Msh side might still represent inflow.

Future work

- Compare R etc. with asymmetric reconnection simulations with guiding fields, which can be better applied to Magnetopause observations. Also compare with the simulation without O^+ to find out how O^+ affects the motion of other species and contributes to the reconnection.
- Determine R including the contribution on Msp side. Test more Magnetopause reconnection events with different levels of O^+ to see how and how much the heavy ions are involved in the reconnection.

References & Acknowledgements

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