3D MHD SIMULATION OF FLARE SUPRA-ARCADE DOWNFLOWS IN A TURBULENT CURRENT SHEET MEDIUM

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ABSTRACT

Supra-arcade downflows (SADs) are sunward, generally dark, plasma density depletions originated above postereruption flare arcades. In this paper, using 3D MHD simulations we investigate whether the SAD cavities can be produced by a direct combination of the tearing mode and Kelvin–Helmholtz instabilities leading to a turbulent current sheet (CS) medium or if the current sheet is merely the background where SADs are produced, triggered by an impulsive deposition of energy. We find that to give an account of the observational dark lane structures an addition of local energy, provided by a reconnection event, is required. We suggest that there may be a closed relation between characteristic SAD sizes and CS widths that must be satisfied to obtain an observable SAD.

Key words: magnetohydrodynamics (MHD) – Sun: corona – turbulence

Supporting material: animations

1. INTRODUCTION

Supra-arcade downflow (SAD) features are known to be dark moving trails originated \([40–60] \text{ Mm}\) above eruption flare arcades with decelerating speeds in the range of \([-50–500] \text{ km s}^{-1}\) (McKenzie 2000; McKenzie & Savage 2009; Savage & McKenzie 2011). They were first detected with the \textit{Yohkoh} Soft X-ray Telescope (McKenzie & Hudson 1999). Since then, they have extensively been reported using other instruments such as \textit{TRACE} (Innes et al. 2003a, 2003b), \textit{Solar and Heliospheric Observatory}/SUMER (Innes et al. 2003b), and \textit{SDO}/AIA (Savage et al. 2012). There is a consensus that due to the lack of X-ray and extreme-ultraviolet signatures in images and spectra, these SAD structures are voided flows generated by reconnection processes in a CS above the flare arcade.

Several scenarios have been proposed to give an account of the observations. After new AIA detections with high spatial resolution and temporal cadence, Savage et al. (2012) re-interpreted SADs as density depletions left in the wake of thin shrinking loops. These authors indicated that either retracting loops will be observed when the area above the flare arcade is devoid of plasma (impulsive phase), or SADs will be observed when a hot dense fan of plasma is present above the flare arcade (decay phase). They also proposed that deceleration is expected due to the buildup of downstream magnetic pressure and/or drag mechanisms.

Another scenario was proposed by Linton et al. (2009), where the dynamic of retracting magnetic fields is triggered by a localized reconnection event that produces up- and down-flowing reconnected flux tubes, which are slowed down by underlying magnetic arcade loops. A drawback with this scenario is that the observed SAD speeds are lower than expected for reconnection outflows in regions of typical Alfvén speeds of \(1000 \text{ km s}^{-1}\).

We are especially interested in the turbulent CS description given by McKenzie (2013). He analyzed high-resolution observations in a sheet-like structure above a post-CME flare arcade where the turbulent dynamic of a complex flow is described. He found that the plasma \(\beta\) (the ratio of gas to magnetic pressure) is of the order of unity and described the flow variability in the hot plasma \((T > 10 \text{ MK})\) as a product of strong velocity shears and vortical motion where small vortices moving toward the arcade were interpreted as probable SAD structures.

In Costa et al. (2009), Schulz et al. (2010), Maglione et al. (2011) and Cécere et al. (2012) we reproduced the dynamics of multiple decelerating downflows through the assumption that dark tracks are confined voided cavities—of high \(\beta\) and temperature values—collimated in the direction of the ambient magnetic field and generated by the bouncing and interfering of shocks and expansion waves upstream of the initial localized deposition of energy provided by reconnection events. In this scenario, the different observational SAD sizes could be interpreted either as the consequence of reconnection events that are triggered in a homogeneous background or as the consequence of reconnection events produced in a previously distorted media by the passage of earlier SADs. We found that the observed wavy character (Verwichte et al. 2005) can be interpreted as an indication of interaction between SADs. This interaction is significant when the bursts that trigger the phenomenon act on the wakes left by previous SADs.

Recent observational data and modeling have challenged the scenario described by Cécere et al. (2012). Hanneman & Reeves (2014) measured the plasma temperature of the SAD regions and surrounding plasma sheet using AIA and XRT data. They calculated differential emission measures (EMs) for several flares and their corresponding SADs and found that there is little convincing evidence to sustain the high temperatures in the SADs predicted by Maglione et al. (2011) and Cécere et al. (2012). They also found that SADs are always hotter than the background, but in many cases cooler than the surrounding fan plasma.

Related to thermal conduction considerations, one of the major challenges is to understand how it is possible that SADs can last in hot CS. In fact, structures with typical SAD sizes of decades of Mm, typical coronal number densities of \(n \approx 10^9 \text{ cm}^{-3}\) and temperatures as high as \(T \approx 10 \text{ MK}\)
(McKenzie 2013) will vanish in times (of a few seconds) that are at least two orders of magnitude lower than the observed values. However, we show that considering a typical coronal background ($T \sim 1$ MK) and/or the high density fan region ($n \sim 2 \times 10^{10}$ cm$^{-3}$) as the medium where the SAD dynamic develops, the thermal conduction effects are low enough to allow the comparison with the observations.

In what follows, motivated by the description provided by McKenzie (2013), we explore a new scenario. We consider a quasi-2D turbulent CS as the medium where SAD features can be observed. We propose that SADs are voided cavities formed by nonlinear waves, waves which are triggered by bursty reconnection events (blast wave expansion mechanism, Forbes 1988; Kumar & Innes 2013) that occur during a large-scale reconnection process. That is, the quasi-2D turbulent CS evolution times are much larger than the SAD ones. We emulate these individual reconnection events by pressure pulses.

We perform 3D magnetohydrodynamic (MHD) simulations including magnetic resistivity and assuming that heating and cooling terms compensate each other. The paper is structured as follows: in Section 2 we consider turbulence and CS formation; in Section 3 we justify the assumption made regarding the cooling (conduction and radiation) and heating (reconnection) term; in Section 4 we present the model; in Section 5 we state the numerical setup and initial conditions. In Section 6 we discuss the results obtained, and in Section 7 we summarize the conclusions.

2. RECONNECTION PROCESSES: TURBULENT CURRENT SHEETS AND BURSTY RECONNECTION

The notion of quasi-separatrix layers proved to be fertile since observational and theoretical reconnection studies showed that 3D reconnection requires going beyond the classical generalization of 2D null points and their correspondent separatrices (e.g., Priest & Démoulin 1995; Schmieder et al. 1997).

However, the study of 2D CS formation and evolution is still important even for 3D calculations. Onofri et al. (2004) simulated magnetic reconnection on a slab geometry and showed that the presence of a global guiding magnetic field makes the 3D evolution much similar to those of purely 2D (see also Fermo et al. 2010). The formation of smaller scale structures associated with a direct energy transfer, allowing larger diffusion and faster reconnection rates, is a consequence of the nonlinear evolution that eventually ends in a turbulent regime of many spatial scales. The simulations with a guide field produce both a direct and an inverse energy cascade. The inverse energy transfer generates coalescence of magnetic islands, which are typical 2D structures. In the direct cascade the wavelengths decrease with increasing distance from the CS. Coalescence is mostly suppressed when faster 3D phenomena are significant. Thus, the fact that coalescence is present is an indication that a 2D picture is a good description of a phenomenon.

Typical observational evidence of these quasi-2D CS configurations was described by Guo et al. (2013), where the coalescent plasmoids or those long-lasting slab configurations usually seen above arcades can be observed (e.g., McKenzie 2000; McKenzie & Savage 2009; Savage & McKenzie 2011).

There is a broad range of determinations concerning the thickness of 2D CSs. Guo et al. (2013), using observational data and a 2D simulation, estimated an upper limit of the CS width of 3 Mm. However, related to non-thermal line widths, Ciaravella & Raymond (2008) reported CS thickness ranging within ~[28–56] Mm and Bemporad (2008) attributed the large temperatures and observed CS thickness (~[10–100] Mm) to turbulence. Discrepancies between widths could be due to either the impossibility of observationally distinguishing between the CS and a sheath of hot plasma surrounding the CS (Seaton & Forbes 2009), non-thermal bulk flows and/or turbulence (Bemporad 2008; Ciaravella & Raymond 2008), or different regimes of 2D CSs behavior (Heyvaerts & Kuperus 1978) where an adiabatic description would be accurate.

Deviating from these 2D descriptions, flares that release impulsive energy in the absence of a sustained gradual phase were extensively studied (e.g., Priest 1982). The existence of explosive events in reconnection processes implies that they occur on a faster timescale than large-scale ones. It was suggested that this could be either due to the presence of stressed magnetic flux tubes that become unstable and produce individual bursty reconnection in the frame of the longer term process or because reconnection itself is inherently impulsive and bursty (Priest 1986; Priest & Forbes 2000). Forbes (1988) pointed out the importance of blast waves produced by pressure-driven expansions and shocks due to impulsively driven reconnection and recently Kumar & Innes (2013) observed a limb flare and proposed a flare blast wave scenario to describe it.

Thus, due to the above discussion we will consider a turbulent quasi-2D CS of a different thickness as the medium where SADs may be observed.

3. THE EFFECTS OF THERMAL CONDUCTION

Seaton & Forbes (2009) studied a CS model to analyze reconnection outflow jets considering thermal conduction. Based on a model by Somov et al. (1987) they assumed that a 2D CS is generated by a Petschek-type reconnection model and found that for large heat conduction values, the internal CS temperatures are almost uniform and equal to the background values (see Figure 7 in Seaton & Forbes 2009). Considering that surrounding a CS an expanded thermal halo is formed, they assumed an almost steady configuration where, in accordance with observations, density is uniform and internally enhanced over the background coronal densities (Schwenn et al. 2006). However, this CS scenario of almost uniform density and low temperature, dominated by heat conduction, does not seem to be consistent with a typical turbulent inhomogeneous hot media where SADs are observed. It seems that only when conduction is not dominant with respect to the reconnection process (they did not consider cooling by radiation), would higher internal CS temperatures and nonuniform density distributions be obtained.

In fact, Ciaravella & Raymond (2008) studied the CS associated with the 2003 November 4th CME and found large non-thermal [Fe XVII] line broadening. The corresponding speeds were as high as 380 km s$^{-1}$ at an early stage, and later—in a fairly constant phase—they ranged between [50–200] km s$^{-1}$. They concluded that these non-thermal effects are explained by the presence of turbulence and bulk flows.

Although conduction and radiation are both cooling processes, while conduction proceeds to distribute heat—being highly efficient in hot CSs—the radiation acts as a sink
function that takes heat away locally. Thus, the heat conduction tends to expand the system distributing the energy, and the radiation tends to narrow it by reducing the gas pressure with respect to the surrounding media. Theoretical and observational CS studies (e.g., Bemporad 2008; Ciaravella & Raymond 2008) support the existence of CSs with quasi-stable thickness values, thus reconnection processes should provide the energy to stabilize the CS width for times comparable with the observations. Thus, a certain set of CS parameters could give an account of an energy balanced open system where diffusion is limited, allowing the observation of SADs for times comparable with the observations.

There are three main physical processes for energy balance in the CS: thermal conduction, radiation, and reconnection. The timescales of conductive and radiative cooling are:

\[ t_{\text{cond}} = \frac{3nk_B L^2}{\kappa_0 T^{5/2}}, \quad t_{\text{rad}} = \frac{3k_B T}{nE_t}, \]  

where \( n \) is the number density, \( k_B \) is the Boltzmann constant, \( L \) is a characteristic length, \( \kappa_0 \approx 10^{-6} \text{ erg K}^{-7/2} \text{ cm}^{-1} \text{ s}^{-1} \) is the heat conduction coefficient along the magnetic field, \( T \) is the temperature and \( E_t \) is the radiative loss function \( (E_t \approx 4 \times 10^{-23} \text{ erg cm}^{-3} \text{ s}^{-1} \text{ for } T \approx 10 \text{ MK}) \) (Aschwanden 2005).

To evaluate the timescale of reconnection heating, \( t_{\text{rec}} \), we follow Lazarian & Vishniac (1999), who proposed a low dissipation model where a turbulent quasi 2D CS is formed due to the presence of a guiding magnetic field that reduces the transverse scale for reconnection flows. Turbulent motion create small regions of intense field gradients and reconnection occurs in small layers spread throughout the larger direction. Associated with their model the reconnection timescale is

\[ t_{\text{rec}} = \frac{L}{v_A M_A^2} \]  

where \( v_A \) is the Alfvén speed and \( M_A \) is the Mach Alfvén number.

Hence, our aim is now to determine realistic CS physical parameters that lead to timescales compatible with an almost non-diffusive description, i.e., where SAD features can develop for times comparable with the observations.

4. THE MODEL: SADS AS BLAST WAVES—EXPLOSIVE EVENTS DURING A LONG DURATION RECONNECTION PROCESS IN A TURBULENT MEDIUM

We assume that SADs are voided and expanded cavities resulting from bursty reconnections (Forbes 1988; Kumar & Innes 2013) that occur during a larger scale 2D turbulent CS reconnection process. The triggering blast wave mechanism was proposed in Costa et al. (2009 see, e.g., the explanation given in Cécere et al. 2012 and Figure 3 therein). They are assumed as local features independent of the overall turbulent quasi-2D CS. Thus, they may eventually be triggered outside the CS reconnection region. However, because of the simplicity of the setup used (where the background is not modeled, only the CS environment was used to analyze the dynamic behavior) we can only simulate the case where SADs are triggered (already immersed) inside the CS; but we will argue in the conclusion section about what could happen when they are triggered outside the CS (see Figure 1).

![Diagram](image)

Figure 1. Simplified scheme of the 2D CS, formed by stochastic reconnection (Lazarian & Vishniac 1999), immersed in a coronal background media. A blast-wave reconnection process (Kumar & Innes 2013) leading to the formation of a SAD, is also indicated.

The initial conditions for the chosen CS parameters are: an average temperature value of \( T = 10 \text{ MK} \), an initial sunwardly guiding magnetic field value of \( \mathbf{B} = 5.9 \text{ G} \) (y axis), and an enhanced CS number density value of \( n = 2 \times 10^{10} \text{ cm}^{-3} \). As heat conduction is strongly inhibited across the magnetic field lines, and considering that the guiding magnetic field is oriented in the \( y \) direction, we calculate the heat conduction timescale considering a typical CS length of \( L = 140 \text{ Mm} \). With these values and using Equation (1) we obtain \( t_{\text{cond}} \approx t_{\text{rad}} \approx 5100 \text{ s} \).

With the above CS parameters, the Alfvén speed results in \( v_A = 92 \text{ km s}^{-1} \) and considering an average turbulent speed of \( v = 50 \text{ km s}^{-1} \) (Ciaravella & Raymond 2008; McKenzie 2013), using Equation (2) we obtain \( t_{\text{rec}} \approx 5247 \text{ s} \).

If we consider that a typical SAD is triggered by a blast phase associated with an initial adiabatic expanding shock, thermal conduction will not play a significant role in the exchange of heat with the surroundings at this early stage. Later, the thermal exchange with the SAD neighborhood will strongly depend on the field orientation. The blast stage leads to a magnetic configuration where the magnetic field lines tend to displace and envelope the SAD, thus the tendency is to thermally insulate it from the surroundings. Meanwhile, considering that SADs travel \( \sim (20-40) \text{ Mm} \) along the sunward \( y \) direction (appearing as elongated features of \( \sim 40 \text{ Mm} \) in the fan region) we obtain \( t_{\text{cond}} \approx (105-400) \text{ s} \), which is consistent with observational times. See, e.g., the animations provided by Savage et al. (2012).

With these assumptions, taking into account the calculated timescales, we consider that the cooling and heating terms compensate each other and that the conduction will not substantially alter the results for times comparable with the SAD observations. Different values of the chosen physical parameters would lead to a different scenario. In favor of this interpretation we can argue that lower thermal conduction times associated with other realistic parameters would lead to a rapid extinction of the observed features. We speculate that this particular scenario could explain why SADs are not always observed as associated with supra-arcade CSs. A model considering cooling terms due to anisotropic thermal conduction, radiation, and reconnection heating is in progress.
5. NUMERICAL CODE AND INITIAL CONDITIONS

We numerically solve the MHD equations. In conservative form they read (CGS units):

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

\[ \frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v} - \mathbf{B} \mathbf{B}) + \nabla p = 0, \]

\[ \frac{\partial e}{\partial t} + \nabla \cdot \left[ \left( e + p_\ast \right) \mathbf{v} - \mathbf{B} (\mathbf{v} \times \mathbf{B}) \right] = \nabla \cdot \left[ \mathbf{B} \times (\eta \nabla \times \mathbf{B}) \right], \]

\[ \frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{v} \mathbf{B} - \mathbf{B} \mathbf{v}) = \eta \nabla^2 \mathbf{B}, \]

\[ e = \frac{1}{2} \rho \mathbf{v}^2 + E + \frac{B^2}{2}, \]

\[ p_\ast = p + \frac{B^2}{2}, \]

\[ p = (\gamma - 1)E, \]

where \( \rho \) is the mass density, \( t \) is the time, \( \mathbf{v} \) is the plasma flow velocity, \( p \) is the thermal pressure, \( \mathbf{B} \) is the magnetic field divided by \( \sqrt{4\pi} \), \( E \) the total energy, \( \eta \) the internal energy, \( \gamma = 5/3 \) the rate of heat coefficients, and \( \eta \) is the resistivity.

The software used in this work was in part developed by the ASC/Alliance center for Astrophysical Thermonuclear Flashes at the University of Chicago (Fryxell et al. 2000). We perform 3D MHD simulations with the extensively validated FLASH4 code using the adaptive mesh refinement procedure with the Powell’s eight-wave scheme (Powell et al. 1999) to solve the MHD equations.

To generate a turbulent CS we start from a monolithic CS configuration with Lundquist value \( S \gtrsim 10^{10} \), greater than the critical value \( (S_c \sim 10^4) \) at which the Sweet–Parker CS becomes unstable. In this way, a turbulent regime is generated that gives an account of a hierarchical configuration of overdense plasma features connected by secondary CSs as described in the literature (see the references in Priest & Forbes 2000). The initial regime is set up with a uniform diffusivity of \( \eta \approx 1 \text{ m}^2 \text{s}^{-1} \), which is larger than the Spitzer value for a typical CS background temperature of \( T = 10 \text{ MK} \) \( (\approx 0.03 \text{ m}^2 \text{s}^{-1}) \), \( \eta \approx 10^3 T^{-3/2} \text{ m}^2 \text{s}^{-1} \) with \( [T] = \text{MK} \), yet lower than the estimated anomalous diffusivity (Bemporad 2008). We assume the CS parameters discussed above: \( n = 2 \times 10^{10} \text{ cm}^{-3} \), \( T = 10 \text{ MK} \) and \( B_0 = 5.9 \text{ G} \). A Cartesian grid with four levels of refinement was employed, leading to a maximum grid refinement of \( (128, 256, 64) \). The physical domain was set up to \( (50, 100, 25) \text{ Mm} \) (see the bottom right corner of Figure 2), with the y coordinate pointing sunward and the \( x \) and \( z \) coordinates perpendicular to the initial magnetic field direction. The basic CS device is initialized assuming a corona in pressure equilibrium with a velocity perturbation in the \( x \) direction given by

\[ \text{pert} = v_0 \sin(2\omega y) \times \text{random}, \]

\[ \omega = \frac{2\pi}{y_{\max} - y_{\min}}, \]

where \( v_0 = 2 \text{ km s}^{-1} \), random is a uniform distribution of numbers (varying between \( 0-1 \)) and \( y_{\max} - y_{\min} \) is the domain size in the \( y \) direction. In addition to this perturbation, we consider various CS models with initial perturbed shear velocities (at \( t = 0 \text{ s} \)) in the \( y \) and \( z \) directions (see Table 1). The magnetic field configuration is

\[ B_y = \begin{cases} B_0 & \text{if } x < 0 \\ -B_0 & \text{if } x \geq 0 \end{cases}. \]

where \( B_0 \) depends on the model. Periodic boundary conditions are assumed in the direction where a shear will be imposed (a \( K \) variable satisfies in direction \( n \): \( K(n_{\min}) = K(n_{\max}) \) because no boundary effects are expected in the development of turbulence), otherwise outflow conditions are assumed.

6. RESULTS AND DISCUSSION

6.1. A Turbulent Picture

From the initial conditions of the coronal plasma parameters (model \( M0 \) see Table 1) we obtain a turbulent configuration. Density slices of the \( z = 0 \text{ plane} \) (edge-on view) are shown in Figures 2(a) and (b) for the time: 20 and 40 minutes, respectively. As shown in the figure, and extensively described in the literature, the tearing mode instability leads to a turbulent regime composed of dynamic and coalescent plasmoids where the desired subdense structures are only obtained as secondary linear CSs (they connect neighbor plasmoids). Thus, the usual tear-drop-shaped SAD features are not easy to obtain from models of the \( M0 \) type in times comparable to the observations.

However, if an instantaneous shear in the flow speed to the sides of the CS is introduced at \( t = 0 \text{ s} \) (models \( M1-M3 \) of Table 1), the turbulent features change markedly, allowing the appearance of subdense cavities. It is well known that Kelvin–Helmholtz perturbations destabilize CSs (Bemporad 2008). When a shear initiates Kelvin–Helmholtz
perturbations and combines with the tearing instability, the overall dynamic is modified. Accordingly, McKenzie (2013) reported strong coronal velocity shears (up to \(|\pm 250–350|\) \(\text{km s}^{-1}\)). Also, as large sunward flow values \((v_{\text{flow}} \approx v_{A} \approx [300–500] \text{ km s}^{-1}, v_{A} \) is the external Alfvén speed\(^4\)) are expected coming from a reconnection site, strong shears in the flow could arise due to e.g., the inhomogeneities of the flaring medium (see, e.g., the flow speed coming from the right side into the fan structure in slices between 11:58:09 and 12:02:09 of movie 1b by Savage et al. 2012).

We thus perform several runs with initial strong shear velocities (see Table 1) to gain insight into the turbulent features. Figure 3 shows density slices of the \(z = 0\) plane for M1 and for the same times as in Figure 2. The model configuration is the same as in M0 with the addition of a random speed with a shear in the \(y\) direction. Comparing Figures 2 and 3 we note that models with shear can generate subdense cavities, lasting for times of the order of decades of minutes as the main features of the turbulent regime.

We also performed runs with a shear in the \(z\) direction (models M2 and M3). As in Figure 3, Figures 4(a) and (c) show evolving subdense structures. The viewing orientation of Figures 4(b) and (d) is, face-on, perpendicular to the CS plane. These \(x = 0\) plane descriptions resemble observational inhomogeneities as seen, for example, in animations 1a and 1b, or Figure 1 of Savage et al. (2012). Nevertheless, these sunward subdense features are not stable during times comparable with the observation of the inhomogeneities; they cannot sustain their shape for more than 1.2 minutes.

### 6.2. Later Energy Depositions

Once the turbulent CS is developed, we apply an instantaneous pressure pulse to emulate a blast reconnection event (Forbes 1988) occurring high in the corona where reconnection is prone to occur, triggered by a local change in the magnetic field line linkage and the magnetic topology, e.g., null points, separatrices, or 3D quasi-separatrix layers, (see Demoulin et al. 1996). Such initially localized processes that lead to bursts of impulsive deposition of energy that evolves, producing an expansion of the plasma, have been proposed in Scott et al. (2013), Cécere et al. (2012), Maglione et al. (2011), and Costa et al. (2009). Also, the reconnection flare blast wave scenario was observationally confirmed by Kumar & Innes (2013), revealing the formation of initially expanding cavities that later collapse inward while they approach an arcade, i.e., as they reach a supposedly denser medium.

Figures 5(a) and (b) show one of these events (model M4), resulting from an instantaneous spherical pressure pulse that is four times its background value\(^5\) at \(t = 46.1\) minutes. We assume a perturbation diameter of \(d = 4\) Mm located at \((0, 35, 0)\) Mm leaving the medium density unaltered and allowing the increase of the internal temperature. The figure shows the \(z = 0\) slice for the number density and the temperature at \(t = 50.3\) minutes. We obtain a tear-drop SAD that travels

\(^{4}\) \(v_{A}\) is the background Alfvén speed, where density and temperature have typical coronal values, e.g., considering \(n = 10^{7} \text{ cm}^{-3}\) and \(B_{0} = 5.9\) G, \(v_{A} = 414 \text{ km s}^{-1}\).

\(^{5}\) This increase in the pressure can be produced, e.g., by a burst reconnection of a stressed magnetic flux tube. To estimate the pressure pulse note that the temperature of a flaring loop can be as large as 40 MK (Aschwanden 2005), and assuming that the density of the pulse is initially the same as the environment one, we obtain \(\Delta P/P = \Delta T/T = 4\), considering that the fan CS temperature is of \(\approx 10\) MK. The pressure pulse value could be larger if an increase of the density is also allowed, e.g., the number density of a flaring loop can be as high as \(n \approx 10^{11} \text{ cm}^{-3}\), much larger than the fan value considered.
sunward a distance of $\sim 60 \text{ Mm}$ with a speed of $\sim 240 \text{ km s}^{-1}$, leaving a persistent voided region along a distance of $\sim 38 \text{ Mm}$. The fan number density is at least twice that of the SAD, and the SAD temperature is 22.4 MK, whereas the number density of the turbulent background (Figure 3) is only $\sim 1.23$ times the eddy subdense cavities of temperature 10 MK. In accordance with the observations (McKenzie 2013) our simulations show that the turbulent background has $\beta \gtrsim 1$ values.

### 6.3. Dynamic Behavior

To analyze the behavior of the subdense regions, we show in Figures 6(a) and (b) the $z = 0$ slice of the velocity (arrows), superimposed to the number density for the turbulent vortice ($M_1$) of Figure 3(a) and the SAD structure ($M_4$) of Figure 3(a), respectively. Figures 6(c) and (d) are the same as Figures 6(a) and (b) but the arrows are the magnetic field vector. As in McKenzie (2013) we obtain a variable spectrum of velocities and vortice-like frames that correlate with the motion of density depletions.

The initial $\beta$ parameter value is $\approx 9$ and, at later times, in the fan region, ranges between $\sim [3–100]$. In the vortical turbulent case (Figures 6(a), (c)) the magnetic pressure is larger inside than outside the vortex and the gas pressure is almost constant ($\beta_{\text{inside}} < \beta_{\text{outside}} < 1$). As pointed out by McKenzie & Savage (2009; Savage & McKenzie 2011), Figure 6(c) suggests that the larger inside magnetic pressure could be the reason subdense cavities avoid being filled in immediately by the surrounding plasma. Here, the cavities are the subdense eddies. On the contrary, the total pressure and the $\beta$ parameter vary smoothly around the SAD features or are almost uniform (Figures 6(b), (d)). Figure 6(d) shows that the magnetic field is larger outside than inside and as in Cécere et al. (2012), the larger internal gas pressure—due to the large temperature values—resists the filling in of the SAD. This can also be observed in animations 1 and 2 where the triggering and the evolution of the density and temperature of a SAD are displayed. Note that the subdense SADs correspond to enhanced temperature values; the pressure is almost constant.

The eddy-like feature of size $\approx 20 \text{ Mm}$ (indicated by a square in Figure 6(a)) has an average speed of 50 km s$^{-1}$. During the
run we note the formation of eddies of sizes ranging between \(~[10–20] \text{ Mm}\) and average speeds of \([10–60] \text{ km s}^{-1}\). Unlike the interpretation offered in Cécere et al. (2012), where the zigzag behavior is due to the interaction of SADs between each other and with the inhomogeneous medium, Figures 6(b) and (d) show that the tail shape is produced by the interaction of a SAD with the turbulent fan.

### 6.4. The Emission Measure

To analyze if the subdense features seen in Figures 3 and 4 are compatible with an SAD description we first evaluate the EM (Aschwanden 2005) as

\[
EM = \int n^2 \, dx. \tag{12}
\]

Figure 7 shows the EM of the face-on CS view for M1 and M2. The integration along the line of sight (LOS) direction (x) is performed considering a CS width of 4 Mm (see estimations in Guo et al. 2013). The temperature range obtained is \(~[9.4–10.8] \text{ MK}\) for these models. The weak contrast obtained for the EM—where the subdense cavities have EMs that are less than \(~\sim 1.2\) the background features—\(\sim\) is lower than the values reported by Savage et al. (2012) for \([10–13] \text{ MK}\), where the EM SAD values were a factor of \([2–4]\) with respect to the surroundings (see Figure 4 of the mentioned paper). Larger width values (e.g., considering turbulent characteristic eddy sizes as \(\sim 22 \text{ Mm}\)) will lead to lower EM contrast values. Thus, the turbulent picture by itself is not sufficient to fully give an account of dark observational regions.

Finally, Figure 8 shows the CS view of the emission measure at \(t = 50.3\) minutes for model M4. The EM is calculated along the LOS considering the whole temperature range \((110–22] \text{ MK})\) and assuming a thickness of the CS of \(\sim 4 \text{ Mm}\) (Guo et al. 2013). At the initial times the SADs appear as rapidly increasing spherical features (e.g., see the high cadence movies of Savage et al. 2012). Later, as shown in Figure 8, they acquire a tailed tear-drop shape while they are elongated and collimated by the turbulent background plasma.

As stated in Savage et al. (2012), during times comparable with the observations \((\sim 270 s)\), the SAD EM is approximately 2.1 times lower than its background value. However, if we consider a larger CS width the SAD EM contrast is insufficient to be appreciated.

Hence, we run the M4 model considering a CS thickness of 22 Mm to obtain a SAD using the same instantaneous pressure pulse as before but with a larger diameter of 12 Mm, located at \((0, 30, 0) \text{ Mm}\) and triggered at 27.5 minutes. This value is in accordance with a rough estimation of the eddy width in Figure 3. Figures 9(a) and (b) show the number density (with the superimposed arrows indicating the magnetic field) and the temperature, respectively, for the new run, at \(t = 33\) minutes. The subdense cavity (three times less than its background value, Figure 9(a)) sustains its structure for 5.5 minutes tracing a path of 93 Mm length. The sunward SAD velocity is \(\sim 280 \text{ km s}^{-1}\). The eddies move with an average speed of \(\sim 40 \text{ km s}^{-1}\) at the neighbors of the SADs (McKenzie 2013). Figure 9(b), shows larger SAD inside values of the temperature than the surrounding background. In Figure 10 we show the
EM considering the mentioned thickness and a temperature threshold of $[10-20]$ MK, taking into account the AIA temperature filters, which are not sensitive to temperatures higher than 20 MK (Boerner et al. 2012). Note that the EM contrast is sufficient (3.4) to be observed.

7. CONCLUSIONS

In this paper, motivated by recent CS observations (Savage et al. 2012; McKenzie 2013), we simulate a turbulent CS generated by a combination of the tearing and the Kelvin–Helmholtz instabilities that develops subdense cavities with transient and variable vortical motions. Comparing these features with SAD observations we find that the EM contrast and characteristic times are not enough to match the observations. However, imposing a pressure pulse to this turbulent background—in order to emulate a local deposition of energy produced by an impulsive reconnection event—we obtain that—depending on the CS thickness—the EM, characteristic times, and the speeds are comparable with the observations. If the CS is thin enough ($\sim 4$ Mm), the EM contrast will be sufficient to allow the detection of SADs. Thicker CSs ($\sim 22$ Mm) require larger depositions of energy to produce a detectable SAD. In both cases we use a triggering pressure pulse that is four times the background pressure, which is a reasonable value for a pressure perturbation in a flaring medium. In the first case, a $d = 4$ Mm size is used to obtain a detectable EM; in the second one the requirement was an augmented flaring region of diameter $d = 12$ Mm. These diameter values are typical SAD sizes.

To summarize, for appropriated physical parameters, and a given pressure pulse intensity, it seems that there is a closed relation between characteristic SAD sizes and CS widths that must be satisfied to obtain an observable SAD. This could be a reason why SADs are not always detected during long duration flaring events.
In contrast with the results given by Hanneman & Reeves (2014), our simulated SAD temperatures are always higher than the fan ones. These authors pointed out that there is little evidence that SADs contain substantially hotter plasma than the surrounding fan. Despite actual SAD temperatures being significantly lower than in Maglione et al. (2011) and Cécere et al. (2012), we would like to emphasize that the scenario presented here (the scheme in Figure 1) may allow an explanation where the SAD temperature is not necessarily larger than the fan one. A more complex setup simulation where an SAD is triggered outside the fan region (Figure 1), may lead to an SAD with internal temperatures always higher than the surrounding background but not necessarily higher than the fan ones, e.g., if the background temperature is $T = 2$ MK, and the fan temperature is $T = 10$ MK, the SAD initial temperature will be $T = 8$ MK, considering a pressure pulse of $\Delta P/P = 4$. In this case the SAD would enter the fan while it narrows and collapse due to the total pressure difference with the fan environment, as can be also seen in animation 1b by Savage et al. (2012).

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REFERENCES

Aschwanden, M. J. 2005, Physics of the Solar Corona: An Introduction with Problems and Solutions (2nd ed.; Chichester: Praxis Publishing Ltd.)

Bemporad, A. 2008, ApJ, 689, 572

Boerner, P., Edwards, C., Lemen, J., et al. 2012, SoPh, 275, 41

Cécere, M., Schneider, M., Costa, A., Elaskar, S., & Maglione, S. 2012, ApJ, 759, 79

Ciaravella, A., & Raymond, J. C. 2008, ApJ, 686, 1372

Costa, A., Elaskar, S., Fernández, C. A., & Martínez, G. 2009, MNRAS, 400, L85

Demoulin, P., Henoux, J. C., Priest, E. R., & Mandrini, C. H. 1996, A&A, 308, 643

Fermo, R. L., Drake, J. F., & Swisdak, M. 2010, PhPl, 17, 010702

Forbes, T. G. 1988, SoPh, 117, 97

Fryxell, B., Olson, K., Ricker, P., et al. 2000, ApJS, 131, 273

Guo, L.-J., Bhattacharjee, A., & Huang, Y.-M. 2013, ApJL, 771, L14

Hanneman, W. J., & Reeves, K. K. 2014, ApJ, 786, 95

Heyvaerts, J., & Kuperus, M. 1978, A&A, 64, 219

Innes, D. E., McKenzie, D. E., & Wang, T. 2003, SoPh, 217, 267

Innes, D. E., McKenzie, D. E., & Wang, T. 2003, SoPh, 217, 247

Kumar, P., & Innes, D. E. 2013, SoPh, 288, 255

Lazarian, A., & Vishniac, E. T. 1999, ApJ, 517, 700

Linton, M. G., DeVore, C. R., & Longcope, D. W. 2009, EP&S, 61, 573

Maglione, L. S., Schneider, E. M., Costa, A., & Elaskar, S. 2011, A&A, 527, L5

McKenzie, D. E. 2000, SoPh, 195, 381

McKenzie, D. E. 2013, ApJ, 766, 39

McKenzie, D. E., & Hudson, H. S. 1999, ApJ, 519, 93

McKenzie, D. E., & Savage, S. L. 2009, ApJ, 697, 1569

Onofri, M., Primavera, L., Malara, F., & Veltri, P. 2004, PhPl, 11, 4837

Powell, K. G., Roe, P. L., Linde, T. J., Gombosi, T. I., & De Zeeuw, D. L. 1999, JCoPh, 154, 284

Priest, E. R. 1982, Solar Magneto-Hydrodynamics (Dordrecht: Reidel)

Priest, E. R. 1986, SoPh, 104, 1

Priest, E. R., & Demoulin, P. 1995, IGR, 100, 23443

Priest, E., & Forbes, T. 2000, Magnetic Reconnection (Cambridge: Cambridge Univ. Press)

Savage, S. L., & McKenzie, D. E. 2011, ApJ, 730, 98

Savage, S. L., McKenzie, D. E., & Reeves, K. K. 2012, ApJL, 747, L40

Schmieder, B., Aulanier, G., Demoulin, P., et al. 1997, A&A, 325, 1213

Schulz, W., Costa, A., Elaskar, S., & Cid, G. 2010, MNRAS, 407, 89

Schwenn, R., Raymond, J. C., Alexander, D., et al. 2006, SSRv, 128, 127

Scott, R. B., Longcope, D. W., & McKenzie, D. E. 2013, ApJ, 776, 54

Seaton, D. B., & Forbes, T. G. 2009, ApJ, 701, 348

Somov, B. V., Titov, V. S., & Vemeta, A. I. 1987, IntSA, 34, 136

Verwichte, E., Nakariakov, V. M., & Cooper, F. C. 2005, A&A, 430, 65