THE COOL SURGE FOLLOWING FLUX EMERGENCE IN A RADIATION-MHD EXPERIMENT

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ABSTRACT

Cool and dense ejections, typically Hα surges, often appear alongside EUV or X-ray coronal jets as a result of the emergence of magnetized plasma from the solar interior. Idealized numerical experiments explain those ejections as being indirectly associated with the magnetic reconnection taking place between the emerging and preexisting systems. However, those experiments miss basic elements that can importantly affect the surge phenomenon. In this paper we study the cool surges using a realistic treatment of the radiation transfer and material plasma properties. To that end, the Bifrost code is used, which has advanced modules for the equation of state of the plasma, photospheric and chromospheric radiation transfer, heat conduction, and optically thin radiative cooling. We carry out a 2.5D experiment of the emergence of magnetized plasma through (meso) granular convection cells and the low atmosphere to the corona. Through detailed Lagrange tracing we study the formation and evolution of the cool ejection and, in particular, the role of the entropy sources; this allows us to discern families of evolutionary patterns for the plasma elements. In the launch phase, many elements suffer accelerations well in excess of gravity; when nearing the apex of their individual trajectories, instead, the plasma elements follow quasi-parabolic trajectories with accelerations close to $g_\odot$. We show how the formation of the cool ejection is mediated by a wedge-like structure composed of two shocks, one of which leads to the detachment of the surge from the original emerged plasma dome.

Key words: magnetohydrodynamics (MHD) – methods: numerical – Sun: atmosphere – Sun: chromosphere – Sun: corona – Sun: flares

Supporting material: animations

1. INTRODUCTION

Cool, chromospheric-temperature ejections are key dynamical elements of the solar atmosphere. Surges, in particular, usually appear in connection with magnetic flux emergence episodes, where they are often associated with hot, high-speed EUV or X-ray jets. Even though observationally known for several decades now, the theoretical understanding of the surges has progressed slowly, and there are still many unsolved questions. First detections of chromospheric surges date back to the 1940s, when they were described as Hα absorption markings related with bright eruptions (flares) corresponding to outward velocities followed by inward motion (Ellison 1942; Newton 1942). Further observational properties were obtained in the 1970s and 1980s (Kirchner & Noyes 1971; Roy 1973; Cao et al. 1980; Schmieder et al. 1984, among others): the surges were seen as blue and redshifted absorptions in Hα that typically have a length of 10–50 Mm, and line-of-sight velocities of a few to several tens of km s$^{-1}$, reaching, in extreme cases, 100–200 Mm and 200 km s$^{-1}$, respectively. The surges were also observed in Ca ii (Rust 1976); a close relationship between Hα surges and EUV ejections was found as well (Schmahl 1981). Later, different observations focused on the role of the magnetic field, suggesting that the Hα surges could be an indirect result of flux emergence processes and the interaction (possibly reconnection) of the upcoming magnetized plasma with the ambient coronal field (Kurokawa & Kawai 1993; Schmieder et al. 1995; Canfield et al. 1996; Chae et al. 1999). Those suggestions were based mainly on the detection of the cool ejections next to emerging bipolar regions and quasi-simultaneously with hot coronal plasma jets (observed in the EUV or in X-rays). The high resolution observations of the past decade (e.g., Yoshimura et al. 2003; Jibben & Canfield 2004; Brooks et al. 2007; Jiang et al. 2007; Uddin et al. 2012; Vargas Domínguez et al. 2014) have provided further evidence for the frequent relation between magnetic flux emergence, chromospheric ejections and hot jets. Other chromospheric-temperature ejections, such as macrospicules, show some analogies with the surges: they are multithermal structures observed mainly in He ii 304 Å and Hα, with a cool core surrounded by a thin sheath of 1–2 × 10^7 K (e.g., Bohlin et al. 1975; Habbal & Gonzalez 1991; Pike & Harrison 1997; Madjarska et al. 2006; Bennett & Erdélyi 2015).

Concerning the theoretical effort, the seminal paper by Heyvaerts et al. (1977); see also Forbes & Priest (1984) discussed how the emergence of magnetized plasma from the solar interior could lead to a conflict of magnetic orientation with the preexisting coronal field, and hence to reconnection and the ejection of hot plasma. Using this flux emergence paradigm, Shibata et al. (1992) and Yokoyama & Shibata (1995, 1996) then showed, through a 2.5D numerical model with an initial uniform coronal field, that cool plasma could be ejected next to a hot jet as a consequence of the emergence of magnetic flux from the interior. The authors tentatively identified those cool ejections with Hα surges and described them as resulting from the sling-shot effect due to reconnection, which produces a whip-like motion (Yokoyama & Shibata 1996). Their cool surge had a density around $10^{-11}$ g cm$^{-3}$, speeds in the range 50–90 km s$^{-1}$, and a maximum vertical size of several megameter. Nonetheless, due
to the computational limitations of the time, the corona used in
the experiment had unrealistic values of density and tempera-
ture. Using the same sort of setup, but with more realistic
coronal parameters, Nishizuka et al. (2008), through morpho-
logical image comparisons, suggested that the cool ejections
associated with flux emergence could be the cause for the jet-
like features seen in Ca II H + K observations. The more recent
flux-emergence experiment of Jiang et al. (2012) had a canopy-
type configuration of the ambient coronal magnetic field, and
also led to the ejection of cool and hot plasma. A study of the
cool ejection in three-dimensions following magnetic flux
emergence has only recently been published (Moreno-Insertis
& Galsgaard 2013). This experiment yielded a cool (from
$10^4$ K to a few times $10^5$ K) and dense (between $10^{-12}$
and $10^{-13}$ g cm$^{-3}$) wall-like plasma domain surrounding the
emerged flux region. Through Lagrange tracing, the authors
explained the formation of the wall through plasma, which was
being transferred from the emerged region attached to field
lines that change connectivity in the main reconnection site.
The cool ejecta had speeds of typically less than 50 km s$^{-1}$
and were not collimated. Similar surge speeds were found by
MacTaggart et al. (2015) in 3D flux emergence experiments for a
variety of magnetic configurations.

All of those theoretical models, whether 2D or 3D, have been
helpful in providing basic indications for the mechanisms that
may lead to the simultaneous ejection of cold and hot plasma;
nevertheless, they lack essential physical processes relevant in
the photosphere, chromosphere, and corona, and can therefore only
be taken as first steps when trying to understand the physics of the
surges. The aim of this paper is to provide a new perspective of the
cool ejections introducing some of those physical processes, like
thermal conduction, photospheric and chromospheric radiative
transfer, optically thin radiative cooling, and a realistic equation
of state (EOS). To that end, we use the Bifrost code as a
computational tool (Gudiksen et al. 2011). For a first approach,
in this paper we are using a 2.5D setup. The initial phase of the flux
emergence process takes place through solar-like granular
convection, which influences the sizes of the resulting structures in
the low atmosphere. We can study the subsequent phenomena
of reconnection and plasma ejection in the atmosphere with high
temporal cadence and spatial resolution, focusing on the
formation, maximum development, and decay phases of the
surge. The study includes detailed Lagrange tracing of the mass
elements in the surge, which allows us to analyze in detail their
origin and thermal evolution, the role of the various entropy
sources, and the acceleration mechanisms. We show that the cool
dense ejection is a complex and fascinating phenomenon in
which the entropy sources play an important role.

The layout of this paper is as follows. Section 2 describes the
physical and numerical model. In Section 3 we show the initial
phases of the experiment prior to the initiation of the cool
ejection. Sections 4 and 5 analyze the surge in detail through its
various phases (ejection, detachment, and decay), focusing on
the heating sources, kinematics, and dynamics of the plasma
elements. Finally, Section 6 contains the discussion and the
summary.

2. THE PHYSICAL AND NUMERICAL MODEL

2.1. The Numerical Code

The experiment we present in this paper was run using the radiation-magnetohydrodynamics (RMHD) Bifrost code
(Gudiksen et al. 2011). This code includes thermal conduction
along the magnetic field lines and radiation transfer adequate to
the photosphere, chromosphere, and corona; it takes into
account entropy sources such as Spitzer thermal conductivity,
optically thin cooling, and radiative losses by neutral hydrogen,
singly ionized calcium, and magnesium, among others; details
are provided in the papers by Skartlien (2000), Hayek et al.
(2010), Gudiksen et al. (2011), Leenaarts et al. (2011), and
Carlsson & Leenaarts (2012). The code also has an EOS that
includes the ionization/recombination of the relevant atomic
species. On the other hand, because of the validity range of the
radiation tables in the code, there is an ad hoc heating term that
forces the plasma to stay above $T = 1660$ K (a discussion in
detail concerning this term can be found in the paper by
Leenaarts et al. 2011). The advantages of the Bifrost code
probably make the simulation in this paper the most realistic
one to date for the formation and dynamics of surges (but see
the discussion concerning various limitations of the present
model in Section 6.3).

The description of the model underlying our experiment is
divided into two parts: (1) the background stratification,
numerical grid, and boundary conditions and (2) the twisted
magnetic tube.

2.2. Background Stratification, Numerical Grid
and Boundary Conditions

Concerning the background stratification, we started from a
preexisting statistically stationary magnetoconvection config-
uration that includes, in a self-consistent manner, the uppermost
layers of the solar interior, the photosphere, the chromosphere,
the transition region, and the corona. The convection patterns
range between granular and mesogranular. The corona has a
temperature of about 1 MK and a quasi-uniform vertical
magnetic field of 10 G in order to mimic a coronal hole medium.
The initial magnetic field is contained in the $x$ -- $z$ plane, with
$z$ being the vertical coordinate. The left panel in Figure 1
shows the horizontal averages for our initial condition for
density $n$, gas pressure $P_g$, and temperature $T$; all of them
normalized to their photospheric values at $z = 0$ Mm, namely,
$n_{ph} = 3.09 \times 10^{-17}$ cm$^{-3}$, $P_{gph} = 1.11 \times 10^3$ erg cm$^{-3}$
and $T_{ph} = 5.62 \times 10^3$ K. In the right panel we present a 2D
temperature map where a number of magnetic field lines have
been superimposed in black. In the image, the granulation
pattern is distinguishable through the vertical field concen-
trations in the convective downflows and through the horizontal
field lines in the center of the granules in the photosphere.

The physical domain is $0.0 \text{ Mm} \leq x \leq 16.0 \text{ Mm}$ and
$-2.6 \text{ Mm} \leq z \leq 14.4 \text{ Mm}$, with $z = 0$ Mm corresponding
to the solar surface, or more precisely, to the horizontal level
where $\langle T_{5000}\rangle = 1$. The numerical box has 512 $\times$ 512 points in the
$(x, z)$ directions, respectively. The grid is uniform in the
$x$-direction with $\Delta x = 31$ km, and non-uniform in the vertical
direction in order to better resolve the lower photosphere. The
vertical grid spacing varies between 19 km, reached in the
photosphere and chromosphere, and 90 km at the top and
bottom of the domain. The boundary conditions are periodic in
the horizontal direction. At the top of the box characteristic
boundary conditions (as described by Gudiksen et al. 2011)
have been chosen that suppress incoming waves so as to
eliminate any signal reflexion while the plasma can leave the
domain. Additionally, the corona is expected to have
temperatures of order 1 MK but the two-dimensional nature
of this experiment prevents a self-consistent magnetic heating resulting from photospheric field line braiding, as in the 3D experiment of Gudiksen & Nordlund (2005). To alleviate this problem, a hot-plate is implemented at the top boundary, meaning a Newton cooling term that forces the temperature in the boundary cells to stay fixed at 10⁶ K. For the bottom boundary the code uses a technique often implemented in magnetohydrodynamics simulations (e.g., Stein & Nordlund 1998; Hansteen et al. 2007), namely, it keeps the bottom boundary open so that plasma can go across it, and constant entropy is set in the incoming material to keep the convection going, while the rest of the variables is extrapolated.

2.3. The Twisted Magnetic Tube

In order to produce magnetic flux emergence, we inject a twisted magnetic tube with axis pointing in the y-direction, the ignorable coordinate in this 2.5D experiment. The injection is done through the lower boundary of the box following the method described by Martínez-Sykora et al. (2008). The longitudinal and transverse components of the magnetic field in the tube have the canonical form of a Gaussian profile with an r-independent pitch (e.g., Fan 2001),

\[ B_y = B_0 \exp \left(-\frac{r^2}{R_0^2}\right), \]

\[ B_\theta = q \, r \, B_y, \]

where r and \( \theta \) are the radial and azimuthal coordinates relative to the tube axis, \( R_0 \) is a measure for the tube radius, q a constant twist parameter, and \( B_\theta \) the magnetic field in the tube axis. To favor the emergence, we inject the tube in an inflow region, namely \( x_0 = 8.0 \text{ Mm} \) (marked with a black arrow in the right panel of Figure 1). The rest of the parameters are selected within the ranges that lead to a coherent emergence pattern at the surface; the chosen values are presented in Table 1. The initial axial magnetic flux is \( \Phi_0 = 1.5 \times 10^{19} \text{ Mx} \), which is in the range of an ephemeral active region (Zwaan 1987). This magnetic field configuration has positive helicity. The field lines have pitch \( \Delta y_p = 2\pi/q = 2.6 \text{ Mm} \) independently of the

\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{Parameter} & \Phi_0 (\text{Mx}) & \rho_0 \text{ (g cm}^{-3}\text{)} & \text{q (Mm}^{-1}\text{)} & \text{B}_0 \text{ (kG)} \\
\hline
\text{Initial} & 8.0 & -2.9 & 0.16 & 2.4 & 19 \\
\hline
\end{array}
\]

radius. In other words, all field lines execute two turns around the axis along a distance of 5.2 Mm.

3. INITIAL PHASES

We call initial phases the time interval when the injected magnetic flux is rising through the convection zone and the photosphere until it reaches the low corona, or more precisely, until an emerging plasma dome is formed, as explained in Section 3.3. The initial phases share similarities with previous RMHD experiments of magnetic flux emergence (Cheung et al. 2007; Martínez-Sykora et al. 2008; Tortosa-Andreu & Moreno-Insertis 2009) and also with more idealized MHD experiments (Yokoyama & Shibata 1996; Fan 2001; Magara 2001; Archontis et al. 2004; Moreno-Insertis et al. 2008; Moreno-Insertis & Galsgaard 2013). Figure 2 illustrates the module of the magnetic field, \( B \), at four different instants of the initial phases. In the following, we explain the different panels of the figure.

3.1. Emergence Through the Convection Zone

The first stage of the rise of the magnetic tube is an expansion away from the injection point with velocities of order 1 km s\(^{-1}\). As the tube rises through the convection zone, it starts to develop a dumbbell shape that is easily identifiable because of the high field concentration on either side of the tube axis, panel (A) in Figure 2. Afterwards (Panel (B)), the action of the convection flows on the rising tube starts to be evident. They deform and break the twisted magnetic tube into smaller fragments in the regions of strong shear, typically where the downflows hit the tube. We can identify five large fragments during the emergence process. One of the fragments of the tube, the one tagged “(I)” in panel (C), reached the surface approximately 35 minutes after the initiation of the
experiment. At that instant, this fragment had a horizontal size of 1.3 Mm, i.e., on the order of a granular size. Two further pieces, “(2)” and “(3)”, get to the surface at $t \sim 38$ and 43 minutes respectively, although they are smaller than the previous one. The fragments labeled “(4)” and “(5)” were strongly braked and pushed down by the convection downflows, and they do not reach the surface. Most of the eruptive phenomena observed in the atmosphere after the emergence are associated with the first fragment, so we focus attention onto it in the following.

3.2. Anomalous Granulation and Buoyancy Instability

Once in the photosphere, in the transition between super- and sub-adiabatic stratified regions, the magnetized plasma starts to pile up, consequently increasing the magnetic pressure. The enhanced pressure produces a sideways growth of the fragment leading to an anomalous granule of about 2.6 Mm horizontal extent (Figure 2, panel (C), $x = 7.4$–10 Mm), which is twice the size it had when it reached the surface. Similar anomalous granulation related with flux emergence was found in the numerical experiments by Cheung et al. (2007), Martínez-Sykora et al. (2008), and Tortosa-Andreu & Moreno-Insertis (2009), and in the observations by Orozco Suárez et al. (2008), Guglielmino et al. (2010), and Ortiz et al. (2014), among others. The later evolution of the anomalous granule occurs in the frame of the buoyancy instability (Newcomb 1961), along the general lines described by Tortosa-Andreu & Moreno-Insertis (2009) and, to some extent, also in idealized models without radiation (see Magara 2001; Archontis et al. 2004; Moreno-Insertis 2006; Murray et al. 2006). In all those cases the development of the instability allows the magnetized plasma to rise well above the photospheric heights.

3.3. The Emerged Magnetized Dome

Following the buoyancy instability, the plasma belonging to the anomalous granule suffers a rapid expansion into the atmosphere with radial velocities of 15 km s$^{-1}$ at heights around 1–2 Mm. This expansion leads to the classical dome (or mountain) formation already found in the past (see, e.g., Yokoyama & Shibata 1996; Archontis et al. 2004; Moreno-Insertis & Galsgaard 2013 and references therein). In panel (D) of Figure 2 we show the early stages of the emerged dome between $z = 0$ Mm and $z = 2$ Mm approximately. In the upper subpanel (above $z = 0$, marked by a thick horizontal line in blue), magnetic field lines are shown superimposed in red: they are seen to collect into compact field line bunches at the location of photospheric downflows. One of those bunches is located at $x \approx 7.2$ Mm; the region between those lines and the left side of the dome corresponds to a current sheet that is described in Section 3.4.

As the dome expands, its plasma temperature decreases significantly, reaching the lower limit allowed in our simulation explained in Section 2. This is expected for expansion phenomena in the chromosphere (e.g., Hansteen et al. 2006; Martínez-Sykora et al. 2008; Tortosa-Andreu & Moreno-Insertis 2009; Leenaarts et al. 2011). Simultaneously, the dome interior suffers a draining process owing to the gravitational flows that take place along the loop-like magnetic field lines, as described by Moreno-Insertis & Galsgaard (2013). The combination of the expansion and the draining produces a density change from the values during the first stages of the dome evolution ($10^{-11}$ to $10^{-12}$ g cm$^{-3}$) to values on the order of $10^{-14}$ g cm$^{-3}$ in later phases.

3.4. The Current Sheet: Unsteady Reconnection

The expansion of the dome pushes its magnetic field against the preexisting vertical coronal magnetic field. This generates an orientation conflict on the left-hand side of the dome, giving rise to a thin concentrated current sheet. In Figure 3, we illustrate the latter using as inverse characteristic length of the magnetic field variation the quantity

$$L_B^{-1} = \frac{\left| \nabla \times B \right|}{|B|}. \quad (3)$$

This quantity permits good visualization of any abrupt change of $B$. For comparison, in a pure rotational discontinuity of the field, $L_B^{-1}$ is $\pi$ times the inverse width of the sheet, while in a Harris sheet it goes through infinity at the center of the sheet. In the figure, the pixels where $L_B < 1000$ km are shown in color, with magnetic field lines superimposed as solid lines. There is a reconnection site located at $x \sim 6.8$ Mm and $z \sim 1.8$ Mm (black cross). Along its lifetime, the current sheet repeatedly experiences the formation of plasmoids (like the one at $z \sim 2.4$ Mm in Figure 3) through the development of the tearing-mode-instability (Furth et al. 1963). This behavior has been detected in previous flux emergence experiments, e.g., in 2D by Yokoyama & Shibata (1996) and in 3D by Archontis...
et al. (2006), Moreno-Insertis & Galsgaard (2013), and Archontis & Hansteen (2014). In our case, the timescale of plasmoid formation is between several tens of seconds and a few minutes. This range is compatible with the theoretical value for the growth time of the tearing mode (see Goldston & Rutherford 1995): the latter is close to the geometric mean between \( \tau_a \) and \( \tau_d \), where \( \tau_a \) is the Alfvén velocity and \( \eta \) is the diffusivity. In our current sheet, \( \tau_a = 10^{-2} - 10^{-3} \) s and \( \tau_d = 10^7 - 10^8 \) s, and the geometric mean of those quantities is near the measured values in the experiment.

As time goes on, the area where the orientation conflict is located grows in length because of the dome expansion. During this phase, the plasmoids are ejected as part of the reconnection process, probably through the melon seed ejection mechanism (Schlüter 1957), which can be launched when there is an imbalance in the Lorentz force holding the plasmoid on its sides along the current sheet. Some of the plasmoids also merge forming bigger ones as a result of the coalescence instability (Finn & Kaw 1977).

4. THE EJECTION OF COOL, HIGH-DENSITY PLASMA

As a result of the reconnection process taking place at the boundary between emerged dome and coronal material, a substantial amount of plasma with chromospheric temperatures and densities is ejected to coronal heights. We refer to this phenomenon as the cool and dense ejection or surge and avoid the word jet, since the ejecta are not collimated and do not have large speeds, as shown in this section. In Figure 4, the overall evolution of the surge from the initial stages to the decay phase is illustrated using grayscale maps for the density and with a number of temperature contours with values indicated in panel (A). In panels (A) and (B) we can see an apparent peeling process that is carrying dense and cool plasma to greater heights towards the right of the dome. At the same time, a hot coronal jet is forming on the left side as can be identified through the pink contours in Panel (B). In panel (C), the dome seems to be splitting into two parts at \( t \approx 12 \) Mm. In panel (D), we can distinguish the cool and dense plasma ejection as the elongated structure located to the right of the emerged dome with temperatures below \( 3 \times 10^7 \) K, i.e., chromospheric temperatures, including a colder core of lower temperatures down to \( 2 \times 10^6 \) K. Around this instant, the ejecta reach their maximum height, \( z = 13.2 \) Mm, and the density range in the surge is between \( 10^{-14} \) and \( 10^{-11} \) g cm\(^{-3} \). The rest of the panels (E), (F), (G), and (H) show the decay phase. During the decay, the surge moves first to the left and then to the right in a swaying motion caused by the Lorentz force associated with the bending of its magnetic field lines. The cool surge remains as an easily identifiable feature until \( t \approx 66 \) minutes, so its lifetime can be estimated to be about 7–8 minutes. The accompanying Movie 1 shows the time evolution of the density and temperature of the system.

In order to analyze the fundamental aspects of the surge, we have followed more than 3 \( \times 10^7 \) plasma elements through Lagrangian tracing. The choice of tracers was carried out at the time of maximum vertical extent of the cool ejection, \( t = 61 \) minutes, and is shown in panel (I) of Figure 5 with dots of different colors superimposed on the image. We set the side and top boundaries of the surge to coincide with the isocontour \( T = 3 \times 10^7 \) K (blue curve) and use as lower limit the \( z = 2 \) Mm horizontal axis. The tracers are then evenly distributed in that domain with high-resolution spacing \( \delta x = \delta z = 10 \) km. For later reference, we have drawn the tracers in four different colors (cyan, yellow, purple, and red) according to the four different populations of plasma elements that are introduced and discussed from Section 4.1 onward. The resolution is high enough for the individual tracers to be indistinguishable in the figure: the domains looks like a continuous surface. Once the distribution is established, we follow the tracers backward in time until \( t = 51 \) minutes, to study their origin, and also forward, until \( t = 65 \) minutes. The tracking has a high temporal cadence of 0.2 s in order to reach good accuracy even in locations with high gradients and phases of fast changes, like when going through the current sheet.

The rest of this section is divided into three blocks devoted to the heating and cooling sources of the surge (Section 4.1), the plasma acceleration (Section 4.2), and the velocities, densities, and temperatures (Section 4.3).

4.1. Heating and Cooling Sources

Here we analyze the heat sources and sinks in the surge, since they are key for understanding its structure and evolution. From all the entropy sources included in the Bifrost code, the relevant ones for the surge are those resulting from the Spitzer thermal conductivity, the optically thin cooling, the radiative losses by neutral hydrogen, and the ohmic and viscous heating. The rest, like those associated with the chromospheric radiative losses by singly ionized calcium and magnesium, have much longer characteristic times and need not be discussed. The following results are focused on the rising phase of the ejecta until they reach their maximum height at around \( t = 61 \) minutes. Thereafter, the characteristic times of the heating and cooling processes become much longer than the general evolutionary timescale of the surge: the temperature changes in the decay phase are due to adiabatic compression.

The study of the thermal properties of the individual Lagrangian elements allows one to discern four different
plasma populations within the ejecta of different origin and evolution that we have identified with labels “A”, “B”, “C”, and “D”, and drawn in colors cyan, yellow, purple, and red, respectively, in Figure 5. In Panel (I) we have already introduced the distribution of the Lagrangian elements when the cool ejection reaches its maximum height. Panels (II.1)–(II.4) show the evolution of those elements during previous stages of the surge. These panels illustrate the origin of the plasma in the surge and how the different populations evolve to give rise to the distribution shown in Panel (I). A more complete view of the formation of the surge is also provided via the accompanying Movie 2. The nature of the different populations is analyzed in the following.

4.1.1. Population A

Population A, plotted in cyan in Figure 5, corresponds to plasma originating in the dome (see panel (II.1)) and it is heated through Joule and viscous dissipation during the early stages of formation of the surge. Owing to the high density of this population, those entropy sources are not able to heat the plasma to values above $3 \times 10^4$ K. At $t = 61$ minutes, this population covers 44% of the cross section of the surge and its total mass per unit length in the y direction is $10^{-3} \text{g Mm}^{-1}$. The top-left panel in Figure 6 shows with a black solid line the time evolution of the temperature of a representative plasma element of this population. The element jumps from dome temperatures, close to $2 \times 10^3$ K, to values around the temperature of the hydrogen ionization/recombination, namely $6 \times 10^3$ K. In the same panel (red curve), the values of $L_B^{-1}$ at the positions reached by that plasma element indicate that it passes near the current sheet, but not quite through it: the typical values of $L_B$ in the current sheet are less than 100 km (see Figure 3).

4.1.2. Population B

The second group of Lagrange tracers is what we call Population B, drawn in yellow in Figure 5. Its defining feature is that the plasma elements in it, in spite of originating in the dome, reach temperatures between $10^5$ and $10^6$ K during the launch phase, and then cool down to temperatures below...
3 × 10^4 K. This family leaves the dome later than the elements of population A, as shown in the panels (II.1)–(II.4) of Figure 5; it ends up covering 34% of the surge’s cross section at \( t = 61 \) minutes, but it has comparatively low densities, so its integrated mass at that time is \( 4.7 \times 10^{-5} \) g Mm\(^{-1}\) only. There are two main reasons for the sudden increase in temperature of the elements of this population, namely:

1. Unlike for Population A, some of its plasma elements pass through the current sheet, and are strongly heated there (see the yellow tracers above the blue temperature contour, \( 3 \times 10^4 \) K, in panels (II.3) and (II.4)). The top-right panel in Figure 6 depicts an example of this behavior for a representative member of this population. The characteristic length \( L_B \) reaches a small value, around 25 km, after which it decreases, indicating that the plasma element is then leaving the current sheet. When in the current sheet, the Joule dissipation and, to a lesser extent, the viscous dissipation become highly efficient, with short characteristic timescales from several seconds to a few tens of seconds, as shown in the left panel of Figure 7.

2. Some plasma elements of this population, those close to the blue contour on the left side of the surge in panel (I) of Figure 5, are affected by their passage through a strong shock. This shock is a central feature of the dynamics of the surge and is described separately (Section 5).

Additionally to the foregoing, the heating processes are particularly effective at increasing the temperature of the particles of this population given their comparatively low initial density: their late ejection from the emerged dome implies that the density of the latter has already been substantially reduced through the gravitational draining explained in Section 3.3. The late ejection furthermore explains their appearance on the left hand side of the surge and with comparatively low density (see the left side of the surge in panel (D) of Figure 4 in comparison with its right side).

The short duration of the high temperature spurt of these mass elements is explained by the activation, when the temperature is nearing \( 10^6 \) K, of thermal conduction and optically thin radiative losses as effective entropy sinks. The associated characteristic times (\( \tau_{Spitz} \), \( \tau_{thin} \), respectively) for the plasma element studied above can be seen (Figure 7, right panel) to reach low values of several seconds (\( \tau_{Spitz} \)) or of a few tens of seconds (\( \tau_{thin} \)). When \( T \) decreases to values around \( 10^4 \) K, the radiative losses by neutral hydrogen can also be important (see the curve labeled \( \tau_H \)). It is through these cooling processes that the elements of this population eventually adopt the cool temperatures of the surge.
from the dome, following the motion of the magnetic field lines explained in Section 4.2.1. Along this process, they are never heated by Joule or viscous dissipation. The local values of $T$ and $L_B^{-1}$ for a representative plasma element of this population are given in Figure 6, bottom-left panel. In fact, those plasma elements expand along their motion, which explains why this population is barely visible in panels (II.1) and (II.2) of Figure 5 in comparison with panels (II.3) and (II.4). The density of the elements decreases by approximately one order of magnitude, but their temperature is kept constant through the ad hoc heating term mentioned in Sections 2 and 6.3.

4.1.4. Population D

A small fraction of the Lagrange elements in the surge, plotted in red in Figure 5, have tracks that start in coronal heights at $t < 57$ minutes (panels II.1)–(II.3)). The ensemble of such elements is called Population D in the following. They cover 7% of the cross section of the surge at $t = 61$ minutes (panel I). The temperature and $L_B^{-1}$ evolution for a representative plasma element of this population is shown in the bottom-right panel of Figure 6. The tracks start at heights well above the reconnection site, with standard coronal temperature and density. When approaching the current sheet, though, these elements go through regions of large density gradients. The diffusion term included in the mass conservation equation becomes important, with characteristic timescale less than one minute, i.e., similar to the evolutionary time of the particles. The evolution that takes place then is effectively equivalent to a process of mixing across the density gradient with plasma elements coming from the dome, after which their behavior is equivalent to that of population A. This kind of effective mixing is peculiar of population D: the density diffusion term is small for the elements of the other populations. A proper study of the evolution of this population must therefore await a numerical experiment with much higher spatial resolution and correspondingly small numerical diffusion (see also the discussion in Section 6.3).

4.2. The Acceleration of the Surge

We turn now to the dynamics of the surge and study the acceleration of the plasma elements first during the launch phase (Section 4.2.1) and then when they are near the apex of their trajectory (Section 4.2.2).

4.2.1. Acceleration During the Launching Phase

The initial acceleration of the mass elements of the surge takes place when they are not far from the thin current sheet that covers the top-left region of the dome (Section 3.4). In this region, the Lorentz force may reach values well above gravity because of the high curvature of the magnetic field lines after reconnection. The gas pressure gradient may also reach large values because of the low values of the magnetic field at the center of the current sheet. For an estimate, call $a_t$ and $a_p$ the acceleration associated with those forces, use $L_B$ as given in Equation (3) and define $L_p$ as the corresponding length scale of variation of the gas pressure. One obtains

$$\left| \frac{a_t}{g_\odot} \right| = \frac{v_a^2}{2 L_B g_\odot} \approx 18 \frac{(v_a)^2}{(L_B)_{\text{Mm}}} \frac{1}{(L_B)_{\text{Mm}}},$$

(4)
where the subindices “100” and “Mm” indicate velocities measured in units of 100 km s\(^{-1}\) and lengths measured in macrometers, respectively, and \(\nu_c, c_p, g_\odot,\) and \(\gamma\) have their customary meaning (Alfvén and sound speed, solar gravity, and ratio of specific heats, respectively). In the reconnection region, the characteristic lengths are substantially smaller than 1 Mm and either the Alfvén velocity or the sound speed (or both) are of order 100 km s\(^{-1}\). Equations (4) and (5) tell us, therefore, that \(a_L\) and \(a_p\) can easily exceed \(g_\odot\); in fact, in some extreme cases they reach values of a few times 100 \(g_\odot\) for a short period of time.

Figure 8 shows the vertical acceleration components \(a_L\) (red) and \(a_p\) (blue) for the representative Lagrangian elements used in Figure 6. We note the following behavior:

1. In Section 4.1.1 we saw how the elements of Population A pass near, even though not quite through, the current sheet. In the top-left panel of Figure 6 we see how, in that phase, they are ejected by the Lorentz force with accelerations of tens of \(g_\odot\). We also note the close relationship between the dynamic and thermodynamical changes (compare this panel with the corresponding one in Figure 6).

2. In the case shown in the top-right panel (Population B), the element is ejected upward in a short time interval around \(t = 58.5\) minutes. The acceleration values are extreme in this case, reaching \(a_L/g_\odot = 6.4 \times 10^2\) and \(a_p/g_\odot = -3.5 \times 10^2\) and last for about 10 s. Those values result from the fact that the element is going through the current sheet at that point and the characteristic lengths are correspondingly small, \(L_q = 40\) km and \(L_p = 50\) km (compare these lengths with those shown in Figure 3).

3. The elements in Population C, like the one shown in the left-bottom panel, are the furthest away from the current sheet and their characteristic lengths are the largest ones. As a consequence, the acceleration values are lower than for other populations but are, anyway, typically a few to several times \(g_\odot\). The plasma in this population is dragged by the magnetic field following the highly dynamical motion initiated in the current sheet and the gas pressure does not play any important role.

4. The right-bottom panel shows an element from Population D. The large pressure gradients in the boundary between the corona and the current sheet lead to a small characteristic length \(L_p = 100\) km and to the predominance of \(a_p\) compared to \(a_L\). The extreme values of the acceleration in this case are around \(a_L/g_\odot = -0.8 \times 10^2\) and \(a_p/g_\odot = 1.6 \times 10^2\), and last for about 20 s.

In the foregoing we have proved that the Lorentz force and gas pressure gradients in the region at and near the current sheet can easily cause substantial accelerations of tens to hundreds of \(g_\odot\). This may seem quite large, but it is naturally associated with the fact that the plasma elements must jump by, in some cases, 6 Mm in height (from the top of the dome to the top of the resulting surge, check Figure 4) in a matter of, say, one minute. As an elementary calculation shows, sustained accelerations of several times \(g_\odot\) (or impulsive accelerations of from tens to hundreds of times \(g_\odot\)) ought to be expected.

4.2.2. Acceleration Near the Apex of the Trajectories

We examine now the acceleration of the plasma elements during the central period of development of the surge, namely when the Lagrange elements are close to the apex of their trajectories. To do this, we call \(\tau_{\text{apex}}\) the time when each individual element reaches its maximum height and use \(t - \tau_{\text{apex}}\) as the time variable. Figure 9 contains three histograms for the vertical accelerations of the plasma elements for \(|t - \tau_{\text{apex}}| = 1\) minute (black curve), 2 minutes (red curve), and 3 minutes (blue curve). Additionally, we have carried out a statistical study using the sample of the vertical accelerations of all elements during the indicated time intervals with a cadence of 0.2 s. The basic moments of the statistical distribution and their mode are given in Table 2. The three distributions are highly peaked (positive kurtosis) and their most frequent value (the mode) is very near \(-g_\odot\) in all cases. The mean of the most
representative histogram (black curve) also coincides with $-g_0$. Yet, the distributions are not narrow, with standard deviations ranging from $6g_0$ to $11g_0$. Also, as wider time ranges around $t_{\text{spec}}$ are chosen (red and blue curves), upward accelerations linked to the launch phase are more frequently represented and the mean of the distributions then shifts toward positive values.

### 4.3. Further Properties: Velocity, Temperature and Density.

We describe now some further properties of the ejecta: velocities, temperatures, and densities. Figure 10 contains double PDF plots for the vertical velocity $u_z$ (upper row), and the density $\rho$ (lower row) versus the temperature, $T$, of the Lagrangian elements. The panels illustrate representative phases of the surge: the launch phase (A panels); and the instant where the surge reaches its maximum vertical extent (B panels).

1. In the (A) panels we see that the majority of the plasma elements have cold temperatures (close to $2 \times 10^4 \text{K}$), densities around $10^{-13} \text{g cm}^{-3}$, and velocities of a few tens of km s$^{-1}$; these are elements located in the dome at that time. Further, there is a group of elements clustered at a temperature of 6–7 thousand K, possibly near the phase of hydrogen ionization/recombination, with small, positive velocities also of tens of km s$^{-1}$. This group contains a mixture of elements that have reached that temperature either through heating of cold plasma (Population A) or cooling of hot plasma (Populations B and D) through the action of different entropy sources. Additionally, in the density panel there are two extended tails of elements toward higher temperatures and velocities. Those elements correspond, on the one hand, to the hot, low density Population-D plasma originating in the corona, and, on the other hand, denser plasma from Population B undergoing its heating-cooling phase. As we saw in Section 4.2.1, the elements of Populations B and D suffer the largest accelerations and, as a consequence, the range of velocities is between 20 and 150 km s$^{-1}$.

2. The (B) panels in the figure are representative of the phase of maximum vertical development of the ejection. We see that basically the whole ensemble is already falling, albeit with small velocities ($|u_z| < 30 \text{ km s}^{-1}$). Concerning the temperatures, there is an important concentration of particles at the temperatures of hydrogen ionization/recombination ($\sim 6 \times 10^4 \text{K}$), ionization/recombination of He $\text{I}/\text{He II}$ (around $T \sim 10^4 \text{K}$, label “4”) and, to a lesser extent, of He $\text{II}/\text{He III}$ (around $T \sim 2 \times 10^4 \text{K}$, label “5”)—see also the discussion about this issue in Section 6.3. The density range for this phase of the cool surge is between $10^{-14}$ and $10^{-11} \text{g cm}^{-3}$. In the later phases of the surge, the velocities continue in the range of a few to tens of km s$^{-1}$.

The resulting global picture of the surge during its main development phase corresponds to plasma with velocities of tens of km s$^{-1}$. The temperatures tend to be $0.6–1 \times 10^5 \text{K}$ (but with a small population which have retained their original cold temperature of a few thousand K) and the densities are in a large range between $10^{-14}$ and $10^{-11} \text{g cm}^{-3}$.

### 5. THE DETACHMENT OF THE COOL EJECTION FROM THE DOME

Looking back at Figure 4, we realize that from panel (D) onward the ejecta adopt the shape of a detached wall, a cool and dense wall. Going a little earlier in time (panel (C)), we locate the origin of the detachment in the fact that the dome is being split in two at $x \approx 11 \text{ Mm}$, the process taking place mainly between $z \approx 4$ and $z \approx 6 \text{ Mm}$. The appearance of this cleft is especially noticeable following the blue temperature contour ($T = 3 \times 10^4 \text{K}$). In panels (D) and (E), the detachment is seen to be complete and the ejecta are from then on a separate wall-like structure.

The explanation of this phenomenon lies in the formation of a series of shocks above the dome starting at $t \approx 59$ minutes (check also the density and temperature evolution shown in the accompanying Figure 4). Successive blobs of plasma coming up from the reconnection site along the top of the dome impinge on the surge. Strong shocks are created that deform and redirect plasma in the blob, last for a brief period of time and then weaken. A new blob arrives and creates again a shock system of the same kind. To illustrate the shock region in one of these collision events, Figure 11 (left panel: general view; right-panel: blow-up of the shock region) shows a map of the
The divergence of the velocity field, $\nabla \cdot \mathbf{u}$, thus signposting the locations where a large compression is taking place. Further, the figure contains the blue ($3 \times 10^4$ K) and pink ($1.2 \times 10^6$ K) isotherm contours of Figure 4, and a collection of field lines drawn as black curves. Also, the arrows show the velocity field in the detachment region, between the hot jet and the cool ejecta.

From the color map we see that the shock front has a wedge-like or arrowhead shape, which is a common feature of the successive shocks seen during the detachment phenomenon. The shocks cause high levels of compression and heating of the plasma going through it. The two sections of the arrowhead show distinctive features: the upper part, which is roughly horizontal and nearly perpendicular to the field lines in the postshock region, resembles a slow-mode shock almost of the switch-off kind. This could be related with the slow-mode shocks generated when plasmoids collide with the ambient magnetic field after being ejected, as illustrated by Yang et al. (2013). This shock is directly related with the hot jet: it is located at the base of the latter (see the pink contours) and the plasma goes through it before flowing along the horn-like jet field lines. We leave its study for a follow-up paper dealing with the properties of the hot jet.

The lower, almost vertical branch of the wedge, in turn, is a shock directly associated with the detachment process studied in this section. The field lines cross it but subtending only a small angle to the tangent direction to the shock front. $\nabla \cdot \mathbf{u}$ has high compression values of about $-0.8$ s$^{-1}$, sometimes reaching even $-3.0$ s$^{-1}$. Plasma traverses the structure from the left. Figure 12 shows the profiles across the shock for a number of relevant variables. To that end, we plot those variables along the horizontal black line plotted in the right panel of Figure 11. The $B_z$ component (panel (A)) is not far from the perpendicular component of the field to the front normal. This component increases by a factor of 2 in absolute value across the shock, which suggests that the shock is a moderately strong, fast shock. This is also supported by the fact that the quasi-parallel component of the velocity ($u_\|$, panel (D)) does not change substantially across the shock, whereas the normal velocity changes by a factor 2, approximately. The temperature has a suggestive profile (panel (B)), that we can understand with the help of the entropy sources (panel (C)). In the first half of the shock the temperature increases, mostly because of the compression work experienced by the plasma element when entering the shock. In the center and final half of the shock, however, $T$ reaches a plateau and decreases: this is probably due to the action of the heat conduction (to a limited extent also of the optically thin radiation cooling): the characteristic cooling timescales are low (4 s for the former, see panel (C)), and fit with the duration of the transit of the plasma across the shock if one takes into account the motion of the front as a whole. Finally, the density increases by a factor 5 (panel (B)), which is larger than the maximum allowed for adiabatic shocks: the large compression ratio is reached thanks to the entropy decrease due to the non-adiabatic effects. As a further consequence of the heat conduction, the thermal energy is distributed efficiently along the individual field lines well beyond the shock itself, giving rise to the structure along the left that marks the boundaries of the cool ejection and lets it appear as a separate domain. The velocities involved in the shock, panel (D), are on the order of a hundred km s$^{-1}$.

The plasma diverted downward after crossing the vertical section of the shock penetrates deeper into the underlying dome as successive shock systems are formed. When the last one in the series ends ($t \approx 61$ minutes, Panel (F) of Figure 4), the surge is completely detached from the remnants of the dome on the left. The hot plasma domains at that time have the classical inverted-Y or Eiffel-tower shape commonly seen in observations, with one of the legs of the tower coinciding with the cleft. Meanwhile, the cool surge enters the decay phase following the swaying motion explained at the beginning of Section 4. Both the hot and cool ejections finally disappear almost simultaneously at around $t = 66$ minutes.

6. DISCUSSION

We have performed a 2.5D radiative-MHD numerical experiment of emergence of magnetized plasma through
granular convection and into the atmosphere. The time evolution of the system leads to the ejection of part of the emerged material as a cool and dense surge. The experiment was done with the Bifrost code, which includes a realistic multi-component EOS as well as modules for photospheric and chromospheric radiation transfer, heat conduction, and optically thin radiative cooling in the corona. In the following, we first provide a comparison with observational data (Section 6.1) and then discuss the relevance of some of the entropy sources not included in the flux emergence experiments so far (Section 6.2). The final paragraphs point out a number of limitations of the present experiment that may be overcome in the future (Section 6.3).

6.1. Observations

A first block of quantities that can be compared to observations concern the size, timescale, and kinematic properties of the surge. A more in-depth comparison must be done through a-posteriori synthesis of different spectral lines based on the numerical boxes. However, the most important spectral lines that one could use for this comparison (like Hα, Ca II H+K, or He II 10830Å) require careful treatment including NLTE aspects; this kind of approach must therefore be left for future work.

The height of the surge in our experiment varies considerably in the different stages of the evolution. At the time of maximum development, the ejecta constitute a vertically elongated object with height of about 13 Mm and width of about 2 Mm. The observed length (see Section 1) falls typically in the interval 10–50 Mm, so the height of our surge is within the observed range, even though toward its lower limit. This fits with the fact that the experiment deals with a simple emergence event into a coronal hole, whereas many classical observations refer to surges measured in the context of flare episodes in active regions, which involve a larger amount of magnetic flux and where larger structures should be expected.

The cool ejection in our experiment lasts for about 7–8 minutes, which, again, is toward the lower limit of the observed durations (several minutes to one hour, Jiang et al. 2007; Vargas Domínguez et al. 2014). Regarding the velocities, although high velocities of up to 150 km s⁻¹ can be reached along the launch phase, during most of the surge evolution the mass elements have rising or falling velocities below 50 km s⁻¹, and the ejection is not collimated. The observations, in turn, yield a velocity range of 10–200 km s⁻¹, as inferred mainly from Hα measurements (Roy 1973; Canfield et al. 1996; Chae et al. 1999; Jibben & Canfield 2004; Uddin et al. 2012; Nelson & Doyle 2013; Vargas Domínguez et al. 2014, among others), which is compatible with the results of the experiment.

Concerning the acceleration, in the experiment we have detected two different patterns of behavior: (1) during the launch phase, the mass elements suffer large accelerations, well in excess of solar gravity; (2) when near the apex of their individual trajectories, the acceleration values are remarkably close to gₑ. There is no definitive observational value to use for a comparison here: in the paper by Roy (1973), the author reports a fast rising phase for the surge with acceleration of 0.24–2.1 km s⁻², i.e., roughly 1–10 gₑ. Observed values for the acceleration at the time of maximum and in the decay phase are more difficult to obtain. In their recent paper, Nelson & Doyle (2013) detected an apparent parabolic trajectory for the cool ejection in their study, but no particular value for the acceleration was given.

6.2. The Relevance of the Entropy Sources

An adequate treatment of the entropy sources and sinks in the energy equation, or, more generally, of the material properties of the plasma, like its EOS, is important when studying the formation and time evolution of the cool ejections. Thanks to the possibilities afforded by the Bifrost code and to an extensive Lagrange tracing of the mass elements of the surge, we have been able to distinguish different patterns of behavior among them and group them into separate populations. One of those populations, Population B, provides a good illustration in that sense. That population covers 34% of the surge cross section at the time of maximum development. It reaches high temperatures, between 10⁷ and 10⁸ K, typically when going through the current sheet, but is then brought back down to classical surge temperatures of order 10⁷ K thanks to the action of the radiation losses and thermal conduction terms. This population could not be obtained in more idealized experiments, like those of Yokoyama & Shibata (1996), Nishizuka et al. (2008), Jiang et al. (2012), Moreno-Insertis & Galsgaard (2013), and MacTaggart et al. (2015). The first authors, for instance, find that the material in the surge structure is not heated significantly along its life (which would roughly correspond to the behavior of our populations A and C). Instead, we find that a non-small amount of the plasma in the surge suffers heating/cooling processes that lead them to high temperatures during a fraction of its life. This explains part of the structural properties of the modeled surge and may also be of interest concerning its detection.

The importance of a proper treatment of the entropy sources and of the EOS may also apply to other cool ejections such as the macrospicules. Chromospheric material and hotter, transition-region material probably coexist in these objects, as indicated by their detection both in Hα and in the EUV line He ii 304 Å. However, the numerical experiments in the literature (e.g., Murawski et al. 2011; Kayshap et al. 2013) are of the idealized kind, so, while possibly capturing various basic features of the macrospicule phenomenon, they may also miss important aspects.

6.3. The Progress Toward Realism in the Theoretical Modeling of Surges Following from Flux Emergence

The essential component in the observed solar surge phenomenon is plasma with chromospheric temperatures and densities, as follows from their detection in spectral lines like Hα, Ca ii H+K, Ca ii 8542 Å, or He ii 10830 Å. Like for other important phenomena of the low solar atmosphere (prominences are a prime example for this), their theoretical study is intricate because of the difficulties of coping with the material properties of the chromospheric plasma. All previous numerical studies of surges following from flux emergence were done on the basis of highly idealized models, without radiation transfer nor a multi-component EOS with realistic abundances, partial ionization processes, etc. Our present paper constitutes a large step forward in that direction, given the degree of realism of the material modules of the Bifrost code, as explained in Section 2.1. In the following we first compare our results with those of the 3D experiment of Moreno-Insertis & Galsgaard (2013). Then, a few limitations of the present experiment are
discussed, namely the presence in flux emergence models of cool and dense plasma domains in the low atmosphere, the effects of partial ionization on Ohm’s law, and the lack of ionization/recombination equilibrium in processes occurring on short timescales.

Our approach allowed us to gain new insights compared with previous idealized simulations of the ejection of cool surges, even with the recent 3D experiment by Moreno-Insertis & Galsgaard (2013). Major differences between the two experiments come from the inclusion in our case of detailed material properties, radiation transfer and heat conduction, which have allowed us, e.g., to discern different plasma populations that later constitute the cool surge, or to study the initial interaction of the rising plasma with realistic granulation, or to identify the process of detachment and decay of the surge. In a 2D experiment, one can reach much higher spatial resolution, which facilitates the study of many aspects difficult or impossible to consider in a 3D problem, like the formation and evolution of plasmoids or the shock structures associated with the jets. Finally, our Lagrange tracing has an extremely high cadence (thanks again to the reduced storage demands of a 2D experiment), and this is advantageous when pursuing the motion of the plasma elements across regions with strong gradients. On the other hand, various general properties of the surge in this paper are in agreement with the simulation of Moreno-Insertis & Galsgaard (2013): being three-dimensional, the cool ejecta in their experiment had the shape of an almost circular plasma wall with chromospheric density surrounding the emerged region, even if the largest concentration was found at the base of the hot jet. There, the cool domain had a height (∼10 Mm), similar to that obtained in the present 2.5D experiment, and width (∼6 Mm), which is wider than in the present paper, perhaps because of the lack of realistic convection cells in their experiment, which can modify the horizontal sizes of the emerged structures. The surge velocities, around 50 km s⁻¹, are also within the range given by those authors for their cool ejecta.

When large magnetized plasma domains rise from the solar interior to the low atmosphere, a dense and cold plasma dome is formed, as repeatedly shown in the numerical experiments since the 1990s. At the interface between the dome and the overlying atmospheric material a large density gradient arises. Numerical codes tend to smooth out sharp density contrast through diffusion, in many cases via some explicit diffusion term, like in Bifrost, or, in a less controllable fashion, through the hidden, intrinsic diffusion of the numerical scheme, like in formally ideal MHD codes. Irrespective of whether a process of mixing takes place in such interfaces in the actual Sun, any result associated with this diffusion in the theoretical models must be handled with care. In our case, we have identified a family of plasma elements originating in coronal heights (population D, Section 4.1.4) whose density is increased to a large extent via this kind of diffusion process when they pass near the current sheet before being incorporated to the surge. The initial mass of this family is negligible compared to the final mass of the surge; in some sense, that family is swallowed by the much more dense material coming from the dome, so the qualitative (and, to a large extent, quantitative) properties of the final surge should be widely independent of the evolution of this particular population. A different issue concerns the dome itself: the large expansion associated with the rise leads it to adopt cold temperatures, below 2000 K. The ad hoc heating term mentioned in Section 2 is then activated in the calculation to prevent the plasma from cooling to lower temperatures, for which the radiation tables used by Bifrost become inaccurate (see Leenaarts et al. 2011). The material of the surge originates essentially in the dome, so, in spite of the enormous advantages of the new generation of MHD codes compared with the previous idealized models, a fully realistic treatment of the evolution of the surge in its formation stage must await the completion of material modules for the codes adequate to the very cold plasma volumes in the low atmosphere.

In the same vein, another aspect that must be improved in future models of the solar surges is the use of a generalized Ohm’s Law incorporating partial ionization effects. On the basis of the general results of Leake & Arber (2006), Arber et al. (2007), Martínez-Sykora et al. (2012, 2015), and Leake & Linton (2013), among others, we expect that these effects may allow some slippage of magnetic field and plasma via ambipolar diffusion and counteract to some extent the cold temperatures of the rising dome. This could affect the populations obtained in the surge, especially Population C (see Section 4.1.3). As a final item in the list of limitations in the realism of the current model, we mention here the lack of non-thermal equilibrium in the ionization/recombination processes of hydrogen and helium. As already proposed long ago (Kneer 1980), in chromospheric processes that occur on comparatively fast timescales (e.g., in shocks), the ionized species, especially hydrogen and helium, may take longer to recombine than predicted by local thermodynamic equilibrium (LTE) equations (see the recent results by Leenaarts et al. 2007 and Golding et al. 2014). This problem is particularly important if one tries to obtain a posteriori, i.e., on the basis of the calculated computational boxes, synthetic spectra for the hydrogen or helium lines from plasma at temperatures around 6 × 10⁴ K (for H) or between 1 and 2 × 10⁴ K (for He). However, the time evolution of the system itself may also be affected in a non-negligible way by this departure of LTE. The inclusion of the non-equilibrium effects into the models of surges is therefore another improvement that must be incorporated in future extensions of the present work.

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