Numerical Model on Dynamic Plasma Flows above Post-flare Loops

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Abstract Fast magnetic reconnection is expected to occur in the current sheet region during the solar eruptions, where outflows near the Alfvén speed are predicted from the classic flare models (*Fig. 1*). In observations, the dark, finger-shaped plasma downflows (also referred to as SADs, Fig. 2) moving toward the flare arcade are believed as the principal observational evidence of such reconnection-driven outflows. However, they are often much slower than those expected in theories[2].

Here, we report a three-dimensional magneto-hydrodynamics model, and conclude that the SADs are not the reconnection outflows themselves. Instead, they are self-organized structures formed in a turbulent interface region below the flare termination shock where the outflows meet the flare arcade.

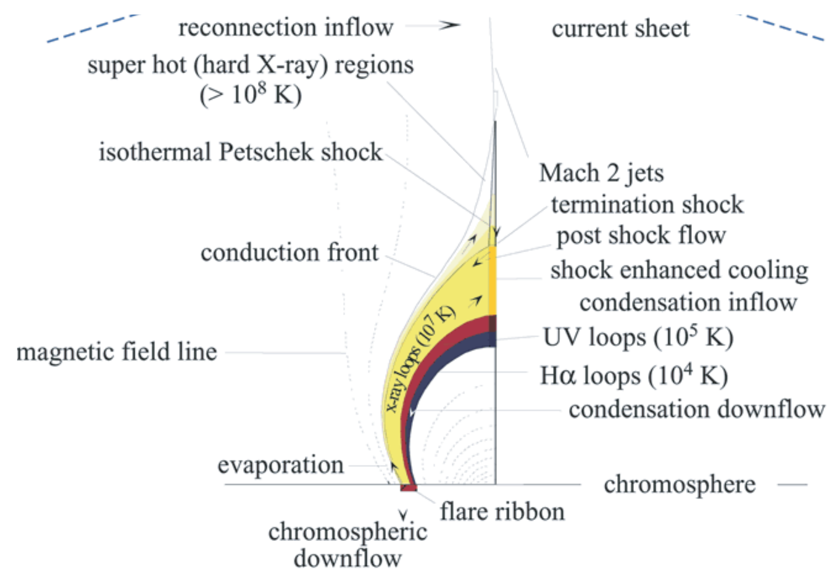

Fig 1. Sketch of the reconnection sheet and post flare loops in a classic solar eruption model (Forbes & Acton 1996[1]).

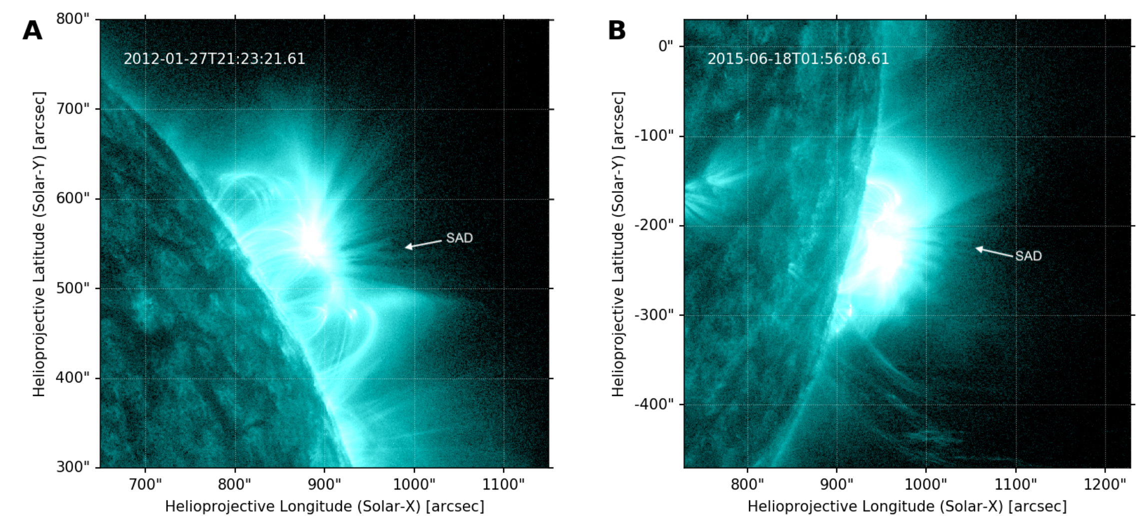

Fig 2. Two example solar eruptive flare events featuring supra-arcade downflows (SADs). The events are observed by SDO/AIA 131 Å on 2012 January 27 and 2015 June 28.

Numerical Model We perform resistive magnetohydrodynamic (MHD) simulations to investigate dynamic features of magnetic reconnection current sheets and plasma flows above flare loops during flare eruptions. The governing equations are as follows:

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho\mathbf{v}) = 0,$$

$$\frac{\partial \rho\mathbf{v}}{\partial t} + \nabla\cdot(\rho\mathbf{v}\mathbf{v} - \mathbf{B}\mathbf{B} + \mathbf{P}^*) = -\rho\nabla\phi,$$

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla\times(\mathbf{v}\times\mathbf{B}) = \eta_m\nabla^2\mathbf{B},$$

$$\frac{\partial E}{\partial t} + \nabla\cdot[(E+P^*)\mathbf{v} - \mathbf{B}(\mathbf{B}\cdot\mathbf{v})] = S,$$

where ρ, v, B, E are plasma density, velocity, magnetic field, and total energy density, respectively. The energy source term (*S*) includes Ohmic dissipation, thermal conduction, radiative cooling and coronal heating terms. The simulations are performed using *Athena*[3] code.

Our simulations are comprised of 2.5D models and 3D models. The 2.5D model is run first to form the classic Kopp-Pneuman configuration of two-ribbon flares[4], and the simulation starts with a vertical current sheet in mechanical and thermal equilibrium that separates two regions of the magnetic field with opposite polarity (*Fig. 3*).

Once the closed flare loops are well-formed at the bottom, we start 3D simulations at *Time=17t₀*. All primary variables are symmetrically extended to the third axis (*Fig. 4*).

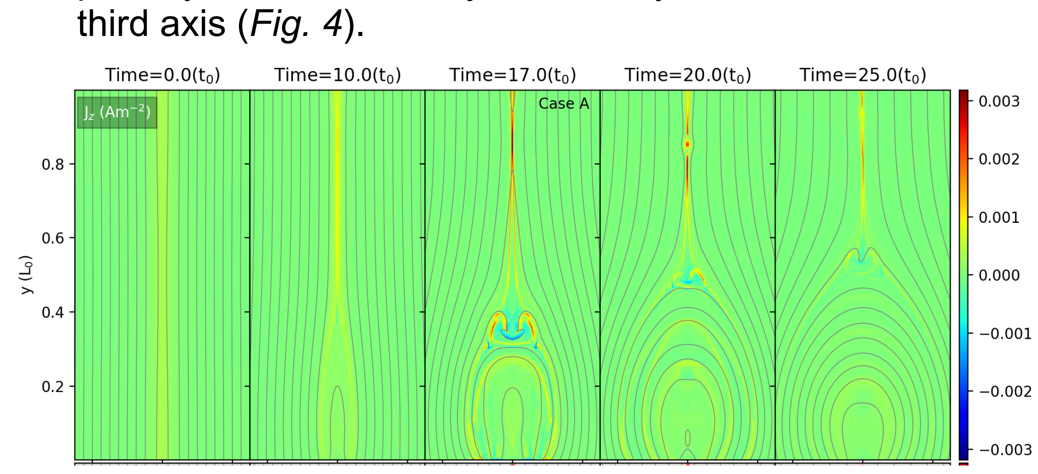

Fig 3. Evolution of current-density (Jz) in 2.5D simulations. The solid contour lines are magnetic field lines. The following 3D simulation is performed based on this 2.5D configuration.

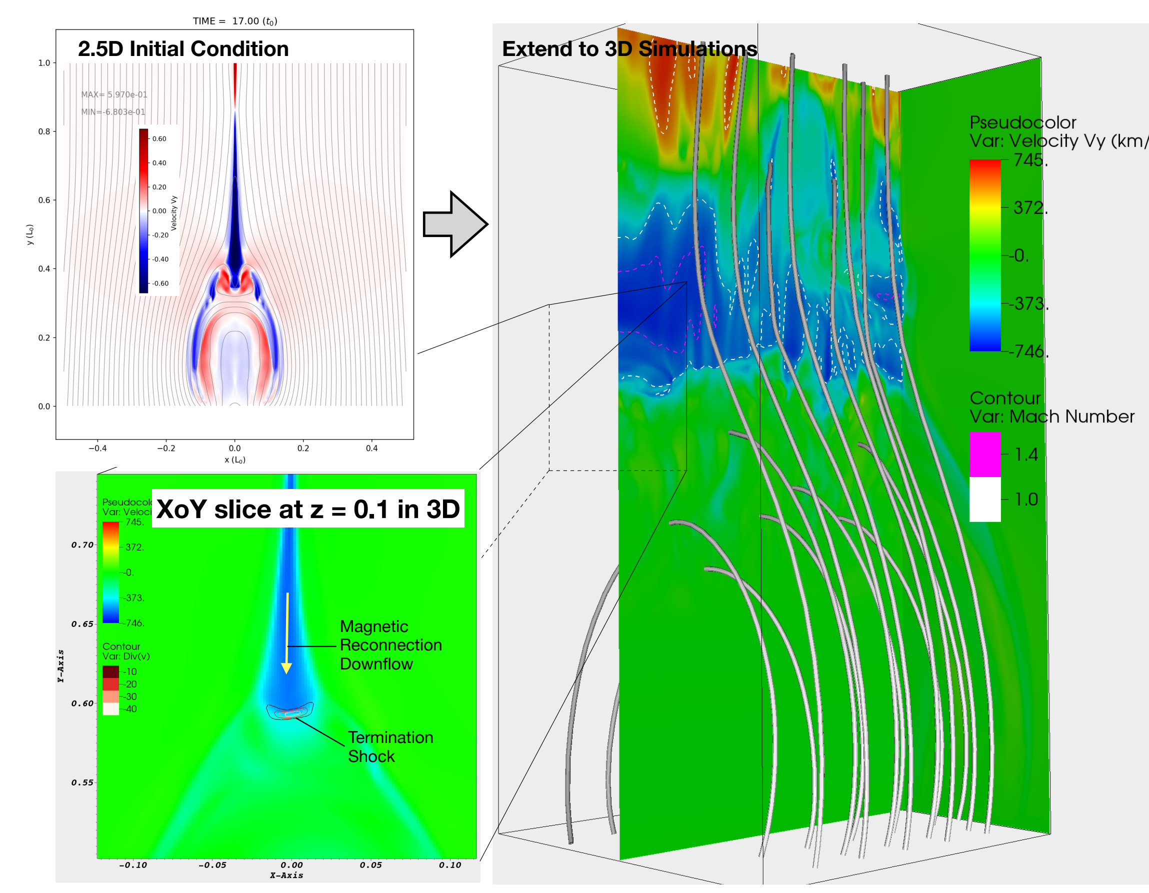

Fig 4. Velocity (Vy component) and fast-Mach number distribution in 3D simulation. The super-magneto-sonic reconnection outflows and associated termination shocks can be clearly identified on the XoY slice as well.

The downward magnetic reconnection outflows can be seen with the maximum velocity (>~700km/s), while less dense finger-type supra-arcade downflows form with lower speeds below the post-shocked regions (*Fig. 5, 7*).

The termination shock front and a turbulent interface region below post-shocked plasma can be seen on the density maps as well. Turbulent flows, and fast- and slow-mode shocks can appear in these areas (*Fig. 6*).

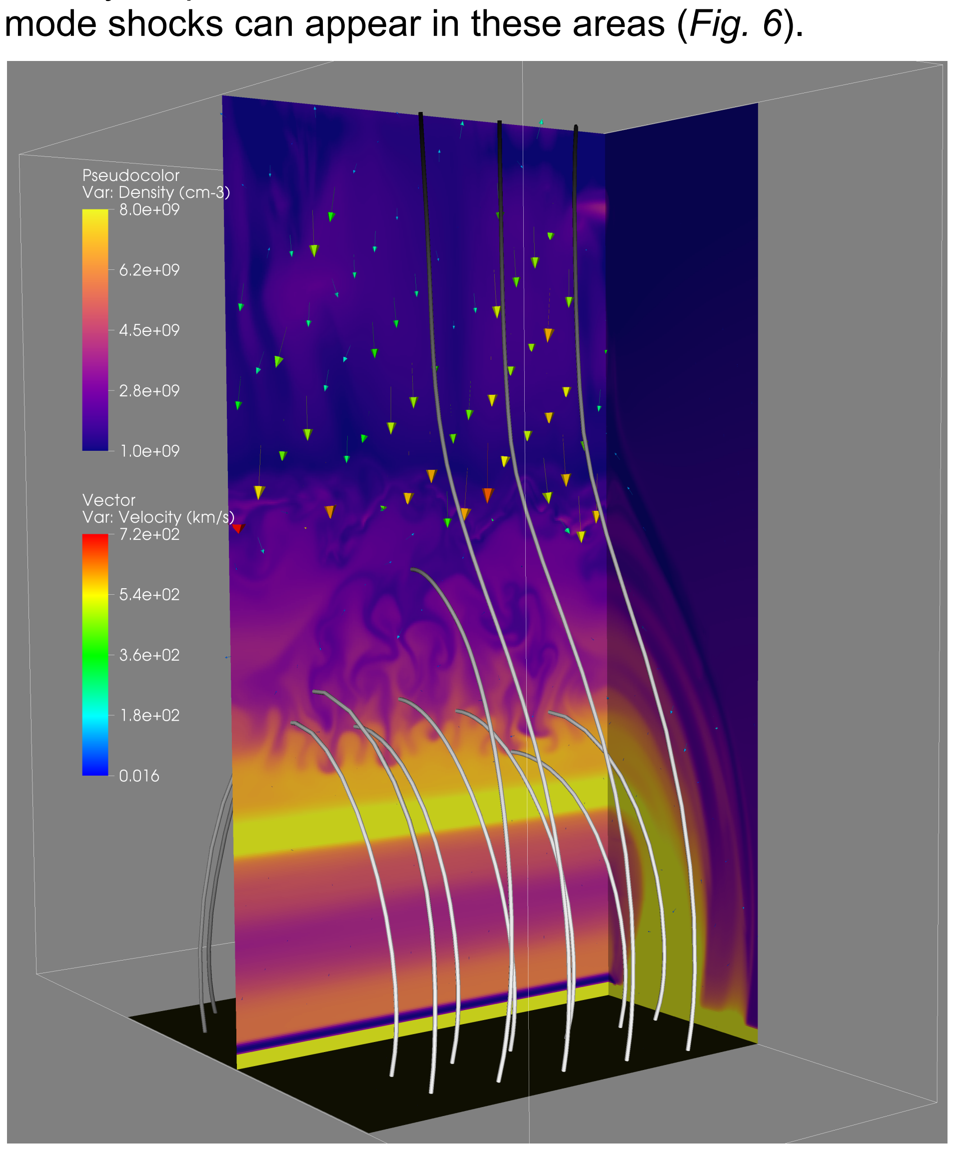

Fig 5. 3D modeling of the reconnection current sheet and post-reconnection flare loops at time=5t₀. The solid curves indicate magnetic field lines and arrows are the velocity vectors

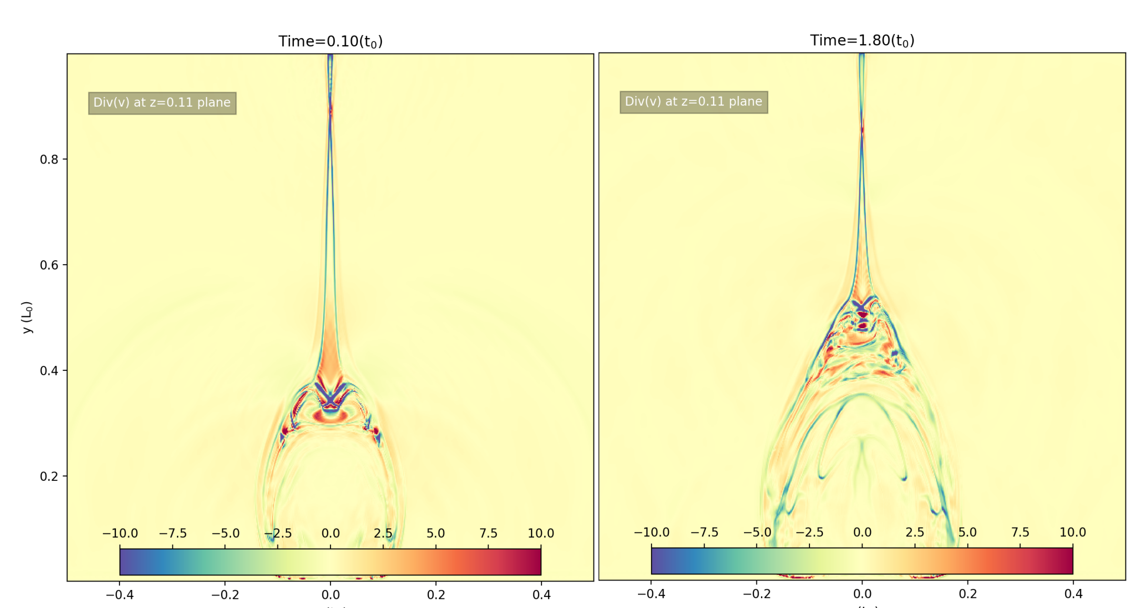

Fig 6. 2D slice on the z=0.11 plane of the 3D model in different times. The fast- and slow-mode shocks can be identified by the minimum Div(V) contours.

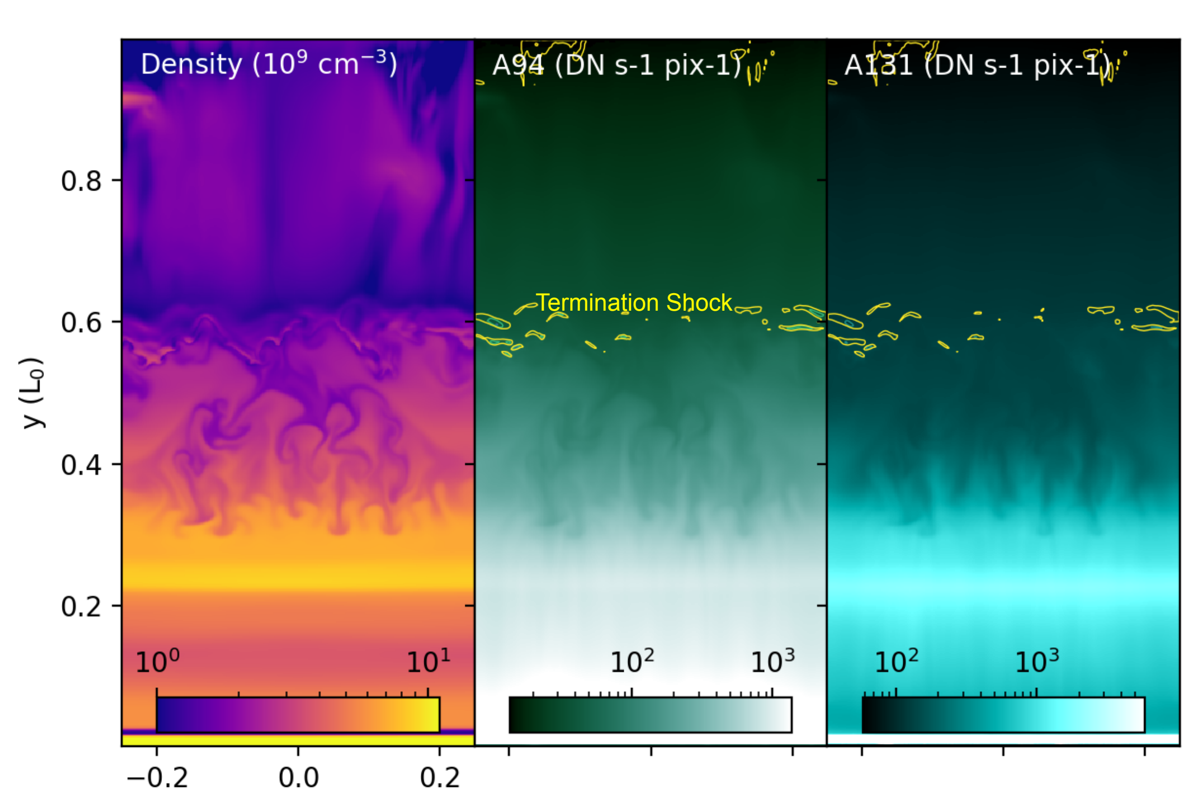

Fig 7. Plasma density at the center plane (x=0) at Time=5t₀, and synthetic AIA 94 and 131 images integrated along the line of sight. The finger-like density depletion structures appear as dark voids seen in the synthetic AIA images, which closely resembles the observed features of SADs.

Summary

- We perform 3D (and 2.5D) MHD simulations with an initial magnetic configuration according to the standard flare model;
- Our simulation reproduces many core features predicted in the standard model: e.g., fast reconnection outflow, slow-mode shocks, termination shock;
- The model also reveals the low-density finger-like downflows in a turbulent interface region where the reconnection outflows meet the flare arcade;
- We calculated the synthetic SDO/AIA images of these finger-like structures, which closely resemble the observed features of SADs.

1. T. G. Forbes, L. W. Acton, Astrophys. J. 459, 330 (1996).
2. S. L. Savage, D. E. McKenzie, Astrophys. J. 730, 98 (2011).
3. J. M. Stone, T. A. Gardiner, P. Teuben, J. F. Hawley, J. B. Simon, Astrophys. J. Supp. 178, 137 (2008).
4. C. Shen, X. Kong, F. Guo, J. C. Raymond, B. Chen, Astrophys. J. 869, 116 (2018).

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