Origins of Highly Structured Distribution Functions in Magnetic Reconnection Exhausts: Understanding Electron Acceleration and Heating

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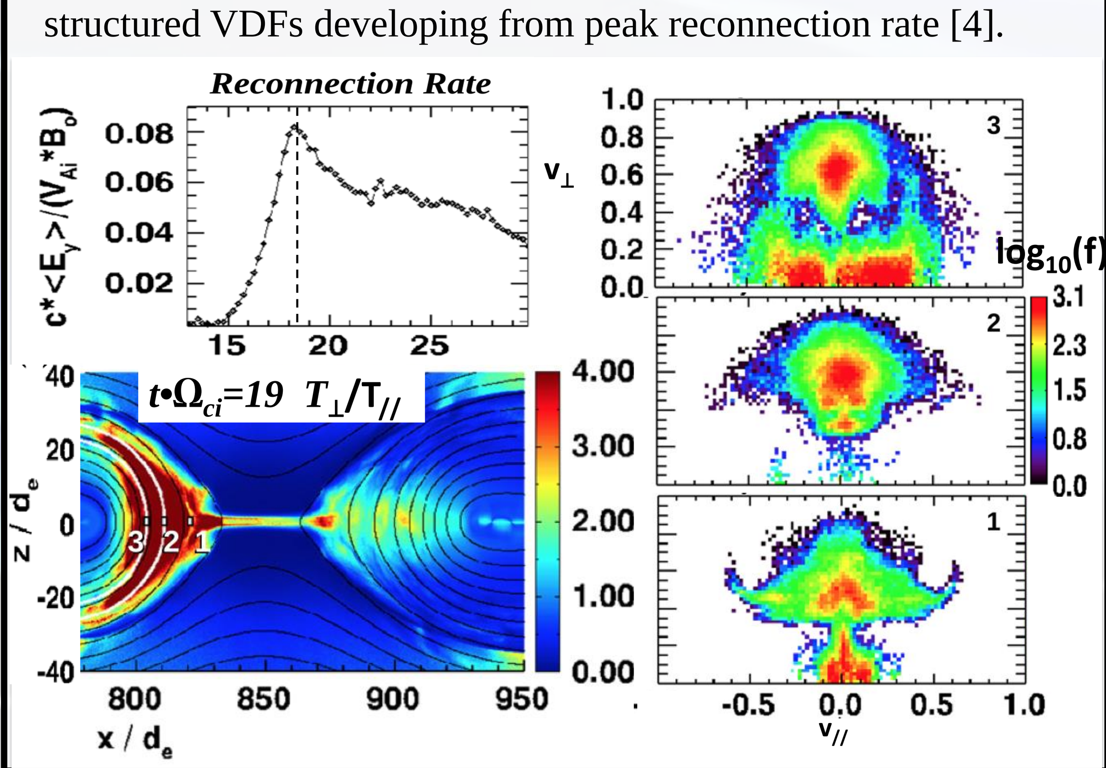
Abstract

Electron velocity distribution functions (VDFs) during magnetic reconnection with negligible guide field from particle in cell (PIC) simulations and Cluster observations are studied to further understand electron acceleration and heating. Our results reveal sub-regions of the temperature profile from the electron diffusion region (EDR) to the exhaust, each with its own highly structured VDF. Using test-particle tracing, we discuss the acceleration and heating mechanisms producing the VDF structures. We apply our understanding to Cluster observations of magnetotail electrons whose velocity-space structures are in good agreement with the simulation predictions. The electron heating is found to be around 2% $m_i v_{Ai}^2$ in simulation and 5% $m_i v_{Ai}^2$ in magnetotail observation. The heating coefficient can be roughly estimated with a simplified EDR VDF, which depends on the electron outflow speed.

Motivation and Context

- Electron bulk heating at dayside magnetopause reconnection ΔT_e was reported to be 1.7%$m_i v_A^2$ [1].
- Exhaust electrons in anti-parallel reconnection were thought to be mostly isotropic [2,3]. Recent simulation results revealed highly structured VDFs developing from peak reconnection rate [4].



PIC simulation

- 2.5D, symmetric, antiparallel
- collisionless, undriven, open boundaries
- m_i / m_e = 400, Cells: 10240×2560
- Domain size: x: [0, 1600]d_e, z: [-200, 200]d_e
- Current sheet v_{Ai0}=1/40c, Lobe v_{Ai}=4.47 v_{Ai0}

Particle Tracing Results

Energy equation $\frac{dU}{dt} = -e\vec{E}\cdot\vec{v}$

Momentum equation for $v_{||}$ $\quad m\frac{dv_{//}}{dt} = m\left(\hat{b}\cdot\frac{d\vec{v}}{dt} + \vec{v}\cdot\frac{d\hat{b}}{dt}\right)$

1[st] term: acceleration by $E_{||}$

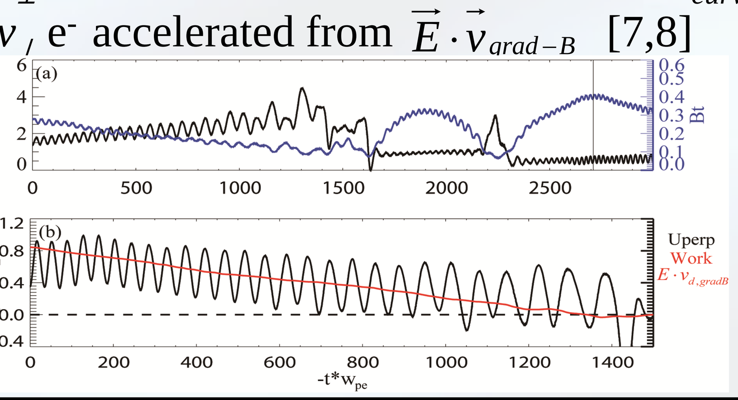
2[nd] term: energy source $\vec{E}_{\perp}\cdot\vec{v}$, due to changes of B direction

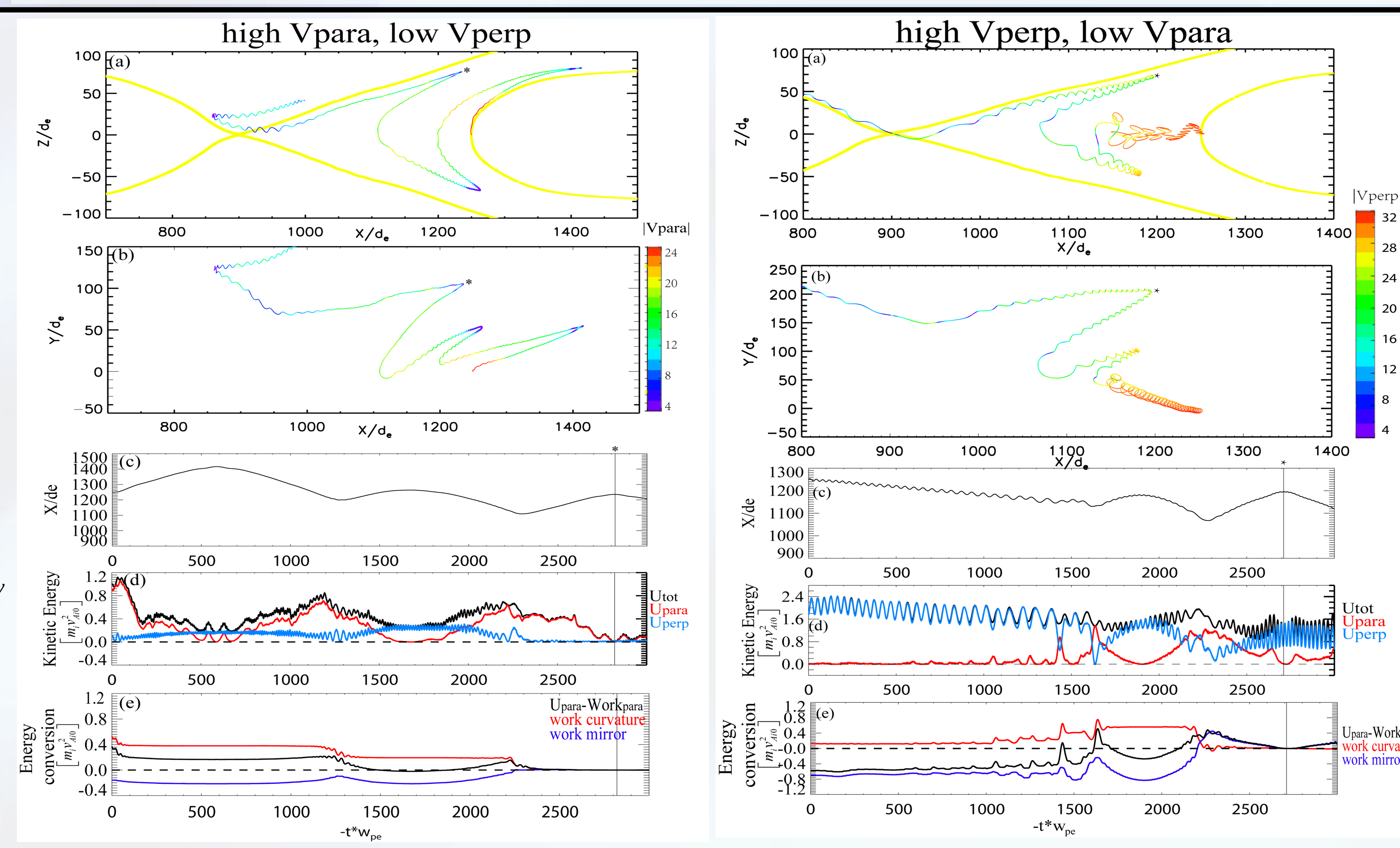
$$m\vec{v}\cdot\frac{d\hat{b}}{dt} = m\vec{v}\cdot\left(\vec{v}_{//}\cdot\nabla\hat{b} + \vec{v}_{\perp}\cdot\nabla\hat{b}\right)$$

$$F_{curv} = m\left(\vec{v}\cdot\hat{b}\right)\vec{v}\cdot\left(\hat{b}\cdot\nabla\hat{b}\right) \qquad F_{mirror} = m\vec{v}\cdot\left(\vec{v}_{\perp}\cdot\nabla\hat{b}\right)$$

- By III-IV, electrons gain energies from E_y acceleration in EDR OR $e\Phi_{||}$ between separatrix and the mid-plane;
- In IV, PA scattering to be isotropic [6]
  - Caused by F_{curv} and F_{mirror}
- In V (Only works for mid-plane)
  - high $v_{||}$ & low $v_{\perp}$ e⁻ accelerated from $\vec{E}\cdot\vec{v}_{curv-B}$ with F_{curv}
  - low $v_{||}$ & high $v_{\perp}$ e⁻ accelerated from $\vec{E}\cdot\vec{v}_{grad-B}$ [7,8]

low $v_{||}$ & high $v_{\perp}$ particle: μ not conserved; $U_{\perp}$ gain matches the work by $\vec{E}\cdot\vec{v}_{grad-B}$

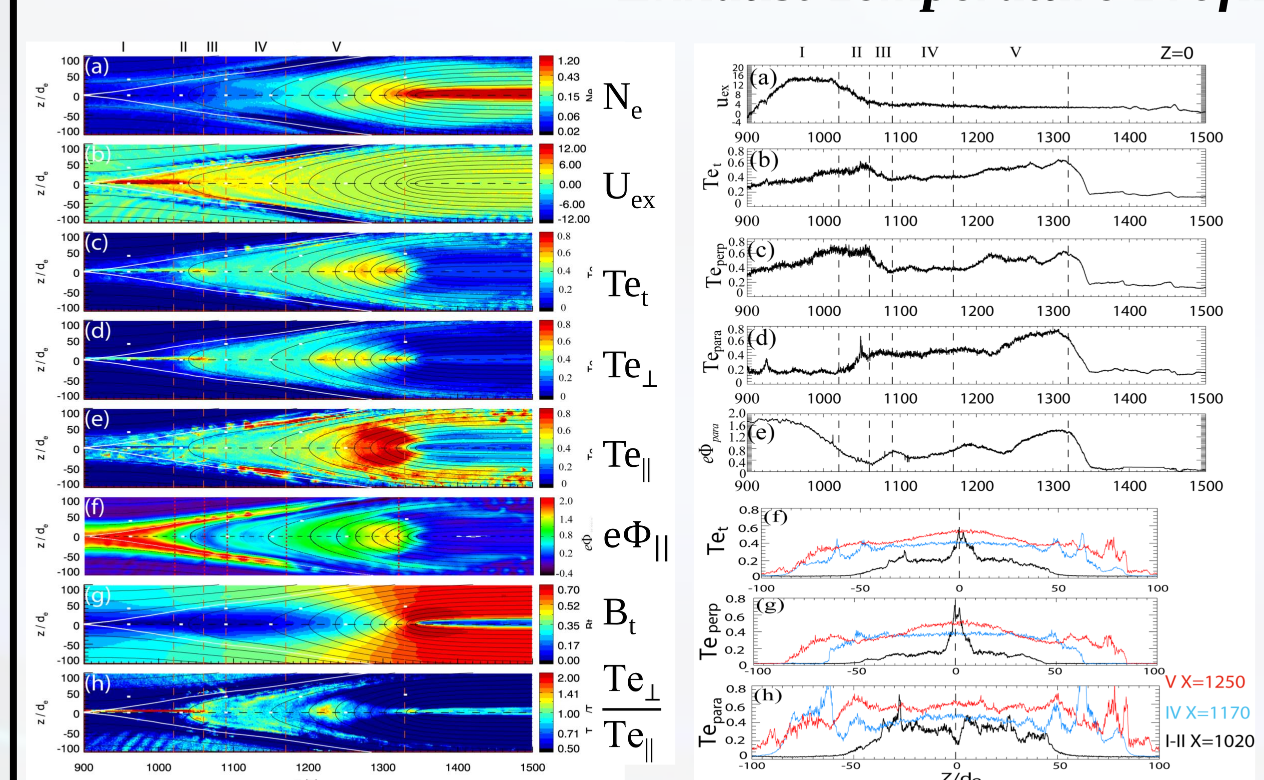




Backward test-particle tracing with fixed E&B fields at t = 29ω_{ci}^{-1}

Results

Exhaust Temperature Profile



t = 29ω_{ci}^{-1} , *I-II: EDR, V: close to piled-up region, III-IV in between.*
u_{ex} in unit of v_{Ai0}, and T_e in unit of $m_i v_{Ai0}^2$.

T_e sub-regions

T_e variation along x at z=0

- I: $T_{e//}$ stays low, $T_{e\perp}$ ↑
- II: $T_{e//}$ ↑, $T_{e\perp}$ —; outer edge at the end of the e⁻ jet
- III: $T_{e//}$ — , $T_{e\perp}$ ↓
- IV: $T_{e//}$, $T_{e\perp}$ —, isotropic
- V: both $T_{e//}$ and $T_{e\perp}$ ↑

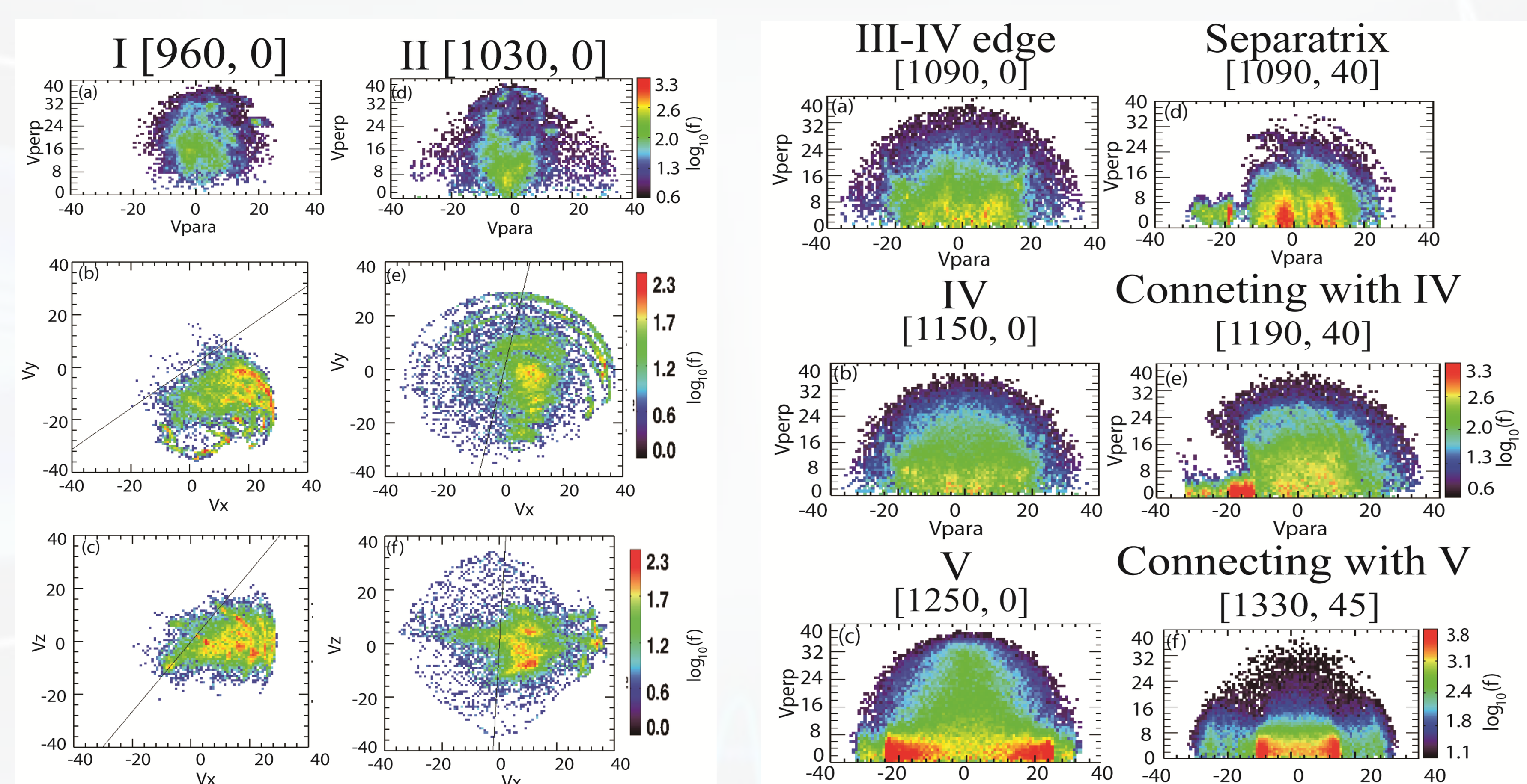
T_e variation along z

- T_e ↑ near separatrix region
- I-II: $T_{e//}$ dips, $T_{e\perp}$ peaks at z=0
- IV: small variations along z
- V: $T_{e//}$ and $T_{e\perp}$ ↑ toward z=0

Electron heating

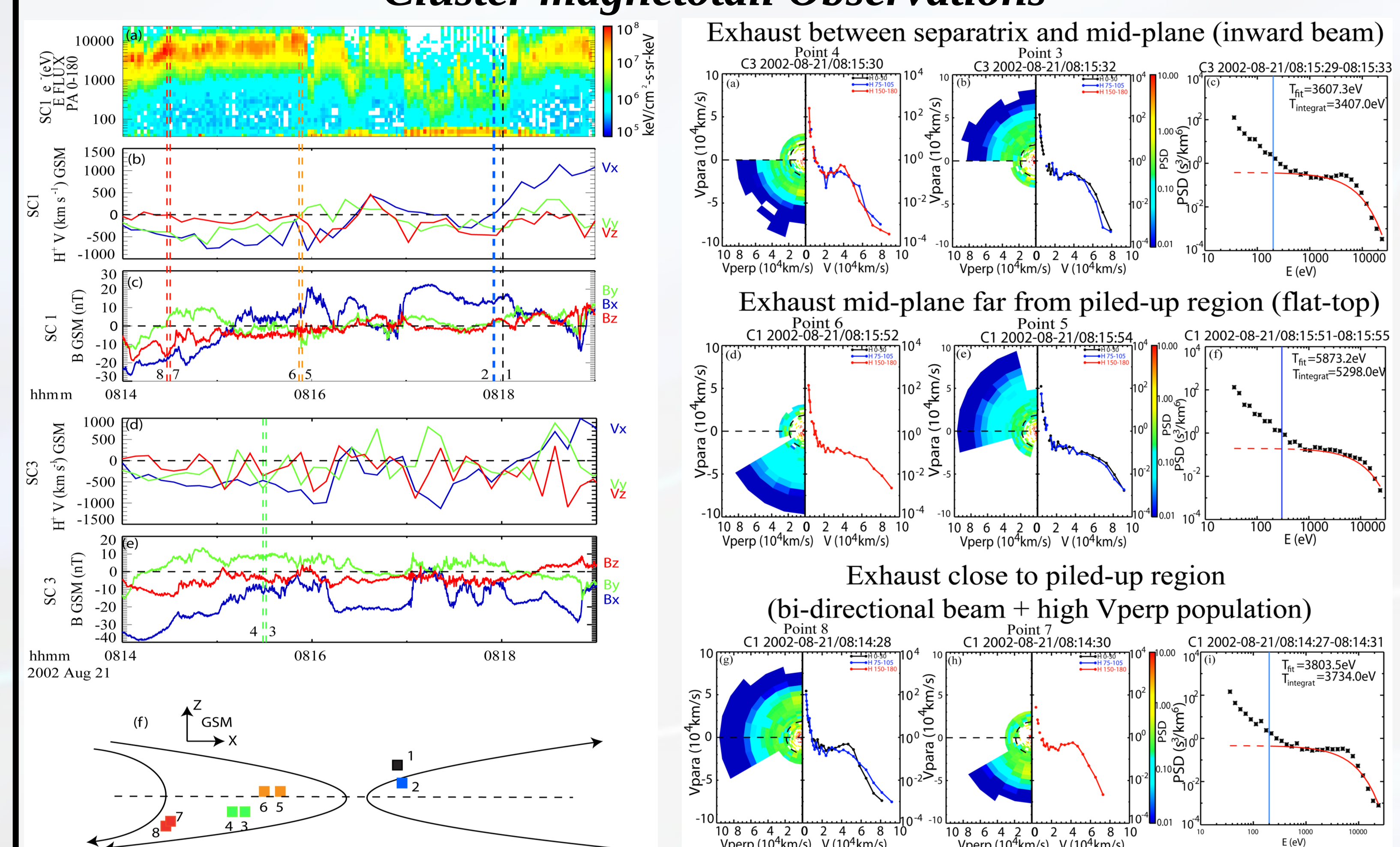
- Lobe T~0, exhaust T_t as ΔT
- T_t maximum in II: 2.4% $m_i v_{Ai}^2$
- Isotropic T_t in IV: 2.0% $m_i v_{Ai}^2$

Electron VDFs



- **I**: rotating triangle, meandering motion + rotation around Bz, $T_{e\perp}$ ↑ from $v_{\perp}$ acceleration;
- **II**: perpendicular arcs + parallel elongation, further rotation + e⁻ from separatrix ($T_{e//}$ ↑);
- **III**: transition region, high-E e⁻ ↓ + more isotropic + parallel elongation at low-E, high-E e⁻ ejected ($T_{e\perp}$ ↓) + PA scattering + e⁻ crossing separatrix/bouncing back;
- **IV**: after transition in III, quasi-isotropic flat-top, PA scattering;
- **Off mid-plane on same field lines with IV**: inward beam, formed around separatrix, scattered at mid-plane [5];
- **V**: counter-streaming beams + high $v_{\perp}$ ring, less efficient PA scattering + acceleration;
- **Off mid-plane on the same field lines with V**: counter-streaming beams with smaller $v_{//}$

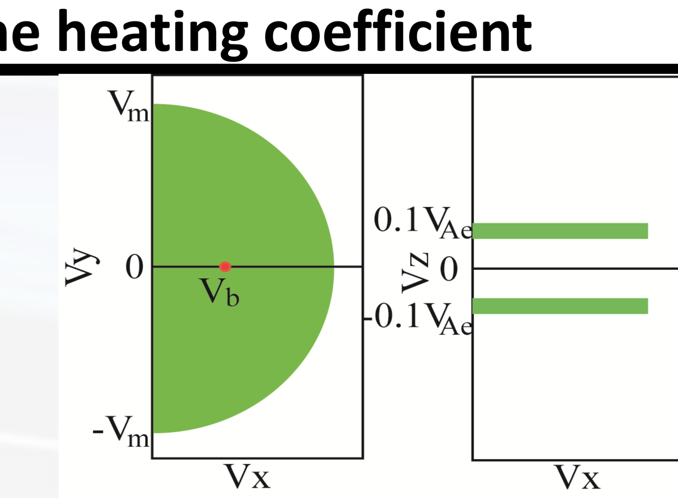
Cluster magnetotail Observations



- Points 3-4 between separatrix and mid-plane, inward beam;
- Points 5-6 close to the mid-plane, isotropic flat-top;
- Points 7-8 close to the piled-up region, counter-streaming beams.
- T_e calculation
  - PA distribution integration, $T_{||(\perp)} = \frac{m\int v_{||(\perp)}^2 f d^3v}{(2)k_B\int f d^3v}$ $\quad T_t = (T_{para} + 2T_{perp})/3$
  - Maxwellian fitting with PA-averaged distribution
- Electron heating: lobe V_{Ai}=3335 km/s, T_t~5500 eV (flat-top) $\quad \Delta T = 4.7\% m_i V_{Ai}^2$

Our VDF model to derive the heating coefficient

- Previous VDF model with counter-streaming e⁻ at v_{Ai} estimated e⁻ heating as $1/3 m_e v_{Ai}^2$, → a low heating coefficient 0.02% [9]
- We use a simple VDF model around EDR jet
  - Meandering motion + rotation around Bz
  - Semi-circle in v_x-v_y
  - double-line at $\pm 0.1 v_{Ae}$ (bounce at v_{in})
  - B along z
- T_e from model
  - $T_{e//}$ =0.20 $m_i v_{Ai0}^2$, $T_{e\perp}$~0.89 $m_e v_b^2$=0.44 $m_i v_{Ai0}^2$
  - T_t ~ 0.36 $m_i v_{Ai0}^2$, Heating coefficient 1.8%
- In simulation data
  - $T_{e//}$ =0.20 $m_i v_{Ai0}^2$, $T_{e\perp}$=0.60 $m_i v_{Ai0}^2$
  - T_t ~ 0.47 $m_i v_{Ai0}^2$, Heating coefficient 2.4%



Simplified VDF model around electron jet in EDR

Heating coefficient $\frac{\Delta T_e}{m_i v_{Ai}^2} = 0.003 + 0.6\frac{m_e v_b^2}{m_i v_{Ai}^2}$ depends on e⁻ bulk outflow velocity (super-Alfvenic)

Conclusions

- Electron heating is found to be ~2%$m_i v_{Ai}^2$ in simulation and ~5%$m_i v_{Ai}^2$ in magnetotail observation
- T_e varies along x and z directions, corresponding to highly structured VDFs
  - T_e peaks around the electron jet, and varies according to the meandering motion and re-magnetization; $T_{e//}$ dips and $T_{e\perp}$ peaks at the mid-plane;
  - For later time, there is a region outside EDR with isotropic and steady T_e; VDFs are flat-top at the mid-plane and with inward beams off mid-plane.
  - Closer to the B piled-up region, due to lack of PA scattering, VDFs show counter-streaming beams with increasing spread (larger $T_{e//}$) towards the mid-plane; VDFs near the mid-plane have a distinct population with low $v_{//}$ and high $v_{\perp}$, which increases $T_{e\perp}$.
- Close to the B piled-up region, electrons with initial high $v_{//}$ are accelerated from curvature drift, and electrons with initial high $v_{\perp}$ are accelerated from grad-B drift.
- Heating coefficient can be estimated with simplified EDR VDF, depending on $v_{e,out}$

References and Acknowledgements

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