RAYLEIGH–TAYLOR TYPE INSTABILITIES IN THE RECONNECTION EXHAUST JET AS A MECHANISM FOR SUPRA-ARCADE DOWNFLOWS IN THE SUN

L.-J. GUO1,2,3,4, Y.-M. HUANG1,2,3, A. BHATTACHARJEE1,2,3, and D. E. INNES3,4

1 Space Science Center, University of New Hampshire, Durham, NH 03824, USA
2 Center for Heliosciences, Department of Astrophysical Sciences and Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ 08540, USA; yimin@princeton.edu, amitava@princeton.edu
3 Max Planck/Princeton Center for Plasma Physics, Princeton, NJ 08540, USA
4 Max-Planck Institute for Solar System Research, D-37077 Göttingen, Germany; guol@mps.mpg.de, innes@mps.mpg.de

ABSTRACT

Supra-arcade downflows (hereafter referred to as SADs) are low-emission, elongated, finger-like features observed in active region coronae above post-eruption flare arcades. Observations exhibit downward moving SADs intertwined with bright upward growing spikes. Whereas SADs are dark voids, spikes are brighter, denser structures. Although SADs have been observed for more than a decade, the mechanism of the formation of SADs remains an open issue. Using three-dimensional resistive magnetohydrodynamic simulations, we demonstrate that Rayleigh–Taylor-type instabilities develop in the downstream region of a reconnecting current sheet. The instabilities result in the formation of low-density coherent structures that resemble SADs, and high-density structures that appear to be spike-like. Comparison between the simulation results and observations suggests that Rayleigh–Taylor-type instabilities in the exhaust of reconnecting current sheets provide a plausible mechanism for observed SADs.

Key words: instabilities – magnetic reconnection – Sun: flares

Online-only material: animation, color figures

1. INTRODUCTION

Supra-arcade downflows (SADs, also known as tadpoles due to their wavy appearance) are low-emission, elongated features usually observed in active region coronae above post-eruption flare arcades (McKenzie & Hudson 1999; McKenzie 2000). SADs are usually observed in the extreme ultraviolet (EUV) and X-ray filter images that detect plasma in the temperature range \(10^6 \text{–} 10^7 \text{K}\), and they have a typical lifetime of a few minutes. By using the filter ratio method (Hara et al. 1992) and data from the Soft X-ray Telescope, McKenzie & Hudson (1999) showed that SADs are high-temperature \((\sim 10^7 \text{K})\) structures. Solar Ultraviolet Measurement of Emitted Radiation spectroscopic analysis, conducted by Innes et al. (2003a), suggests that SADs have low density \((<10^9 \text{ cm}^{-3})\). This result was later confirmed by Savage et al. (2012) as well as by Hanneman & Reeves (2014). Asai et al. (2004) suggested that the formation of SADs involves magnetic reconnection or consequent outflows. Khan et al. (2007) conducted a statistical study of the relation between SADs and hard X-ray bursts, and concluded that most SADs are related to the main flare energy release process. Innes et al. (2003b) reported high Doppler-shifted Fe xxi line profiles at the edges of SADs, corresponding to line-of-sight velocity up to 1000 km s\(^{-1}\). More recently, Savage & McKenzie (2011) conducted a statistical study and found that the average velocity of most SADs is around 150 km s\(^{-1}\), which is a fraction of the typical Alfvén speed \((\sim 1000 \text{ km s}^{-1})\) in coronae. Verwichte et al. (2005) reported observations of waves with periods in the range of 90–220 s along SADs and suggested that a fast mode kink wave was responsible for SAD oscillations. Furthermore, McKenzie (2013) performed local correlation tracking on sequences of EUV images and found that vortices existed at the regions where SADs were observed. However, the cause of the observed dynamics of SADs is not yet clearly established.

It is important not to confuse SADs with plasmoids or magnetic islands. Observationally, SADs are density depletion regions (Innes et al. 2003a; Savage et al. 2012), whereas plasmoids are usually density-enhanced structures (Lin et al. 2005; Liu et al. 2010; Guo et al. 2013). Plasmoids are observed edge-on as bright blobs moving along the post-coronal mass ejection (CME) current sheet, whereas SADs are most clearly visible when observing the current sheet and the underlying arcade face-on. This distinction is clearly illustrated in Asai et al. (2004) and Savage et al. (2012).

Although SADs have been the subject of significant theoretical research during the past decade, the physical mechanisms that drive the formation of finger-like SADs remain under debate. The “patchy reconnection” model (Linton & Longcope 2006; Linton et al. 2009) uses spatially localized anomalous resistivity intermittently over time along the current sheet layer to trigger intermittent reconnection. The reconnect magnetic field lines then cause intermittent disturbances in the current sheet as they contract toward the downstream region, and the flux tubes that emerge, with tear-drop-like cross-sections, have been interpreted as SADs. To test this idea, Scott et al. (2013) attempt to reproduce SADs in simulation as the wakes caused by reconnect flux tubes moving at a high speed. On the other hand, the SAD model developed by Costa et al. (2009), Maglione et al. (2011), and Cécere et al. (2012) assumes multiple reconnection sites in which the SADs are a consequence of shocks and rarefactions bouncing back and forth within magnetic structures. In these studies, magnetic reconnection is not directly simulated; instead, reconnection events are modeled with localized pressure enhancements in the initial conditions. Recently, Cassak et al. (2013) proposed that SADs are flow channels carved by low-density, sunward-directed reconnection jets in the high-density flare arcades. In this scenario, reconnection is continuous in time so that the SADs are not filled in from behind as they would be if they were caused by isolated descending flux
tubes. In the models mentioned above, reconnection has to be at least spatially localized to produce SAD-like structures, while in some scenarios reconnection has to be temporally localized as well.

In this Letter, we show that the finger-like SADs can arise as a result of Rayleigh–Taylor-type instabilities in the exhaust of a post-eruption current sheet. This physical mechanism was first suggested in Asai et al. (2004) and explored partially in some scenarios reconnection has to be temporally localized least spatially localized to produce SAD-like structures, while tubes. In the models mentioned above, reconnection has to be at least spatially localized to produce SAD-like structures, while in some scenarios reconnection has to be temporally localized as well.

In this Letter, we show that the finger-like SADs can arise as a result of Rayleigh–Taylor-type instabilities in the exhaust of a post-eruption current sheet. This physical mechanism was first suggested in Asai et al. (2004) and explored partially by TanDokoro & Fujimoto (2005) and Shimizu et al. (2009) in magnetohydrodynamic (MHD) simulations with localized anomalous resistivity that produce Petschek-like reconnection and subsequently finger-like instabilities in a propagating front. While we concur with these studies on the effects of anomalous resistivity, our simulation with uniform resistivity show that Rayleigh–Taylor-type instabilities also arise in the exhaust region of an extended Sweet–Parker current sheet. Synthetic emission count rates of Atmospheric Imaging Assembly (AIA) 131 Å and 193 Å filters calculated from simulation data show qualitative similarities with corresponding AIA images. Among the two simulations we have carried out, the one with uniform resistivity appears to be more consistent with observations. Readers are referred to a companion paper, Innes et al. (2014), for a more comprehensive discussion of SAD observations.

2. SIMULATIONS

2.1. Simulation Setup

Our numerical model solves the following normalized three-dimensional MHD equations:

\[ \partial_t \rho = -\nabla \cdot (\rho \mathbf{v}), \quad \text{(1)} \]

\[ \partial_t (\rho \mathbf{v}) = -\nabla \cdot (\rho \mathbf{v} \mathbf{v}) - \rho \mathbf{v} \mathbf{v} + \mathbf{J} \times \mathbf{B} + \mu \nabla^2 (\rho \mathbf{v}), \quad \text{(2)} \]

\[ \partial_t p = -\nabla \cdot (p \mathbf{v}) - (\gamma - 1) p \nabla \cdot \mathbf{v} + (\gamma - 1) \eta J^2, \quad \text{(3)} \]

\[ \partial_t \mathbf{B} = -\nabla \times (-\mathbf{v} \times \mathbf{B} + \eta \mathbf{J}). \quad \text{(4)} \]

Here \( \rho \) is the plasma density, \( \mathbf{v} \) is the plasma’s velocity, \( \mathbf{B} \) is the magnetic field, \( \mathbf{J} = \nabla \times \mathbf{B} \) is the electric current density, \( p \) is the plasma thermal pressure, \( \mu \) is the plasma viscosity, and \( \eta \) is the plasma resistivity. This model includes Ohmic heating, but does not include viscous heating, heat conduction and radiation cooling. Gravity is also not included.

We consider a triply periodic system in the domain \( -L_x \leq x \leq L_x, -L_y \leq y \leq L_y, -L_z \leq z \leq L_z \). However, simulations are carried out in the region \( 0 \leq x \leq L_x \) and \( 0 \leq z \leq L_z \), and solutions in the remaining part of the domain are inferred by symmetry. The initial magnetic field is the Harris double current layer (TanDokoro & Fujimoto 2005) defined as

\[ B_x = \begin{cases} B_0 \tanh(z/a) & |z| \leq L_z/2 \\ -B_0 \tanh((z - L_z)/a) & z > L_z/2 \end{cases}, \quad \text{(5)} \]

where \( a \) is the Harris current sheet width and \( B_0 \) is the asymptotic magnetic field strength in the upstream region. No guide field is included. The plasma thermal pressure is calculated by

\[ p + \frac{B_z^2}{2} = \frac{B_0^2}{2} + p_0, \quad \text{(6)} \]

and the density profile is determined by the ideal gas law \( p = 2 \rho T_0 \), where \( T_0 \) is the constant initial temperature and the factor two is due to contributions from both electrons and ions. In normalized units, we set \( T_0 = 0.125, B_0 = 1, a = 1 \), and \( \mu = 5 \times 10^{-4} \). The density \( \rho = 1 \) and the plasma beta \( \beta = 2 \rho / B_0^2 = 0.5 \) in the asymptotic region, which is taken to be a region far away from the reconnection layer. The density within the current sheet is higher than the asymptotic region with \( \rho = 3 \) at \( z = 0 \). The initial density profile is seeded with a random noise of magnitude \( 3 \times 10^{-2} \) to facilitate the instability. The dimensions of the simulation box are \( L_x = 150, L_y = 12, L_z = 40 \). The +x direction is interpreted as the sunward direction, and \( x = 150 \) is idealized as the surface of the Sun. We impose \( \mathbf{V}_i = 0 \) at the lower boundary and the footpoints of field lines are not line-tied.

With this basic setting, we have carried out simulations with uniform, as well as with spatially localized anomalous resistivity. Panel (a) of Figure 1 shows the density profile in a two-dimensional (2D) plane in the model with uniform resistivity overplotted with projections of magnetic field lines. Likewise, panel (b) of Figure 1 shows the configuration of the model with anomalous resistivity. These two snapshots are taken at times before instabilities set in, so the configuration is approximately uniform along the out-of-plane direction. Details of these two simulations are discussed below.

2.2. Uniform Resistivity Run

A uniform resistivity \( \eta = 3 \times 10^{-3} \) is used for the whole simulation box in this run, with the grid numbers \( n_x = 800, n_y = 120, n_z = 400 \). To start the reconnection, we add an initial perturbation to the magnetic field in the x and z directions:

\[ \delta B_x = -0.025 B_0 \frac{L_x}{L_z} \cos \left( \frac{\pi x}{L_x} \right) \sin \left( \frac{\pi z}{L_z} \right), \]

(\text{image}) Figure 1. Two-dimensional density profile (unit: \text{cm}^{-3}) overplotted with projections of magnetic field lines for the model with (a) uniform resistivity and (b) anomalous resistivity. (A color version of this figure is available in the online journal.)
Figure 2. Panel (a) shows the magnetic field line (shaded by values of density along its path) configuration and a $x-y$ slice of the density profile at $z = 0.1$ from the MHD model with uniform resistivity. Panel (b) shows the density profile (unit: cm$^{-3}$) along the $z = 0$ plane, panel (c) shows the temperature profile (unit: K) on the same plane, panel (d) shows the synthetic AIA 131 Å emission count rate, and panel (e) shows the synthetic AIA 193 Å emission count rate.

(A color version of this figure is available in the online journal.)

\[
\delta B_z = 0.025 B_0 \sin \left( \frac{\pi x}{L_x} \right) \cos \left( \frac{\pi z}{L_z} \right) .
\]

Subsequently, magnetic reconnection occurs along an extended Sweet–Parker current sheet. Reconnected magnetic field lines form magnetic arcades in the downstream region, as can be seen in panel (a) of Figure 1. The plasma ejected by the reconnection outflows accumulates and forms a high-density region in the arcade. An interface forms between the lower density reconnection outflows and the higher density plasma, which later on becomes wavy and eventually develops finger-like structures. Panel (a) of Figure 2 shows a close-up of the region where the finger-like structures form. Two groups of field lines are traced. One goes through where the instabilities occur and is severely perturbed and distorted. The other goes through a less perturbed region below the instabilities, where the magnetic field lines approximately form arcades. Panel (b) of Figure 2 shows a 2D slice of the density profile in the $x-y$ plane near the center of the current sheet ($z = 0$), panel (c) shows the temperature profile and panel (d) shows the expected count rate (DN s$^{-1}$ pixel$^{-1}$) in the AIA 131 Å channel. The emission count rate is calculated according to the formula \( CR = \int n^2 f(T) dl \) DN s$^{-1}$ pixel$^{-1}$, where \( f(T) \) is the AIA 131 Å response function (Lemen et al. 2012), \( n \) is the electron number density, \( T \) is the temperature, and \( dl \) is the line element along the line of sight. Likewise, we also calculate the emission count rate in the AIA 193 Å channel, shown in panel (e) of Figure 2. To use the response function, the plasma density and temperature have to be converted to dimensional units. Here the density is converted by assuming that unit density in simulation equals 10$^9$ cm$^{-3}$. The temperature is converted by assuming that the normalized Alfvén speed \( V_A = 1 \) in the simulation corresponds to \( V_A = 1000$ km s$^{-1}$ in the corona, which gives the initial temperature \( T_{\text{real}} = (m_p V_A^2/k) T_{\text{code}} = (1.67 \times 10^{-27}$ kg \( \times (10^6$ m s$^{-1})^2 / 1.38 \times 10^{-23}$ m$^3$ kg s$^{-2}$ K$^{-1}) \times 0.125 \approx 1.5 \times 10^7$ K for our simulation. Likewise, the initial normalized magnetic field in the lobe \( (B_{\text{code}} = 1) \) corresponds to \( B_{\text{real}} \approx 14$ G, which is a reasonable value for the coronal magnetic field. The spatial scale in all the figures is dimensionless. Assuming the length of the current sheet \( L = 2 L_x \) is one solar radius, it follows that one simulation length unit equals about 3”. The typical width of the finger-like structures is about two to five simulation length units, corresponding to 6”–15”. These values are consistent with observations.

The finger-like structures in all four panels of Figure 2 appear to be caused by plasma instabilities. As can be seen from panel (b) of Figure 2, the instabilities take place at the interface between lighter reconnection outflows and denser plasma (piled-up density in front of reconnection outflows). Because the reconnection outflows push the relatively stationary plasma ahead, the deceleration existing between lighter and denser plasma plays a role that is equivalent to gravity in the Rayleigh–Taylor instability. In addition, the “unfavorable” curvature of the magnetic field lines on the top of the arcades (panel (a) of Figure 2) makes the system potentially unstable to the ballooning instability (see Bhattacharjee et al. 1998). Because the resistivity is uniform in space and constant over time, the result of this run suggests that the intermittent formation of finger-like SADs does not necessarily require intermittent, locally enhanced resistivity, but can be attributed to ideal instabilities in the downstream region.
Figure 3. Flow pattern overplotted on a frame of the density profile. 
(A color version of this figure is available in the online journal.)

Figure 4. Three snapshots of AIA 131 Å emission count rates demonstrating the evolution of SADs. 
(An animation and a color version of this figure are available online.)

The typical speed of the SADs (speed of the tip motion) in this run is \( \sim 0.05 \) \( V_A \), corresponding to 50 km s\(^{-1}\) which is comparable to the observed value. The instabilities also induce transverse motion of SADs. Figure 3 shows the flow pattern on the \( x-y \) plane at a time slightly later than the snapshot in Figure 2, overplotted on the density profile shown in color. Downward growing tadpoles and upward growing spikes can both be seen in Figure 3, as well as vortices. As a result of flows induced by instabilities, the supra-arcade fan becomes quite turbulent. This result is consistent with the observation of eddies co-existing with SADs reported by McKenzie (2013).

As SAD-like structures are growing and evolving, new structures show up at the top of the supra-arcade fan, qualitatively consistent with observations reported by Innes et al. (2014). Figure 4 demonstrates the evolution of SAD-like structures. Panels (a) and (b) show how instabilities at \( x \approx 130 \) grow, while panel (c) features one newly formed SAD at \( y \approx -2 \) along the tip of a spike. Throughout the whole simulation, new SAD-like structures keep occurring until the supra-arcade fan become extremely turbulent. An animation of the simulation is available in the online version of this Letter.

2.3. Anomalous Resistivity Run

To test how different models of resistivity may affect the instabilities in the downstream region, we have carried out a second run with Petschek-type reconnection triggered by introducing a locally enhanced anomalous resistivity \( \eta = \eta_0 \exp(-x^2 - z^2), \) with \( \eta_0 = 3 \times 10^{-3}. \) The grid numbers of this run are \( n_x = 1600, \) \( n_y = 240, \) \( n_z = 400. \) The Petschek-type reconnection soon creates a shock-like front propagating at the Alfvénic speed along the \( +x \) direction (panel (b) of Figure 1), while the current sheet below the shock front remains unperturbed. This propagating front later develops wavy structures, which subsequently grow in the \( x \) direction. Panel (a) of Figure 5 shows a projected view of magnetic field lines, and a slice of the density profile at \( z = 0.1. \) Two groups of field lines are traced. One goes through where the instabilities occur and is severely perturbed and distorted. The other goes through a less perturbed region above the instabilities, where the magnetic field lines approximately form arcades. Panels (b) and (c) of Figure 5 shows a 2D slice of the density and temperature profile on the \( x-y \) plane near the center of the current sheet (\( z = 0 \).) Panels (d) and (e) shows the AIA 131 Å and 193 Å emission count rate calculated from the simulation data.

The SADs in this run are qualitatively similar to the ones we obtained with uniform resistivity. This suggests that the reconnection mechanism in the upstream region does not directly affect instabilities in the downstream region. Nevertheless, configurations of this model such as the shock front propagating along the current sheet at an Alfvénic speed have not yet been reported in observations. Furthermore, as shown in Figure 5(a), the SAD-like structures develop below the arcade, which is inconsistent with observations. Therefore, among the two simulations, the uniform resistivity run appears to be more consistent with observations.

3. SUMMARY AND CONCLUSIONS

The mechanism causing the formation of SADs has been an open question since their first discovery. Most existing simulations of SADs depend on intermittently and locally induced reconnection events to reproduce finger-like SADs along current sheet layers. In this Letter, we demonstrate that
SADs might be the result of Rayleigh–Taylor type instabilities in the downstream region of a reconnection site. We implement resistive MHD models with both uniform and spatially localized anomalous resistivity. Finger-like structures are generated in both runs with different dynamic behaviors. Therefore, we have shown that SAD-like structures can arise without reconnection being patchy. Our scenario requires that plasma density in the downstream region has to be higher than the outflow jet density. In the uniform resistivity run, this condition is a natural consequence of reconnection, as plasma from the outflow jets gradually accumulates in the arcade. In the anomalous resistivity run, however, the density gradient develops as the propagating front pushes the unperturbed Harris sheet ahead. A density gradient is also noted as essential in the scenario of Cassak et al. (2013). However, SAD-like structures are observed in our scenario when viewing the reconnecting current sheet face-on, which is consistent with observations, whereas they are observed in the scenario of Cassak et al. (2013) when viewing the current sheet edge-on.

The comparisons between our simulations and observations of SADs are discussed and summarized as follows.

1. **Appearance**. The downward developing parts (tadpoles) of the finger-like structures are characterized by low-density and low EUV emission count rate (shown in Figures 2 and 5). The upward developing parts (spikes) are characterized by higher density and higher EUV emission count rate. The downward developing parts in the simulations are very similar to the observations of SADs, while the upward developing parts resemble bright spikes observed among SADs. We also note that in the run with uniform resistivity, SADs formed at the top of fan spikes, which is consistent with recent AIA observations (Innes et al. 2014).

2. **The timeline and the location**. After the initial eruption of a CME, part of reconnection outflows are observed moving toward the Sun. Reconnection outflows soon build up a bright fan (also known as supra arcade fan) above existing flare arcades. After a while (usually less than 1 hr), SADs start to show up as dark flows falling through the supra arcade fan. A single SAD element (or tadpole) is usually visible for a few minutes, and new SADs are seen to fall from higher spatial locations as a falling SAD becomes less visible. The whole event can last for a few hours. A very similar scenario is observed in the simulation with uniform resistivity, where reconnection outflows build up a bright fan and SAD-like instabilities take places at the top of the fan. It is worth noting that SADs are often observed together...
with supra-arcade downflow loops (SADLs), which are downward shrinking bright loops in reconnection outflow. While the models in this Letter are able to reproduce SAD-like structures, SADL-like structures have not been observed clearly in our simulation. This might be because our initial configuration is too idealized, an issue we plan to address in future work.

3. Dynamic characteristics. In most events, SADs move sunward at an average speed much lower than the Alfvén speed (Savage & McKenzie 2011), typically 15% of the Alfvén speed in the corona (1000 km s$^{-1}$). In the run with uniform resistivity, the instabilities occur at the top of the magnetic arcades where reconnection outflows have been decelerated almost to a standstill. The velocity of SADs is essentially the growth rate of the Rayleigh–Taylor-type instabilities, which is approximately 5% of the Alfvén speed. In the run with anomalous resistivity, the instabilities develop at the shock-like front propagating sunward at an Alfvénic speed, which is not in good agreement with observations. In both cases, the Rayleigh–Taylor instabilities introduce transverse flows into the system, making the exhaust region quite turbulent.

4. Thermal structure. Figure 2(b) shows that the SAD-like structures are slightly hotter than the supra-arcade fan, by a factor of about 1.5 and they are dark in the hot 193 Å channel, which is consistent with observations (Hanneman & Reeves 2014). Our MHD model does not include heat conduction and radiation cooling, therefore a more accurate temperature profile needs to be obtained in the future. Furthermore, energetic particles could be an important source of heating in flare plasma, which is beyond the scope of our MHD model. Energetic particles are also likely to be important in the nonthermal hard X-ray bursts correlated with the occurrences of SADs. Further work is needed to account for these observational features.

In conclusion, our results suggest that Rayleigh–Taylor-type instabilities in the downstream region of a reconnecting current sheet provide a plausible mechanism for the formation of SADs. While Rayleigh–Taylor-type instabilities arise in simulations with uniform resistivity and anomalous resistivity, the model with uniform resistivity appears to be more consistent with observations. Rayleigh–Taylor-type instabilities have also been observed in recent fully kinetic particle-in-cell simulations (Vapirev et al. 2013). Further study of the instabilities with different underlying models and detailed comparison with observations should shed new light on the nature of SADs, as well as what can be learned about the structure of the reconnection site from the appearance of SADs.

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