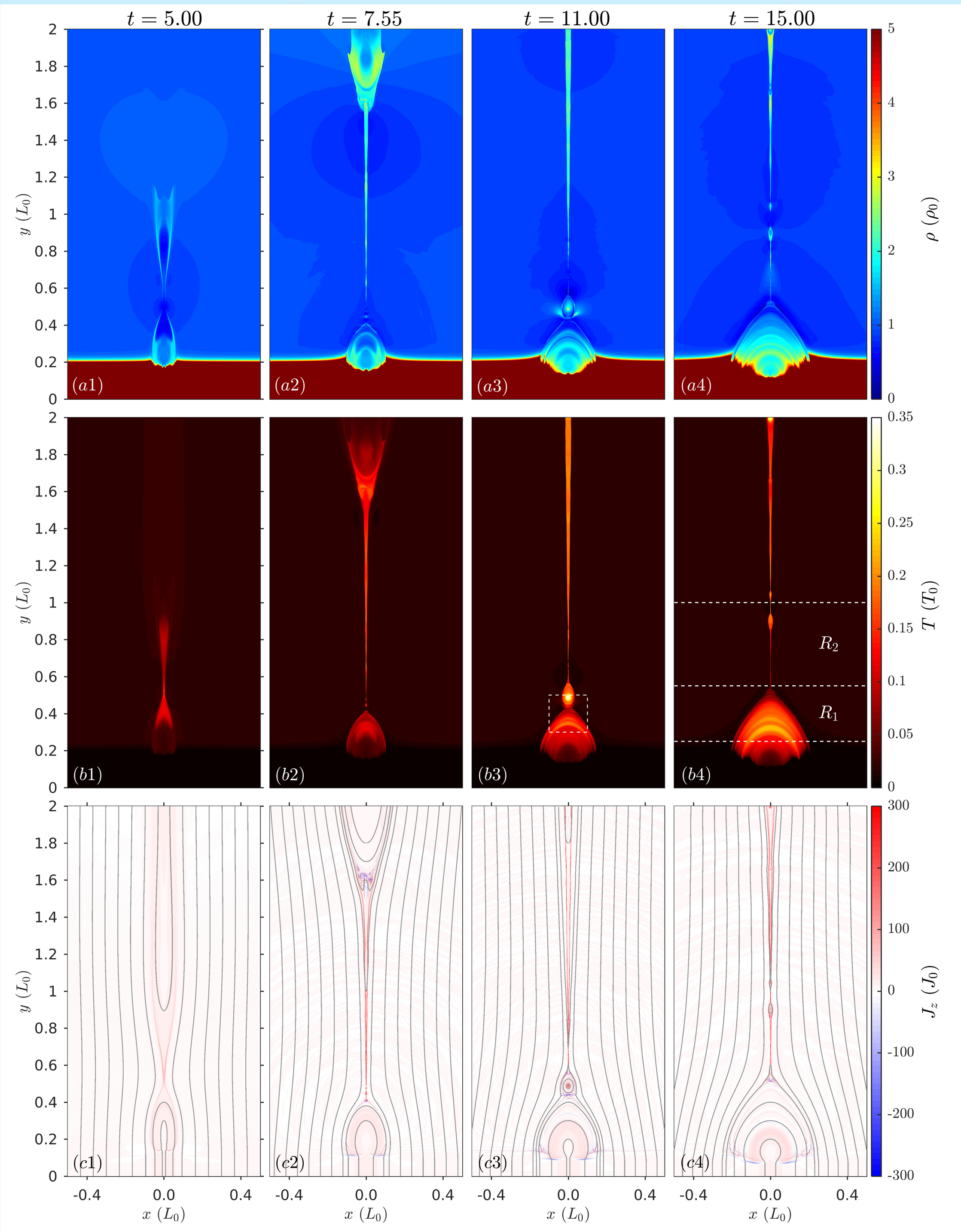
2.5D MHD Simulation of Magnetic Islands Evolving toward Solar Flare Loops

Yulei Wang[1*], Xin Cheng[1], Mingde Ding[1], Quanming Lu[2]
[1]School of Astronomy and Space Science, Nanjing University, PRC
[2]Department of Geophysics and Planetary Science, University of Science and Technology of China, PRC

Abstract

During solar eruptions, magnetic islands (MIs) carried by reconnection downflows will encounter second reconnection process when colliding with the loop top. To investigate the second reconnection of magnetic islands, we perform high-resolution 2.5-dimensional MHD simulations of an eruption current sheet (CS) under the high-Lundquist-number and low-β coronal environment. Our results imply that the annihilation of magnetic islands at the flare loop top, which is not included in the standard flare model, play a non-negligible role in releasing magnetic energy to heat flare plasma and accelerate particles.



Numerical Model

The MHD equation we solve is:

$$\begin{aligned}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) &= 0\,,\\
\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u} - \mathbf{B}\mathbf{B} + P^{*}) &= 0\,,\\
\frac{\partial e}{\partial t} + \nabla \cdot \left[(e + P^{*})\,\mathbf{u} - \mathbf{B}\,(\mathbf{B}\cdot\mathbf{u})\right] &= \nabla \cdot \left(\kappa_{\parallel} \hat{\mathbf{b}}\hat{\mathbf{b}} \cdot \nabla T\right)\\
\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{u} \times \mathbf{B}) &= -\nabla \times (\eta \mathbf{J})\,,
\end{aligned}$$

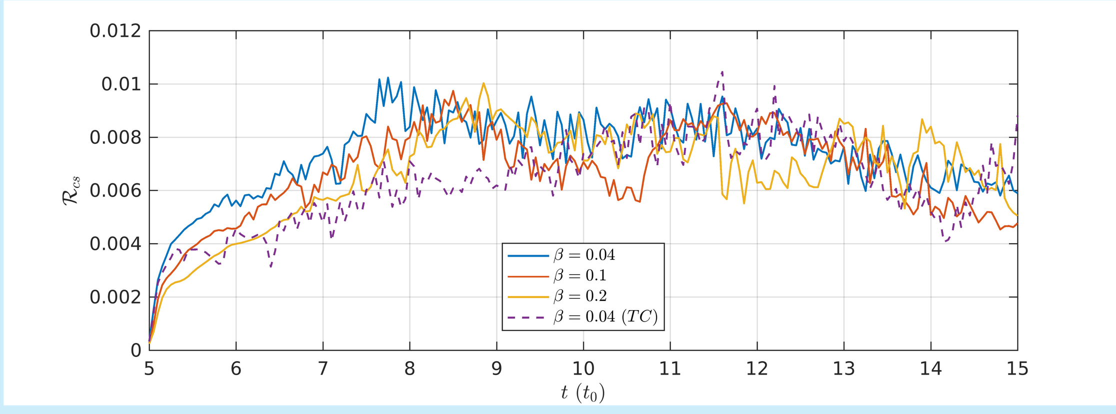
where, $\mathbf{J} = \nabla \times \mathbf{B}$, $P^{*} = p + B^2/2$, $e = p/(\gamma - 1) + \rho u^2/2 + B^2/2$, $\kappa_{\parallel} = \kappa_0 T^{2.5}$, and standard notations of variables are used. Only the thermal conduction (TC) along magnetic field is considered and $\kappa_0 = 10^6\,\mathrm{erg \cdot s^{-1}\,cm^{-1}\,K^{-3.5}}$. All variables are normalized according to: $L_0 = 5 \times 10^9$ cm, $\rho_0 = 1.67 \times 10^{-14}$ g/cm^3, $B_0 = 20$ Gauss, $t_0 = 114.61$ s, $u_0 = B_0/\sqrt{\mu_0 \rho_0} = 4.36 \times 10^7$ cm/s, $p_0 = 3.18$ Pa, $\kappa_{\parallel 0} = 6.02 \times 10^{11}$ erg/s $\cdot$ cm $\cdot$ K, and $T_0 = 11.52$ MK. γ is set as $= 5/3$. The initial magnetic field is based on a simplified CSHKP model (Chen et al. 1999). The chromosphere, transition region, and corona, are approximated by a density distribution similar as Takasao et al. (2015). Fast reconnection is initially triggered by a localized anomalous resistivity η_a at $y = 0.5$ $(t < 5)$ and then is dominated by the uniform background resistivity $\eta_b = 5 \times 10^{-6}$. The bottom boundary is symmetric while the other three boundaries are open. The above system is numerically solved with Athena 4.2. The pixel scales in x and y directions are $\Delta x = \Delta y = 26$ km and The maximum simulation time is $t_{max} = 15$ corresponding to 28.65 minutes.

Reconnection in Main CS

The reconnection rate in the main CS region R_2 is represented by the reconnection electric field at the principal X-point, namely,

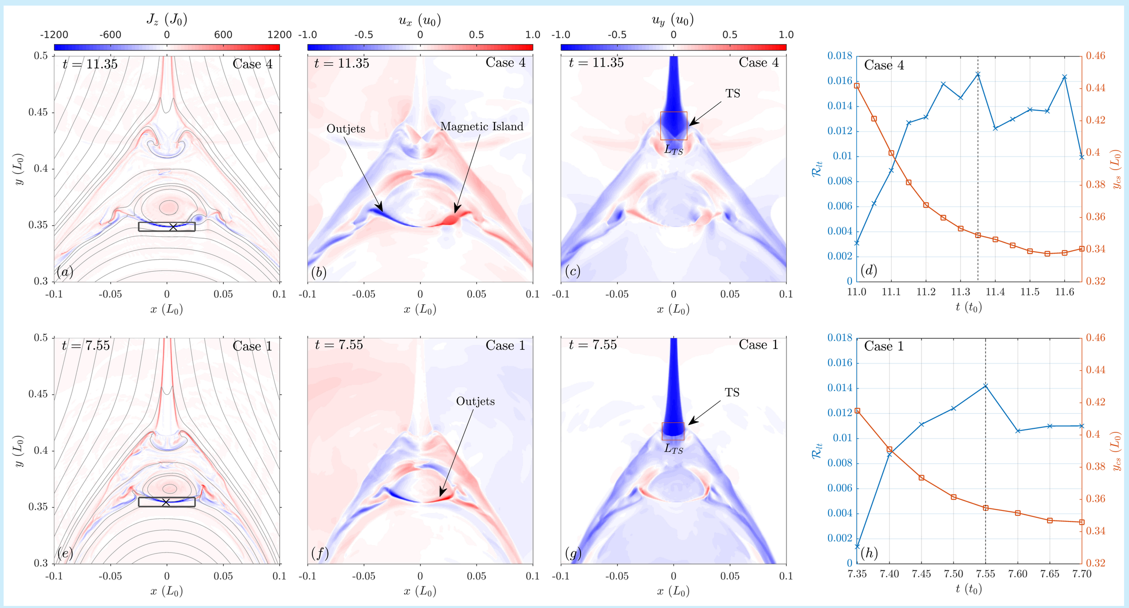
$$\mathcal{R}(t) = \frac{\max\left(\eta_b \left|J_{zxp}(t)\right|\right)}{B_{in}(t)\, u_{in}(t)} \qquad (1)$$

where, J_{zxp} denotes the out-of-plane current density at X-points, $\max(\cdot)$ means taking the maximum value in the target CS region, and magnetic strength B_{in} and Alfvén speed u_{in} are averaged in the region $x \in [-0.05, 0.05]$ and $y \in [0.25, 2]$.



Second Reconnection of MIs

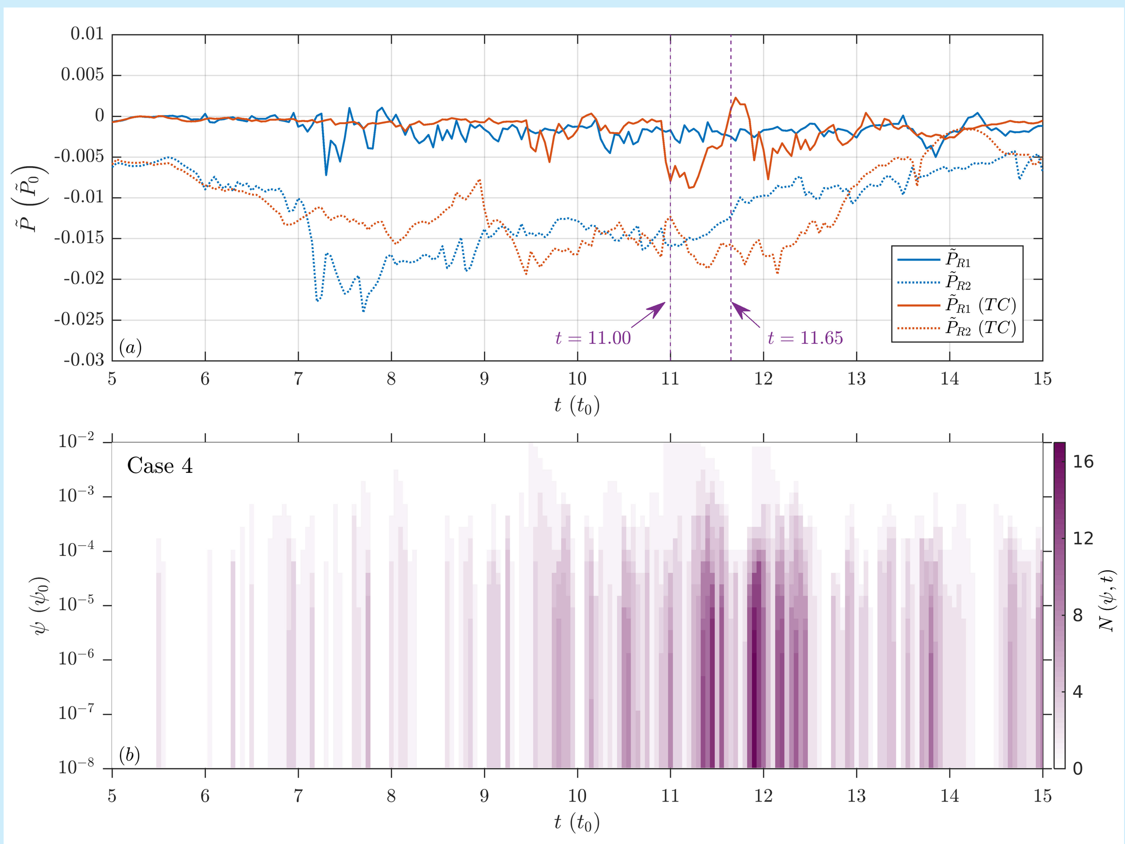
Two typical magnetic island reconnection events in cases with and without TC ($\beta = 0.04$) are shown below. When the magnetic island collides with the loop top field, horizontal current sheet and outjets form. The reconnection rate of the second reconnection can be comparable with that in the main CS.



In an area S, the effective changing rate of magnetic energy is defined as

$$\tilde{P} = \frac{\mathrm{d}}{\mathrm{d}t}\int_S \frac{B^2}{2}\mathrm{d}x\mathrm{d}y + \oint_{\partial S} (\mathbf{E} \times \mathbf{B}) \cdot \mathbf{n}\mathrm{d}l\,, \qquad (2)$$

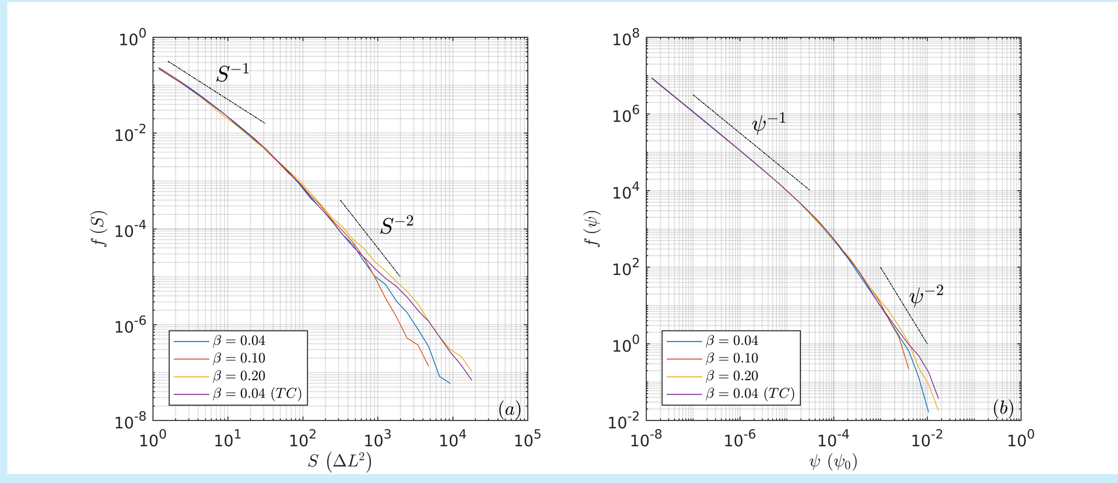
where, ∂S denotes the boundary, $\mathbf{E} = \eta \mathbf{J} - \mathbf{u} \times \mathbf{B}$ is the electric field, $\mathbf{n}$ is the unit normal vector on the boundary, and dl denotes the line element. The negative value of $\tilde{P}$ implies the release of magnetic energy. The evolution of $\tilde{P}$ in the loop-top region, R_1, and that in the main CS, R_2 are shown below. For both cases with and without TC, during most of the time, the magnetic energy release is dominated by the main CS reconnection. However, the second reconnection of magnetic islands is able to further release magnetic energy at the loop-top region (see, negative spikes of solid curves).



The loop-top magnetic islands generated during the second reconnection can be characterized by the evolution of cumulative distribution function (CDF) of island flux $N(\psi, t)$, which measures the number of islands with flux $\geq \psi$ at moment t. When the downflow magnetic islands occur the second reconnection as marked by negative peaks of $\tilde{P}_{R1}$, the CDF of island flux is significantly enhanced.

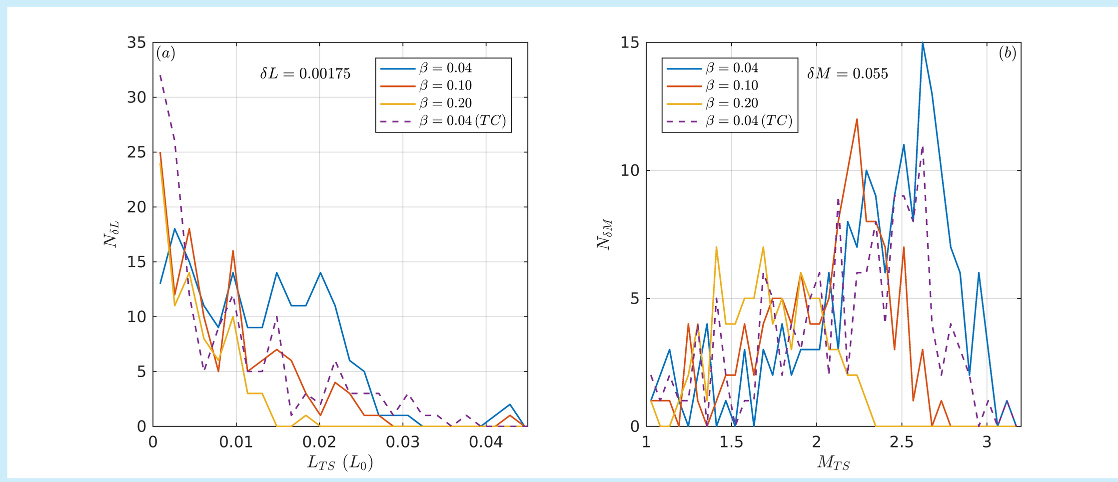
Distribution of Loop-top MIs

The probability distribution functions (PDFs) of magnetic island area and flux at region R_1 is calculated based on the same method by Shen et al. 2013. For most of the sample domain, namely, $S < 10^3$ and $\psi < 10^{-3}$, both $f(S)$ and $f(\psi)$ follow a power-law independent with β and TC. The slopes of PDFs vary from -1 to -2 as the island scale increases.



Termination Shocks

The spatial scale of termination shocks (TSs) is approximately represented by the scale along the x-direction, L_{TS}, while the strength of the TS is approximated by the maximum fast mode Mach number, M_{TS}, near the front of TS. The histograms of L_{TS} and M_{TS} sampled in 200 snapshots show that increasing β and including TC can suppress the scale and strength of TSs.



Conclusions

- When colliding with the semi-closed flux of flare loops, the downflow islands cause a second reconnection with a rate even comparable with that in the main CS.
- The second reconnection releases substantial magnetic energy and also annihilates the main islands, generating secondary islands with various scales at the flare loop top.
- The distribution function of the flux of the second islands is found to follow a power-law varying from $f(\psi) \sim \psi^{-1}$ (small scale) to ψ^{-2} (large scale), which seems to be independent with background plasma β and if including thermal conduction.
- The spatial scale and the strength of the termination shocks driven by main reconnection outflows or islands decrease if β increases or thermal conduction is included.

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Contact

* wyulei@nju.edu.cn