Electron heating during magnetotail reconnection: the heating coefficient and effects of unloading

Shan Wang[1] (shan.wang@wildcats.unh.edu), Li-Jen Chen[2], Christopher G. Mouikis[1], Lynn M. Kistler[1], and Guanlai Li[1]
[1]Space Science Center, University of New Hampshire, Durham, New Hampshire, USA
[2]NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

2015 GEM Workshop, Snowmass, CO, June 14-19, 2015

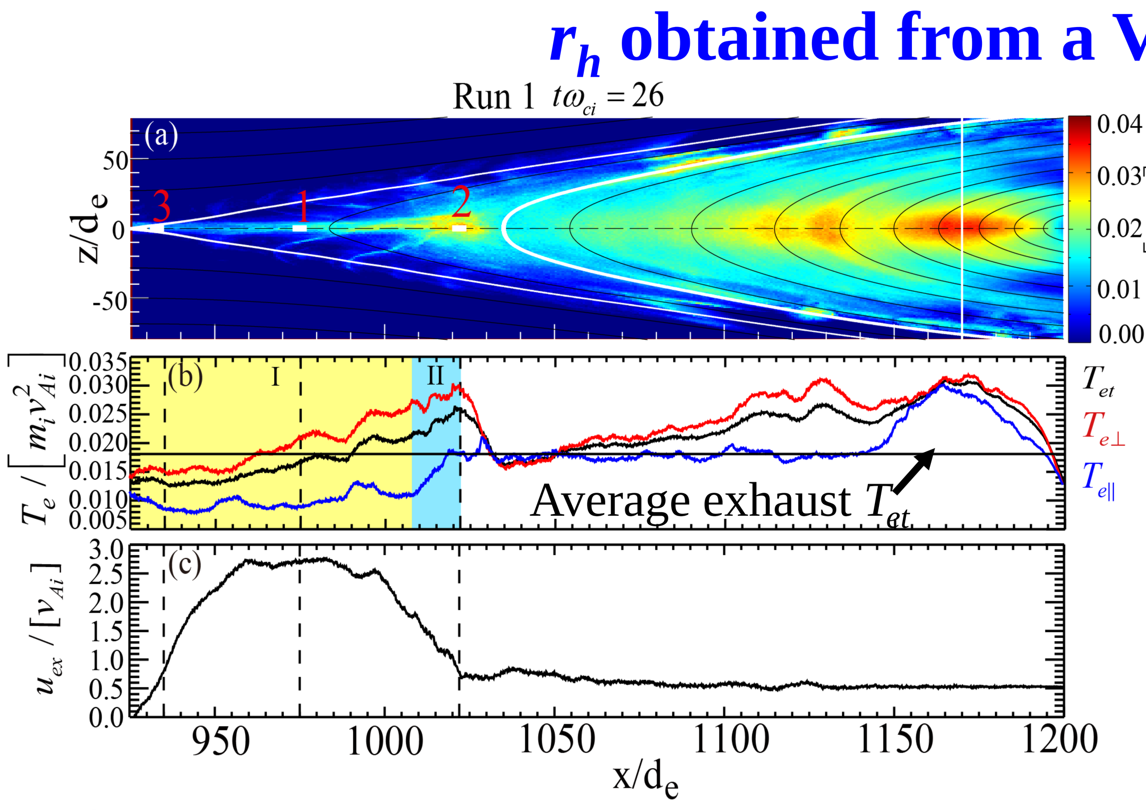
Abstract

We propose a velocity distribution function model based on the electron energization process in the electron diffusion region to obtain the electron bulk heating coefficient $r_h = k_B\Delta T_e/m_i v_{Ai}^2$, where ΔT_e is the temperature increase from inflow to outflow regions, and v_{Ai} is the inflow ion Alfvén speed. The derived r_h depends on the electron outflow speed and agrees with the particle-in-cell (PIC) simulation data within 20% of uncertainties. PIC analysis shows that r_h in symmetric reconnection with negligible guide field is around 2%-3%, increasing with time by ~30%-90% in $8\omega_{ci}^{-1}$. A statistical study of the electron heating in the Earth's magnetotail reconnection using Cluster observations is performed. Using the inflow parameters when the spacecraft crossed the reconnection exhaust regions, r_h is about 2.6%. A significant decrease of the magnetotail pressure during the substorm unloading phase can cause large variations in and uncertainties in estimating r_h. Normalized by the initial maximum $m_i v_{Ai}^2$, the lower limit of r_h is 1.5%.

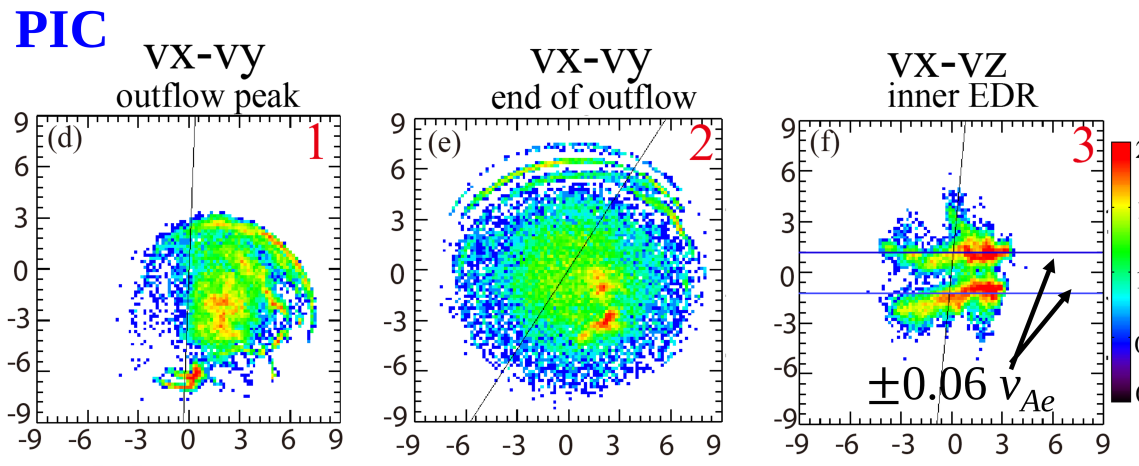
Motivation

- Electron bulk heating (ΔT_e) in reconnection was reported to be proportional to the upstream $m_i v_{Ai}^2$. The heating coefficient : $r_h = \frac{k_B \Delta T_e}{m_i v_{Ai}^2}$
  - 1.7% in the magnetopause observations [1]
  - 3.3% in symmetric reconnection simulations [2];
  - *observations/temporal evolutions are missing*.
- *Explanation for r_h is needed*
  - Energization mechanisms: EDR process, $\Phi_\parallel$, Fermi, ∇B drift.
  - Counter-streaming beams at v_{Ai} (Fermi acceleration): electron (ion) heating underestimated (overestimated) [3]
  - **We consider electron energization in EDR to obtain r_h**

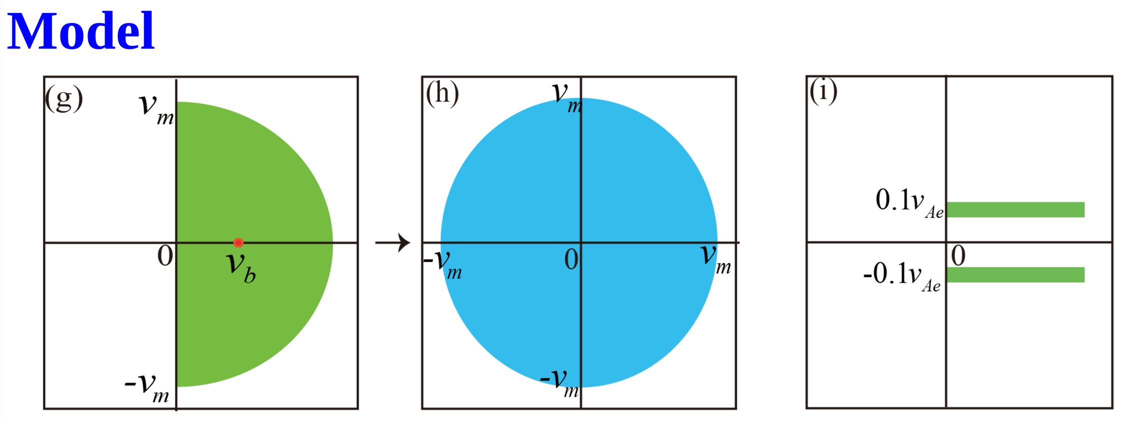
r_h obtained from a VDF model based on EDR physics



PIC



Model



T_e profile in EDR

I. $T_{e\perp}$ increases, $T_{e\parallel}$ stays low (B~B_z)

- EDR energization process: meandering motion+cyclotron turning by B_z [4]
- Points 1-2: range of $T_{e\perp}$; Point 3: $T_{e\parallel}$.

II. $T_{e\parallel}$↑: e⁻ mixture from X-line + from separatrix accelerated by $e\Phi_\parallel$

VDF model and r_h derivations:

1. Semi-circle in the v_x-v_y (perp) plane, uniform phase space density f;

$$n = \frac{\pi}{2} f v_m^2 \quad v_b = \frac{4}{3\pi} v_m \quad \text{Point 1: } v_b \sim 0.135\, v_{Ae}$$

$$T_{e\perp,semi} = \frac{m_e}{2n}\int_0^{v_m}\int_{-\pi/2}^{\pi/2} f\left[\left(v\cos\theta - v_b\right)^2 + v^2\sin^2\theta\right] v\,d\theta\,dv \approx 0.89 m_e v_b^2$$

2. Full circle in the v_x-v_y (perp) plane, uniform $f/2$ (n conserved);

$$T_{e\perp,full} = \frac{m_e}{2n}\int_0^{v_m}\int_0^{2\pi} \frac{1}{2} f v^3 d\theta dv \approx 1.38 m_e v_b^2$$

3. Two δ-functions at $v_z = \pm 0.1 v_{Ae}$ in v_x-v_z

$$T_{e\parallel} = T_z = m_e (0.1 v_{Ae})^2 = 0.01 m_i v_{Ai}^2$$

$\Delta T_e \sim T_e = (T_{e\parallel} + 2T_{e\perp})/3$

$$r_{h,semi} = \frac{T_{e,semi}}{m_i v_{Ai}^2} = 0.003 + 0.6\frac{v_b^2}{v_{Ae}^2} \qquad r_{h,full} = \frac{T_{e,full}}{m_i v_{Ai}^2} = 0.003 + 0.93\frac{v_b^2}{v_{Ae}^2}$$

$[m_i v_{Ai}^2]$	$T_{e\perp 1}$	$T_{e\perp 2}$	$T_{e\parallel 3}$
PIC	0.022	0.026	0.008
model	0.016	0.025	0.01

r_h, PIC	$r_{h,semi}$	$r_{h,full}$
1.8%	1.4%	2.0%

~20% r_h uncertainty

Temporal evolutions of r_h in PIC

Run.	m_i/m_e	B_g/B_0	n_b/n_0
1	400	0	0.05
2	400	0.03	0.05
3	1836	0	0.23
4	1836	0.05	0.23

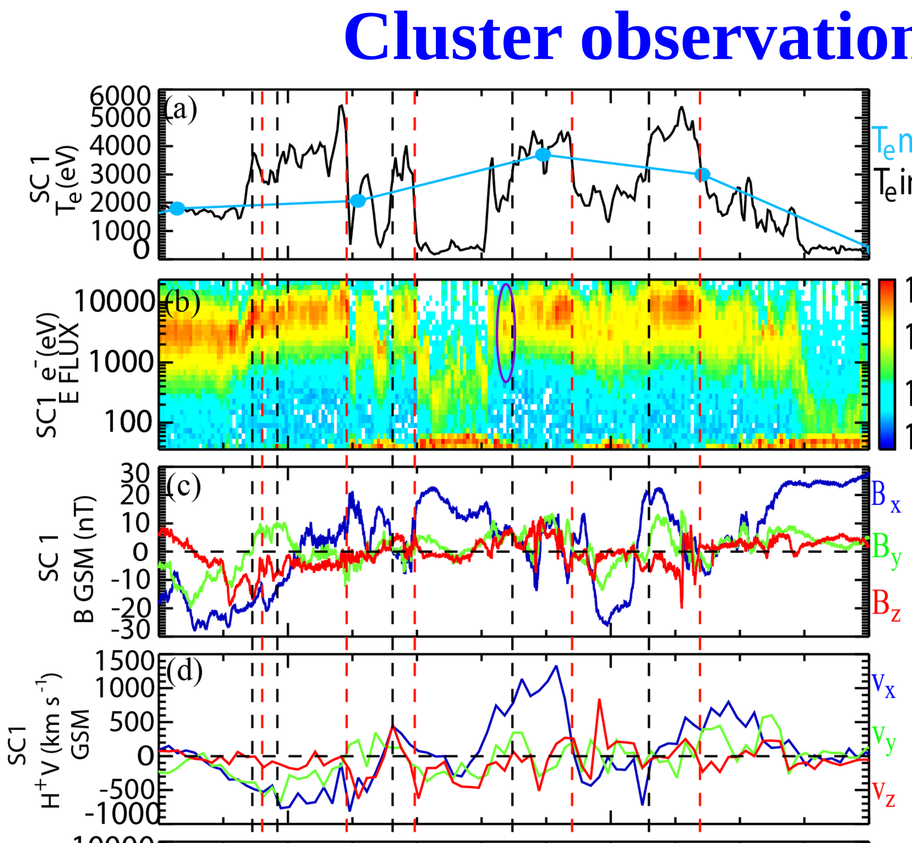
- Times: peak reconnection rate, and $8\omega_{ci}^{-1}$ later
- ΔT_e: average T_e downstream EDR & separatrix layers, and before B pile-up regions

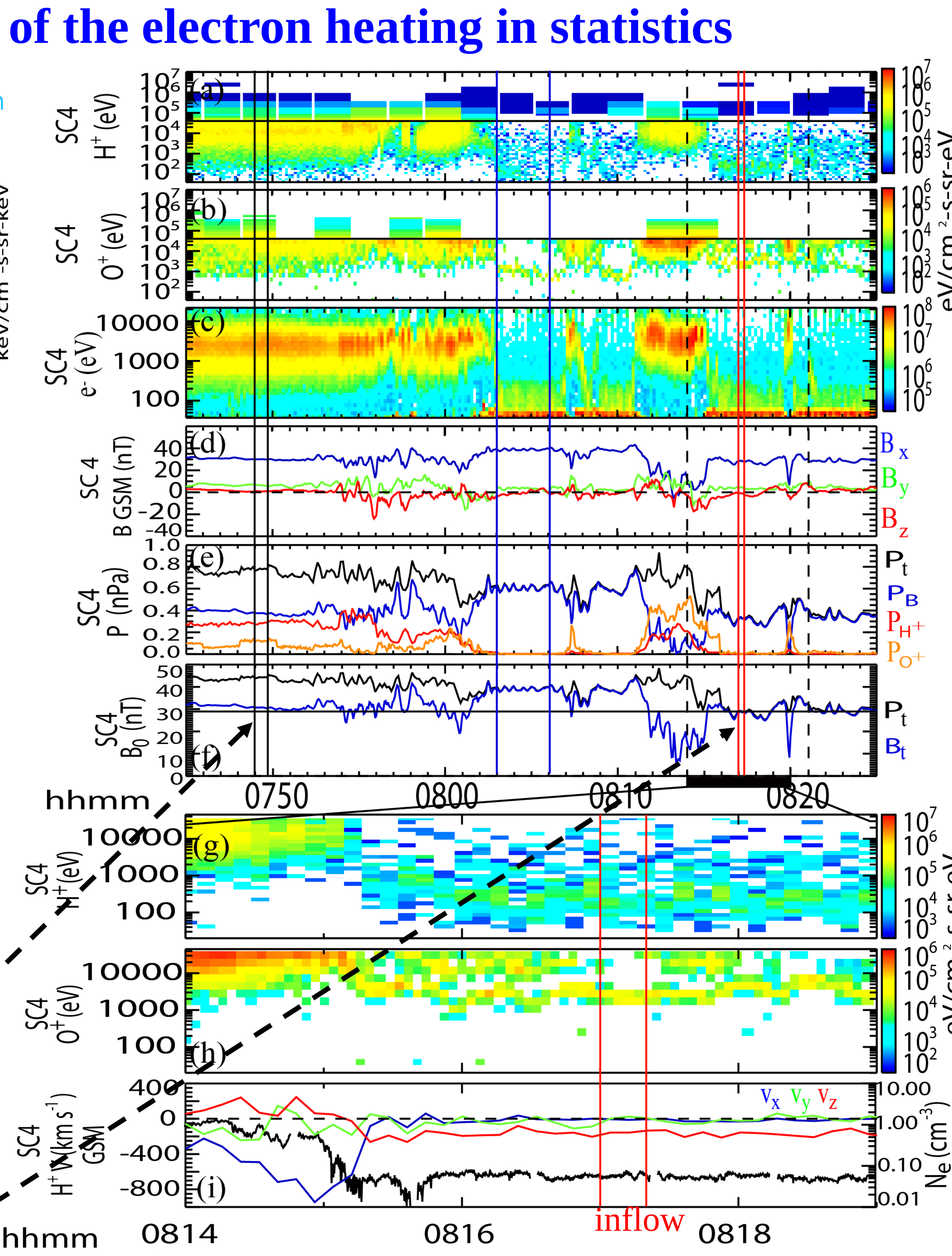
Run NO.	$t\omega_{ci}$	r_{h0}	$\delta r_{h0}/r_{h0}$	r_{ht}
1	18	1.2%±0.1%		1.1%±0.1%
1	26	1.8%±0.4%	50%	2.6%±0.5%
2	19	1.5%±0.2%		1.5%±0.2%
2	27	2.8%±0.4%	87%	4.2%±0.6%
Average		1.8%		2.4%
3	15	2.8%±0.3%		2.5%±0.3%
3	23	3.6%±0.9%	29%	3.4%±0.9%
4	16	2.5%±0.5%		2.3%±0.5%
4	24	3.7%±1.0%	48%	3.5%±0.9%
Average		3.2%		2.9%

*B_0 and n_b change with time, especially for runs 1 and 2 at later times (30% decrease):
r_{h0} : v_{Ai} uses initial B_0 and n_b;
r_{ht} : v_{Ai} uses B_0 and n_b at instant times;
δr_{h0}: r_{h0} change in $8\omega_{ci}^{-1}$ for each run.

- **r_h in the range of 1%-4%,**
- **Time-average r_h: 2%-3%**
- **r_h increases by 30%-90% in $8\omega_{ci}^{-1}$**

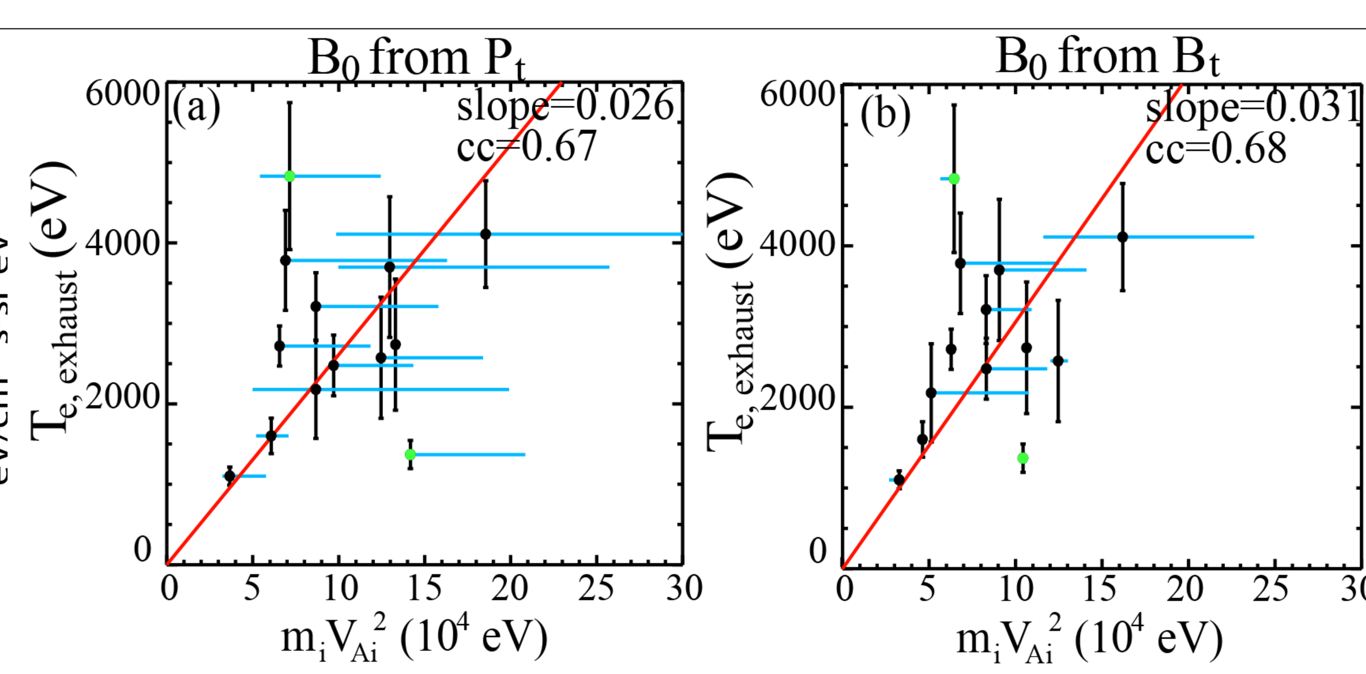
Cluster observations of the electron heating in statistics

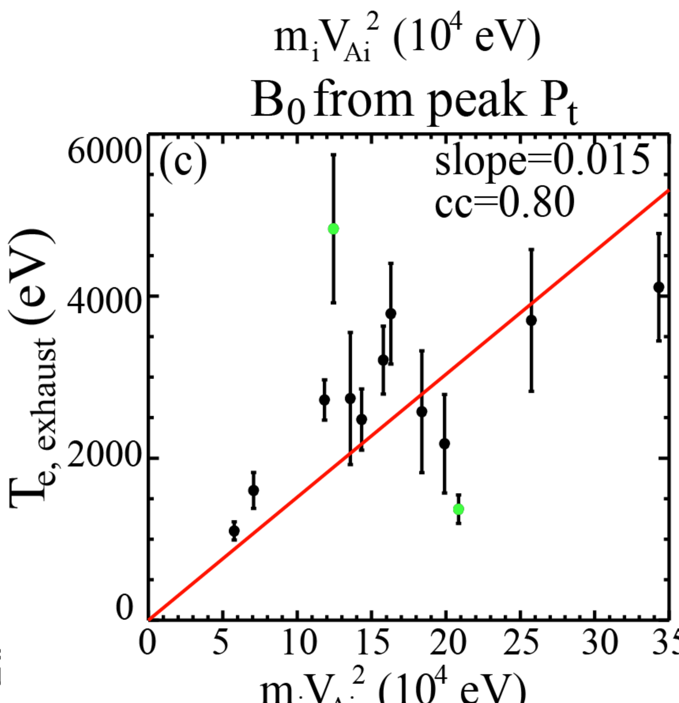




- **Exhaust intervals** selected according to
  - e⁻ spectrogram (high-E);
  - B (smaller than in lobe);
  - v_{ion} (large);
  - plasma β (>1);
  - electron VDFs (non-Maxwellian)
- **ΔT_e** =average T_e in exhaust intervals ± its standard deviation.
- **Inflow n_b**: close to lobe where P_B dominates
- **B_0↓** during the unloading phase: apply pressure balance for B_0 variations
  - B_0 during the exhaust crossing intervals &
  - initial maximum B_0

  are used for r_h fitting
  - B_0 range as the uncertainty





- 11/13 events exhibit clear correlations between $T_{e,exhaust}$ and $m_i v_{Ai}^2$;
- r_h~2.6% using inflow B_0 (with P balance) during exhaust crossings (a);
- r_h~3.1% using inflow B_0 (direct B measurements) during exhaust crossings (b);
- Large variations of T_e and B_0 caused by unloading;
- The lower-limit of r_h~1.5% using maximum initial B_0 (c).

Summary

- We propose an electron VDF model based on the electron energization process in EDR to obtain the heating coefficient r_h. It depends on the electron inflow and outflow speeds, and agrees with the PIC data within 20% of the uncertainty.
- Electron heating is examined in PIC simulations with r_h around 2%-3%, which increases by ~30%-90% in $8\omega_{ci}^{-1}$.
- A statistical study of the electron heating in the magnetotail reconnection is performed using Cluster observations:
  - pressure unloading may cause large variations in T_e and B_0, and uncertainties in r_h;
  - r_h~1.5%-2.6%, agreeing with the simulation results.

References and Acknowledgements

[1] Phan, T. D. et al., 2013, GRL, 40;
[2] Shay, M. A. et al., 2014, POP, 21;
[3] Phan, T. D. et al., 2014, GRL, 41;
[4] Shuster, J. R. et al., 2015, GRL, 42.

Work at UNH and NASA GSFC is supported by NASA grants NNX12AD16G, NNX13AK31G, NSF grant AGS-1202537, and the Theory and Modeling Program of the Magnetospheric Multiscale mission