Super thin current sheets of electron scales observed in planetary magnetotails

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Thin Current Sheets (TCSs) are general structures in planetary magnetotails

MAGNETIZED planets (e.g. the Earth)

UNMAGNETIZED planets (e.g. Mars)

The cross-tail CS is observed in both types of magnetosphere.

The Earth: the cross-tail TCS is the main region of magnetic energy conversion, usually observed during substorm growth phase (e.g. Sergeev et al., 1993; Baker et al., 1996; Nakamura et al., 2006; Runov et al., 2008)

Mars: the cross-tail CS separates the tail lobes with opposite polarity of the magnetic field. It has been identified as a main ion escape channel at Mars (e.g., Yeroshenko et al., 1990; Dubinin et al., 1993; Fedorov et al., 2006; 2008; Barabash et al., 2007; DiBraccio et al., 2015; Grigorenko et al., 2017). Signatures of energy conversion via magnetic reconnection were reported recently (e.g. Harada et al., 2015; 2017; Hara et al., 2017)
One-spacecraft observations (e.g. in the Mars’s magnetotail) allow estimation of 1D Electric current density as: \( J_M = \frac{\Delta B_L}{L_N \cdot \mu_0} \),

\( L_N \) is a half-thickness of the CS: \( L_N = \int_{t_1}^{t_2} V_N \, dt \)

In the Earth’s magnetotail four-point Cluster and MMS observations allow the precise calculation of 3D electric current density by curlometer technique:

\[
J_{i3j} = \frac{\Delta B_{3i} \cdot r_{3j} - \Delta B_{3j} \cdot r_{3i}}{\mu_0 \cdot (r_{3i} \cdot r_{3j})}
\]
The minimal characteristic scale of Cluster tetrahedron is ~ a few hundreds km ($\sim \rho_p$). Cluster can observe ion-scale Current Sheet.

The characteristic scale of MMS tetrahedron $\sim 15$ km (a few $\rho_e$)

In burst mode the magnetic field is measured at 128 samples/s
3D electron velocity distribution function ($\sim 100$ eV – 30 keV) is measured at 30 ms resolution

MMS is a perfect tool to study electron-scale STCS in the Earth’s magnetotail.
CLUSTER observations in the Earth’s magnetotail (e.g. Runov et al., Ann, Geophys. 2005) and MAVEN observations in the magnetotail of Mars (e.g. Grigorenko et al., JGR, 2017)

In spite of the different mechanisms of the Earth’s and Martian magnetospheres formation, the similar features are observed in their cross-tail CSs.

However, these observations cannot detect the strong super thin current layer at the center of the CS produced by electrons at electron kinetic scale.
MAVEN observations of Electron-scale Super Thin Current Sheets (STCSs) in Mars’s magnetotail

Three layers of embedding:

Electron STCS: $L_{STCS} \sim 2$ km, $J_{STCS} \sim 85$ nA/m$^2$

Proton TCS: $L_1 \sim 15$ km ($\rho_p \sim 20$ km), $J_{TCS} \sim 34$ nA/m$^2$

Thick CS: $L_2 \sim 50$ km, $J \sim 13$ nA/m$^2$

(Grigorenko et al., GRL. 2019)
MMS observations of STCSs during the growth phase of substorm

Strong CS flapping

High-velocity plasma flow reversal

Multiple bipolar $B_z$ variations (magnetic islands) with STCSs (marked by red dots)

Spikes in the electric field (tens mV/m)

Spikes in the electric current density (tens of nA/m$^2$)

(Leonenko et al., JGR, submitted)
Reconstruction of the spatial structure of the STCS

$L_{STCS} \sim 20 \text{ km}$
Electron current $J_Y = e \cdot n_e \cdot V_{Y,e}$ and components of the pressure tensor were calculated separately for two electron populations:
1) magnetized electrons ($W_e < 1.2$ keV) and
2) unmagnetized electrons ($W_e > 1.2$ keV)

The electric current in the STCS is carried by the unmagnetized electrons and the stress balance is supported by the gradient of off-diagonal components of their pressure tensor.
Open question: evolution of the STCSs

95 STCSs were observed by MMS during the interval of interest (marked by blue dots)

- Tailward flow
- Earthward flow

- Strong variations of the STCS half-thickness from ~ $10\rho_e$ to ~ $1\rho_e$
- Strong variations of the electric current density
- Strong variations of the electric field

Periodic disruption and formation of the electron-scale STCSs?
Conclusions

- MAVEN and MMS observations revealed the Super Thin Current Sheets ($L_{\text{STCS}} \sim$ a few kilometers $\leq$ a few $\rho_e$) embedded into the cross-tail current sheet in the Mars’s and Earth’s magnetotail.

- In STCSs the current is carried by unmagnetized electrons and stress balance is supported by off-diagonal terms of their pressure tensor.

- In the STCSs the higher energy electrons carry the current, while the low-energy electrons support the stability of the STCS.

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