Direct Observation of Acceleration and Thermalization of Beam Electrons Caused by Double Layers in the Earth's Plasma Sheet

Zhigang Yuan, Yue Dong, Shiyong Huang, Zuxiang Xue, Xiongdong Yu
School of Electronic Information, Wuhan University, Wuhan, China
e-mail (speaker): dxdy@whu.edu.cn

Electron acceleration and thermalization in the plasma sheet (PS) of the Earth's magnetotail are fundamental research topics of magnetospheric physics. Theoretical analyses and numerical simulations have revealed that beam electrons can be accelerated and thermalized by the structure of double layer (DL). Direct observation of PS electron acceleration and thermalization is essential to demonstrate the theoretical prediction.

We report direct observations of the detailed processes for the acceleration and thermalization of beam electrons in the plasma sheet of the Earth's magnetotail. As shown in Fig. 1(a), the parallel velocity of the electron beam increases from ~ 6000 km/s to ~ 15000 km/s due to the acceleration through the DL structure [Fig. 1(b)]. We use the multi-spacecraft timing method to estimate the drift speed of this DL as $V_{DL} \approx 350$ km/s in the spacecraft reference frame. The electrostatic potential can be calculated by $\varphi = -\int E_{||} V_{DL} dt$. The averaged parallel energy of beam electrons (Ee||) is calculated by

$$Ee_{||} = \frac{\frac{1}{2} m_e \int f(v_{||}) v_{||}^2 dv_{||}}{\int f(v_{||}) dv_{||}},$$

where $f(v_{||})$ is the electron 1D VDF, derived from electrons with $\alpha < 45°$. The ΔEe|| and φ curves in Fig. 1(c) are mostly consistent, confirming the parallel acceleration of beam electrons by the DL structure.

The filtered broadband (0.25-4kHz) $E_{||}$ waveform is shown in Fig. 1(d). Root Mean Square (RMS) curves of the filtered $E_{||}$ are displayed in Fig. 1(e). The equivalent parallel temperature of beam electrons ($T_{||Beam}$) and the Omni electron parallel temperature ($T_{||Omni}$) are shown in Fig. 1(f). $T_{||Beam}$ and $T_{||Omni}$ are calculated by

$$T_{||Beam} = \frac{\frac{1}{2} m_e \int_{v_l}^{v_h} f(v_{||})(v_{||} - v_d)^2 dv_{||}}{\int_{v_l}^{v_h} f(v_{||}) dv_{||}}$$ and

$$T_{||Omni} = \frac{\frac{1}{2} m_e \int_{v'_l}^{v'_h} f'(v_{||})(v_{||} - v'_d)^2 dv_{||}}{\int_{v'_l}^{v'_h} f'(v_{||}) dv_{||}},$$ respectively.

Changes in $T_{||Beam}$ and $T_{||Omni}$ are mostly consistent, and both are modulated by the RMS of the broadband electrostatic waves, implying that parallel electric field turbulence mainly thermalizes beam electrons.

In summary, we provide a direct observation for the detailed and complete process of acceleration and thermalization of magnetotail beam electrons: beam electrons are accelerated by the DL structure into high-speed parallel beam electrons, which have strongly nonlinear instability to produce parallel electric field turbulence so as to further cause the thermalization of high-speed parallel beam electrons. These observations imply that DL is a key process controlling the acceleration and thermalization of beam electrons in the plasma sheet of the Earth's magnetotail, which indicates the energy exchange process between nonlinear electric field structures and particles (electrons) in the Earth's plasma sheet, and perhaps, in many space and astrophysical plasmas.

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References

[1] Yuan, Z., Dong, Y., Huang, S., Xue, Z., & Yu, X. (2022). Direct observation of acceleration and thermalization of beam electrons caused by double layers in the Earth's plasma sheet. Geophysical Research Letters, 49, e2022GL099483.

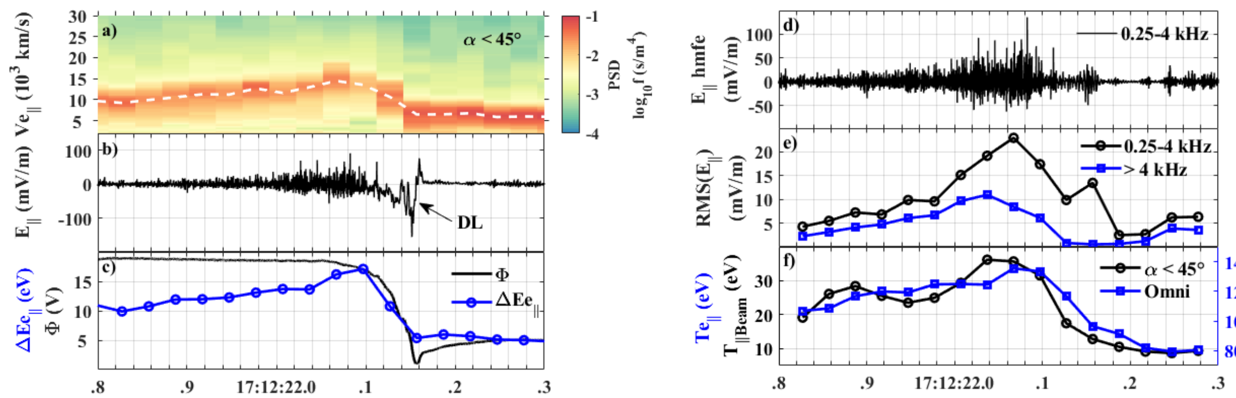

Figure 1. Observations of electron acceleration and thermalization by MMS satellites. (a) Electron 1D VDF in the parallel direction. (b) $E_{||}$ measured by EDP (8 kHz, sampling). (c) Potential (black) and ΔEe|| (blue). (d) Filtered $E_{||}$ waveform with a bandwidth of 0.25–4 kHz. (e) RMS of electric fields in frequency ranges of 0.25–4 kHz (black) and 4–32 kHz (blue). (f) $T_{||Beam}$ (black) and $T_{||Omni}$ (blue).