GENERATION OF QUASI-PERIODIC WAVES AND FLOWS IN THE SOLAR ATMOSPHERE BY OSCILLATORY RECONNECTION

J. A. McLaughlin1, G. Verth1, V. Fedun2, and R. Erdélyi2

1 School of Computing, Engineering and Information Sciences, Northumbria University, Newcastle Upon Tyne, NE1 8ST, UK; james.a.mclaughlin@northumbria.ac.uk, gary.verth@northumbria.ac.uk
2 Solar Physics and Space Plasma Research Centre (SP2RC), School of Mathematics and Statistics, University of Sheffield, Hounsfield Road, Hicks Building, Sheffield, S3 7RH, UK; v.fedun@sheffield.ac.uk, robertus@sheffield.ac.uk

Received 2011 November 21; accepted 2012 January 30; published 2012 March 19

ABSTRACT

We investigate the long-term evolution of an initially buoyant magnetic flux tube emerging into a gravitationally stratified coronal hole environment and report on the resulting oscillations and outflows. We perform 2.5-dimensional nonlinear numerical simulations, generalizing the models of McLaughlin et al. and Murray et al. We find that the physical mechanism of oscillatory reconnection naturally generates quasi-periodic vertical outflows, with a transverse/swaying aspect. The vertical outflows consist of both a periodic aspect and evidence of a positively directed flow. The speed of the vertical outflow (20–60 km s\(^{-1}\)) is comparable to those reported in the observational literature. We also perform a parametric study varying the magnetic strength of the buoyant flux tube and find a range of associated periodicities: 1.75–3.5 minutes. Thus, the mechanism of oscillatory reconnection may provide a physical explanation to some of the high-speed, quasi-periodic, transverse outflows/jets recently reported by a multitude of authors and instruments.

Key words: magnetic reconnection – magnetohydrodynamics (MHD) – Sun: activity – Sun: magnetic topology – Sun: oscillations – waves

Online-only material: color figures

1. INTRODUCTION

Improvements in the spatial and temporal resolution of solar observations have led to a recent deluge in reported magnetohydrodynamic (MHD) wave motions (e.g., see Nakariakov & Verwichte 2005; De Moortel 2005; Banerjee et al. 2007; Ruderman & Erdélyi 2009; Goossens et al. 2011; McLaughlin et al. 2011 for a recent list). Here, we focus on observations of transverse motions in the solar atmosphere (e.g., Tomczyk et al. 2007; De Pontieu et al. 2007; Cirtain et al. 2007; Erdélyi & Taroyan 2008; He et al. 2009a, 2009b; Liu et al. 2009, 2011; Morton et al. 2012; Okamoto & De Pontieu 2011). These transverse motions have been called Alfvén waves by some authors, although this is subject to debate and they are alternatively interpreted as kink waves (e.g., see arguments by Erdélyi & Fedun 2007; Van Doorsselaere et al. 2008). The dispute rests not on the observations themselves, but with the appropriate interpretation: MHD wave modes of an overdense cylinder versus MHD waves of a homogeneous plasma. These arguments and others, e.g., whether or not a stable waveguide actually exists in the solar atmosphere, are not the focus of this paper.

Tomczyk et al. (2007) utilized the CoMP/Coronal Multi-channel Polarimeter instrument to report on ubiquitous, small-amplitude, transverse disturbances, propagating along magnetic field lines. The authors do not report on how the waves are generated, but do speculate that the waves may originate from within the chromospheric network that forms the footpoints of the observed loops. De Pontieu et al. (2007) used Hinode/SOT measurements in an attempt to reveal Alfvénic/transversal waves in the chromosphere with strong amplitudes (10–30 km s\(^{-1}\)) and periods 100–500 s. Ca II H-line images also reveal a plethora of dynamic, jet-like extrusions called chromosphere spicules, or type II spicules. These spicules undergo a swaying/oscillatory motion perpendicular to their own axis, which the authors described as Alfvénic motions. Again, this interpretation is disputed by other authors (e.g., He et al. 2009a; Verth et al. 2011) who interpreted these spicule oscillations as kink waves, due to the fact that spicules are overdense in comparison with the ambient plasma.

De Pontieu et al. (2011) report on a link between chromospheric spicules and their coronal spicules/jets counterparts, i.e., suggesting a mechanism for imparting chromospheric plasma into the corona. The coronal spicules are strongly heated and are seen to rapidly propagate upward, but the authors report that there are currently no models for what drives and heats the observed jets (see also a review by Sterling 2000). Okamoto & De Pontieu (2011) report on the statistical properties of transverse (Alfvénic) waves along spicules and report median velocity amplitudes and periods of 7.4 km s\(^{-1}\) and 45 s, respectively (see also the review by Zaqarashvili & Erdélyi 2009). McIntosh et al. (2011) reported transition region observations of ubiquitous, transverse (swaying/Alfvénic) motions that are outwardly propagating, with amplitudes ~20 km s\(^{-1}\) and periods ~100–500 s, energetic enough to heat the fast solar wind. Again, the authors note that the challenge remains to understand how and where these waves are generated in the solar atmosphere.

Thus, transverse/swaying motions have been observed over a range of temperatures, wavelengths, speeds, and scales. However, the origin of these propagating, transverse oscillations remains a mystery. Liu et al. (2011) summarize possible generation mechanisms including an oscillating wake from a coronal mass ejection or periodic reconnection (e.g., Chen & Priest 2006; Sy et al. 2009).

1.1. Waves versus Flows Interpretation

In addition to transverse MHD wave observations, slow MHD waves have also been observed in the solar atmosphere...
1.2. Flux Emergence and Oscillatory Reconnection

Magnetic field is continuously emerging on the Sun over a range of scales (see Archontis 2008 for a comprehensive review). Magnetic flux tubes, formed at the tachocline, rise buoyantly through the convection zone. As they reach the photosphere, their buoyant rise ends and an instability allows the magnetic flux to penetrate into the solar atmosphere. The subsequent evolution of the newly emerged flux is then dominated both by the properties of the rising flux tube itself and the pre-existing magnetic topology the tube emerges into. Flux emergence is well described in the existing literature, as is the dynamic reconnection associated with the collision of newly emerged flux and pre-existing magnetic field (e.g., Shibata et al. 1992; Yokoyama & Shibata 1995, 1996; Archontis et al. 2004, 2005, 2006, 2007; Isobe et al. 2005, 2006; Murray et al. 2006; Galsgaard et al. 2007; Moreno-Insertis et al. 2008, and references therein).

Shibata et al. (2007) reported Hinode/SOT observations of the ubiquitous presence of chromospheric anemone jets (velocity 10–20 km s$^{-1}$). These numerous, small-scale jets, seen in, e.g., Ca II H broadband, display an inverted Y shape, i.e., the characteristic shape of anemone jets (e.g., Shibata et al. 1994; Yokoyama & Shibata 1995). The anemone shape is formed as a result of magnetic reconnection between an emerging magnetic bipolar and a pre-existing vertical field.

Reconnection can occur when strong currents cause the magnetic field lines to diffuse through the plasma and change the connectivity (Parker 1957; Sweet 1958; Petschek 1964). In two dimensions, reconnection can only occur at null points (Priest & Forbes 2000). Dungey (1953) reported that a perturbed X-point can collapse if the footpoints are free to move, Mellor et al. (2002) studied the linear collapse of a two-dimensional null point, and Imshennik & Syrovatsky (1967) described the collapse with an exact, nonlinear solution of the ideal MHD equations. However, these papers do not include the effect of gas pressure, which acts to limit the growth of the current density. In considering the relaxation of a two-dimensional X-type null point, Craig & McClymont (1991) found that free magnetic energy is dissipated by the phenomenon of oscillatory reconnection, which couples resistive diffusion at the null to global advection of the outer field. McLaughlin et al. (2009) investigated the behavior of nonlinear fast magnetosonic waves near a two-dimensional X-point and found that the incoming wave deforms the null point into a cusp-like point which in turn collapses to a current sheet. The system then evolves periodically through a series of horizontal/vertical current sheets with associated changes in connectivity, i.e., the system displays oscillatory reconnection. Longcope & Priest (2007) investigated the diffusion at the null of a two-dimensional current sheet subjected to a suddenly enhanced resistivity, finding that the diffusion couples to a fast mode which propagates the current away at the local Alfvén speed.

Of particular importance to the work presented in this paper is that of Murray et al. (2009). Flux emerging into a pre-existing field has been studied in great detail before, but Murray et al. (2009) were the first to investigate the long-term evolution of such a system, i.e., many previous simulations end once reconnection is first initiated. Murray et al. utilized a stratified atmosphere permeated by a unipolar magnetic field (representing a coronal hole) and investigated the emergence of a buoyant flux tube. Murray et al. found that a series of “reconnection reversals” take place as the system searches for equilibrium, i.e., a cycle of inflow/outflow bursts followed by outflow/inflow bursts. Thus, the system demonstrates oscillatory reconnection (e.g., Craig & McClymont 1991; McLaughlin et al. 2009), initiated in a self-consistent manner. Murray et al. also detail the physics behind the phenomena.

The aim of this paper is to further generalize the model of Murray et al. (2009) and to detail the oscillatory outputs due to oscillatory reconnection (Craig & McClymont 1991; McLaughlin et al. 2009). We will also investigate the dependency and robustness of the model by varying the initial magnetic strength of the buoyant flux tube. The paper has the following outline: the numerical model is detailed in Section 2, brief recall of Murray et al. (2009) is described in Section 3, and the quasi-periodic outputs are reported in Section 3.1. Section 4 investigates the dependency of the model to the initial strength of the buoyant flux tube and conclusions are presented in Section 5.
The values returned from Equations (1) are made dimensional using the following choice of solar constants: (photospheric)

The coronal hole temperature, density, and field strength are found in Wilkins (1980). Thus, $Q_{\text{shock}}$ represents the viscous heating at shocks. Heat conduction and radiative effects are neglected in the present study.

We now introduce a change of scale to non-dimensionalize all variables. Letting $v = v_0 v^*$, $B = B B^*$, $x = L x^*$, $y = L y^*$, $\rho = \rho_0 \rho^*$, $p = p_0 p^*$, $\nabla^* = \nabla^*/L$, $t = t_0 t^*$, $A = B \Lambda^*$, $g = g_0$, and $\xi = \xi_0$, where $*$ denotes a dimensionless quantity and $v_0$, $B$, $L$, $\rho_0$, $p_0$, $t_0$, and $g_0$ are constants with the dimensions of the variable they are scaling. Here, $A = A_0 \hat{z}$ is the vector potential. We then set $B/\sqrt{\mu_0 p_0} = v_0$ and $v_0 = L/t_0$ (this sets $v_0$ as a constant background Alfvén speed). We also set $\xi_0 t_0/L^2 = R_m^{-1}$, where $R_m$ is the magnetic Reynolds number.

This process non-dimensionalizes Equations (1) and under these scalings, $t^* = 1$ (for example) refers to $t = t_0 = L/v_0$; i.e., the time taken to travel a distance $L$ at the background Alfvén speed. For the rest of this paper, we drop the star indices; the fact that all variables are now non-dimensionalized is understood.

To initiate flux emergence, a magnetic flux tube is placed in the solar interior at $x = 0$ and a depth of $y = -1.7$ Mm. In cylindrical coordinates, the magnetic flux tube is chosen to have $B = B_0(0, \alpha r e^{-r^2/R_0^2}, e^{-r^2/R_0^2})$. We choose $B_0 = 3.25 \times 10^3$ G, $R = 4.25 \times 10^5$ m, and $\alpha = -0.064 \times 2\pi$ for each $L$ length in the axial direction. The buried flux tube is set in radial force balance and in thermal equilibrium with the external plasma. Thus, a density difference exists such that the flux tube is buoyant relative to its surroundings and, at the start of the simulation, will rise bodily upward/toward the photosphere.

We chose a numerical domain $-68$ Mm $\lesssim x \lesssim 68$ Mm, $-4.25$ Mm $\lesssim y \lesssim 63.75$ Mm using 1600 $\times$ 832 gridpoints of uniform spacing. All boundaries are fixed in $x$ and $y$. Convergence testing was carried out with double and half the resolution.

3. FLUX EMERGENCE AND RECREATION OF MURRAY ET AL.’S RESULTS

Flux emergence is well documented in the existing literature (e.g., Murray et al. 2006; Archontis 2008, as well as the papers
Figure 2. Contours of current density ($|J|$, units A m$^{-2}$) and selection of field lines at times $t = 30, 33, 36, 39, 42, $ and 45 minutes. Dotted lines denote horizontal layers of the equilibrium solar atmosphere. Note that the numerical domain plotted and color bars change between the two rows. (A color version of this figure is available in the online journal.)

Figure 3. Contours of current density ($|J|$, unit A m$^{-2}$) and selection of field lines at times $t = 46.7, 47.8, 49.2,$ and 50.8 minutes. Dotted lines denote a horizontal layer of our equilibrium solar atmosphere (i.e., change from transition region to coronal temperature profile). Note that we plot different axes compared to Figure 2. (A color version of this figure is available in the online journal.)

listed in Section 1.2 and references therein). Figure 2 (top row) shows that the buoyant magnetic tube rises and emerges into the model atmosphere, and that the emerging flux compresses the pre-existing magnetic field as it expands. To the northwest side of the emerging flux, the magnetic field is directed positively out of the solar surface whereas the neighboring coronal hole is directed in the opposite direction. Thus, a current sheet builds up at this interface between the two flux systems and this can be clearly seen in the bottom row of Figure 2. Reconnection commences at $t = 41.6$ minutes.

The system demonstrates the phenomenon of oscillatory reconnection as it searches for an equilibrium. In Figure 3, we see that at $t = 46.7$ minutes the system forms a current sheet located around $-3.5 \text{ Mm} < x < -2.5 \text{ Mm}, 4.5 < y < -5.5 \text{ Mm}$, at an angle of approximately $\pi/4$ relative to the positive $x$-direction. In this paper, we shall refer to a current sheet at this angle as an orientation 1 current sheet. At $t = 47.8$ minutes, we see that a new current sheet has formed at a similar location, but now at an angle of approximately $3\pi/4$ relative to the positive $x$-direction. We shall refer to a current sheet formed at this angle as an orientation 2 current sheet. At $t = 49.2$ minutes, we see that a current sheet has formed again in a similar location, but that this current sheet is again of orientation 1. Finally, at $t = 50.8$ minutes, we see the formation of an orientation 2 current sheet, again in a similar location (it is also clear that this current sheet is weaker, i.e., $|J|_{\text{max}}$ is decreased, compared to the previous current sheets). Thus, Figure 3 illustrates the formation of a cycle of current sheets, i.e., the formation of orientation 1, followed by orientation 2, followed by orientation 1 again, and so on. Note that this figure is a qualitative illustration of the periodic nature of the current sheet formation in this system (Section 3.2 will provide quantitative evidence). Note that our terminology of orientation 1 and 2 is purely arbitrary; a similar periodic cycle of current formation was seen in McLaughlin et al. (2009) and was referred to as a cycle of horizontal and vertical current sheets.

Thus, we recover the results of Murray et al. (2009). Murray et al. demonstrated that, using field line tracing, one can quantitatively demonstrate the periodic change in connectivity of the open flux over time, i.e., evidence of reconnection. We recover the field-line-tracing results of Murray et al. (their Figure 4). Hence, we use the terminology oscillatory reconnection to refer to the periodic formation of orientation 1 and 2 current sheets as well as the associated periodic changes in
connectivity. We now focus on the observable consequences and outputs of such an evolving system.

3.1. Generation of Quasi-periodic Outflows

As current sheets form and reconnection commences in the simulation, we observe strong outflows emanating from the ends of the current sheet, in agreement with classic steady-state reconnection theory (e.g., Sweet 1958; Parker 1957; Petschek 1964). Upon leaving the current sheet, these jets (strong outflows) collide with the magnetic field already in the outflow regions and are deflected into two secondary jets at angles of approximately $\pm \pi/4$ to the original jet (a termination shock is also present). The schematic structure of these reconnection jets is in good agreement with the description of Forbes (1988). Since these secondary jets are deflected at angles of approximately $\pm \pi/4$ and due to the orientation of the current sheets, they manifest themselves as either primarily horizontal and/or vertical outflow jets. For orientation 1 current sheets, jets from the lower end of the current sheet give rise (periodically) to negatively directed $v_x$ and $v_y$ motion. Meanwhile, jets from the upper end of the current sheet give rise (periodically) to positively directed $v_x$ and $v_y$ motion. For orientation 2 current sheets, the two jets have mixed velocity components, and this can be clearly seen in Figure 4. Figure 4 shows contours of $v_x$ (top row) and $v_y$ (bottom row) at four snapshots in our simulation (the blue/red color table corresponds to positive/negative motions).

Let us first consider the $v_y$ behavior (top row of Figure 4). The characteristic behavior can be summarized as follows.

1. At $t = 46.7$ minutes (orientation 1 current sheet), we have strong horizontal outflows, with positively directed $v_x$ motions (blue) ejected from the upper end of the current sheet.

2. At $t = 47.8$ minutes (orientation 2 current sheet), we have negatively directed $v_x$ motions ejected from the upper end of the current sheet.

3. This cycle repeats, and we have positively directed $v_x$ motions again at $t = 49.2$ minutes (orientation 1) followed by negatively directed $v_x$ motions at $t = 50.8$ minutes (orientation 2).

A similar pattern is observed emanating from the lower end of the current sheet but with the opposite orientation; i.e., at $t = 46.7$ minutes (orientation 1) we have negatively directed $v_x$ motions, followed by positively directed $v_x$ motions at $t = 47.8$ minutes (orientation 2), again in a repeating cycle.

Let us now consider the $v_x$ behavior (bottom row of Figure 4). The characteristic behavior can be summarized as follows.

1. At $t = 46.7$ minutes (orientation 1 current sheet), we have strong vertical outflows, with positively directed $v_y$ motions (blue) ejected from the upper end of the current sheet. Interestingly, we also have negatively directed (but weaker) $v_y$ motion adjacent to (to the left of) our positively directed $v_y$ outflow. This negatively directed $v_y$ motion is associated with the inflow region of the simulated current sheet, and thus acts at right angles to the current sheet orientation.

2. At $t = 47.8$ minutes (orientation 2), we now have a positively directed $v_y$ motion ejected from the upper end of the current sheet. Again, negatively directed $v_y$ motion appears adjacent to (now to the right of) our positively directed $v_y$ outflow (again associated with inflow into our reconnection region).

3. The cycle then repeats: we have positively directed $v_y$ motions again at $t = 49.2$ minutes (orientation 1) and negatively directed $v_y$ motions at $t = 50.8$ minutes (orientation 2).
The vertical $v_y$ motions are of obvious interest for comparison with observations. Following the terminology of Murray et al. (2009), we refer to these vertical $v_y$ motions as a **collimated jet**.

### 3.1. Transverse/Swaying Collimated Jets

We now consider these vertical outflow jets and swaying, transverse motions in further detail. To do so, we measure the $v_x$ and $v_y$ signal at a fixed point $(x_0, y_0) = (-2.5 \text{ Mm}, 7 \text{ Mm})$ where this particular point has been chosen as it is located close to the upper end of the orientation 1 current sheet (slightly above and to the right) and thus is well placed to measure the transverse motions and $v_y$ outflows of the resultant jets.

By considering the evolution of the collimated jet, we note that the central axis will be horizontally displaced periodically as the current sheet contracts and lengthens (i.e., evolves between orientation 1 and 2, and back again). While evolving from orientation 1 to 2, the collimated jet will appear to move in the negative $x$-direction (i.e., an orientation 1 current sheet first contracts, then lengthens into an orientation 2 current sheet). Conversely, while evolving from an orientation 2 current sheet (back) to orientation 1, the collimated jet will appear to move in the positive $x$-direction. This displacement will repeat itself as the cycle repeats. Thus, the collimated jet displays a characteristic swaying or transverse motion. Note that this transverse behavior is specifically due to the oscillatory reconnection mechanism, and would be absent for a single, steady-state reconnection jet.

Qualitatively, this transverse displacement can be seen by comparing the locations of the (blue) collimated jet in Figure 4 (bottom row). However, such displacement can also be quantitatively measured from our simulation. In Figure 5(a), we see the evolution of $v_x$ (km s$^{-1}$) at the fixed point $(x_0, y_0) = (-2.5 \text{ Mm}, 7 \text{ Mm})$. The oscillatory behavior of $v_x$ can be clearly seen, i.e., the quasi-periodic transverse/swaying displacement. Note that the change from orientation 1 to 2 occurs at $t \approx 47$ minutes. Before this time, the strong positive $v_x$ motion is associated with the initial formation of the orientation 1 current sheet.

#### 3.1.2. Quasi-periodic Vertical Outflows

Figure 5(b) shows the evolution of $v_y$, i.e., the vertical outflow, at the fixed point $(x_0, y_0) = (-2.5 \text{ Mm}, 7 \text{ Mm})$. We can clearly see the oscillatory behavior: the outflow changes from $v_y < 0$ at $t \approx 45.5$ minutes, to $v_y > 0$ at $t \approx 46.5$ minutes, to $v_y < 0$ at $t \approx 47.5$ minutes, and to $v_y < 0$ at $t \approx 49$ minutes. After $t \approx 50$ minutes, the signal is much weaker since the bulk of the (oscillatory) reconnection has occurred by this time.

We fitted the oscillation with an exponentially damped envelope $\sim v_{y,\text{max}} e^{-\lambda t}$ and $\sim v_{y,\text{min}} e^{-\lambda t}$ where $\lambda = 0.1464 \text{ s}^{-1}$. In both panels, the dotted line denotes zero velocity. (A color version of this figure is available in the online journal.)

![Figure 5](image)

**Figure 5.** (a) Time evolution of $v_x$ (km s$^{-1}$) at the point $(x_0, y_0) = (-2.5 \text{ Mm}, 7 \text{ Mm})$. (b) Time evolution of $v_y$ (km s$^{-1}$) at $(x_0, y_0) = (-2.5 \text{ Mm}, 7 \text{ Mm})$. The red dashed lines indicate an exponentially damped envelope $\sim v_{y,\text{max}} e^{-\lambda t}$ and $\sim v_{y,\text{min}} e^{-\lambda t}$ where $\lambda = 0.1464 \text{ s}^{-1}$. In both panels, the dotted line denotes zero velocity. (A color version of this figure is available in the online journal.)

In Section 3.1, we reported on the formation of strong, quasi-periodic, vertical outflows generated by oscillatory reconnection. As detailed in McLaughlin et al. (2009), by considering the evolution of the vector potential at the center of the current sheet, one can obtain a quantitative measure of the oscillatory nature of the system. In our numerical experiment, we track the center of the (rising) current sheet and plot the value of the vector potential at that point versus time. This evolution can be seen in Figure 6.
4. PARAMETER STUDY OF $B_0^*$

We now investigate the dependence of our system to varying $B_0$, i.e., the initial magnetic strength of our buoyant flux tube. This will allow us to see how the period of oscillation changes and investigate how robust our system is to the onset of oscillatory reconnection.

Figure 7(a) shows the full time evolution of $A_z$ (located at the center of the current sheet) for several different values of the initial value of the magnetic field strength of the buoyant flux tube, i.e., we vary the value of $B_0$. Since this is a numerical parameter study, we choose to present values associated with $B_0^*$, i.e., the non-dimensionalized initial magnetic field strength. Specifically, Figure 7(a) reports the evolution of eight values ranging from $2.6 \times 10^3 \text{G} \leq B_0 \leq 3.9 \times 10^3 \text{G}$ or, in non-dimensional units, $2 \leq B_0^* \leq 3$. Note that Section 3 corresponds to $B_0 = 3.25 \times 10^3 \text{G}$, i.e., $B_0^* = 2.5$. From the resultant curves, it is clear that oscillatory behavior is present in all of these numerical experiments. Thus, we can measure the corresponding period of oscillation for each choice of $B_0$, which is shown in Figure 8(a).

We also investigate larger and smaller values of $B_0$ and these results can be seen in Figure 7(b), which presents values of $B_0 = 2.47, 4.55, 5.2,$ and $6.5 \times 10^3 \text{G}$, i.e., $B_0^* = 1.9, 3.5, 4,$ and $5$. These choices yield behaviors of a significantly different nature to those seen in Figure 7(a). This is for two reasons: first, for values of $B_0^* < 2$, i.e., $B_0 < 2.6 \times 10^3 \text{G}$, the initially submerged flux tube does not successfully emerge into the solar atmosphere. This is in agreement with the results of Murray et al. (2006) who found that for low initial magnetic field strengths, the tube cannot fully emerge into the atmosphere since the buoyancy instability criterion is not satisfied. Thus, in this model, for values of $B_0 < 2.6 \times 10^3 \text{G}$, we have no flux emergence (or failed emergence) and thus no onset of oscillatory reconnection. Thus, high in the solar atmosphere, $A_z$ remains constant. In Figure 7(b), we plot $A_z$ corresponding to a $B_0^* = 1.9$ failed emergence (constant value green line) for comparison.

Figure 7(b) also shows the time evolution of the vector potentials corresponding to $B_0^* = 3.5$ (blue line), $B_0^* = 4$ (purple), and $B_0^* = 5$ (yellow). We note that the evolution of...
A2 is again significantly different to that seen in Figure 7(a). B0* = 3 is plotted as a dashed line to aid comparison between the panels. The reason for this significant change in behavior is that for B0* > 3, we have successful flux emergence and current sheet/X-point formation in a similar manner to that detailed in Section 3 but, critically, these strong current sheets now eject plasmoids from their ends and this fundamentally changes the properties of the current sheet/X-point, since the plasmoids take magnetic flux with them as they leave the current sheet/X-point. Thus, although we still have oscillatory behavior present in the behavior of A, corresponding to B0* = 3.5 and 4, this represents a fundamentally different regime to that seen for 2 ≤ B0* ≤ 3 in Figure 7(a). The effect is even more pronounced for B0* = 5 and beyond.

Let us now investigate the period associated with our choice of B0* (Figure 8(a)) where we restrict ourselves to 2 ≤ B0* ≤ 3 (as explained above, values above and below these limits correspond to fundamentally different regimes). We find that the period of oscillation increases with B0* for periods 105–212.5 s, i.e., 1.75–3.5 minutes.

Finally, we investigate how the final location of the X-point depends upon our choice of B0*. We find that the location X-point at t = 100 minutes, i.e., the final/resting location, is displaced both higher and further to the left for stronger values of B0* (again we restrict ourselves to 2 ≤ B0* ≤ 3). This behavior can be seen in Figure 8(b).

5. DISCUSSION AND CONCLUSIONS

We have performed numerical experiments of magnetic flux emerging into a coronal hole, modeled as a pre-existing unipolar magnetic field, within a stratified solar atmosphere, and solve the compressible and resistive MHD equations using a Lagrangian remap, shock capturing code: LARE2D. The long-term evolution of the system is followed and we investigate how the reconnecting magnetic systems behave as they search for an equilibrium. We find that the initial rise and expansion of the emerging magnetic flux tube are in good agreement with that reported in the existing literature (Figure 2). Reconnection is initiated at t = 41.6 minutes (for B0* = 2.5 system), during which inflows acting perpendicular to the current sheet bring the magnetic field into the reconnection region, and magnetic flux is ejected at the ends of the current sheet. We find that oscillatory reconnection occurs in the model (Figure 3), i.e., a process in which resistive diffusion at the X-point is coupled to global advection of the outer field. We find that the first reconnection reversal, i.e., change from an orientation 1 current sheet to an orientation 2, occurs around t ≈ 47 minutes. The mechanism for oscillatory reconnection is well described by McLaughlin et al. (2009) and Murray et al. (2009) and occurs due to a local imbalance of forces, primarily the gradients in thermal pressure, between the neighboring flux systems.

We find strong horizontal outflows from both ends of the current sheet and, once oscillatory reconnection is initiated, these change direction periodically. Similarly, we find strong vertical outflows in the positive y-direction emanating from the upper end of our current sheet, and these sit side-by-side with negative y-direction inflows bringing magnetic flux into the reconnection region. The direction of these positive/negative velocities changes as the system changes from orientation 1 to 2 (Figure 4), but we also find that, on average, there is a vertical upflow directed in the positive y-direction (Figure 5(b)).

We find that the vertical outflows/collimated jet will be displaced horizontally during the shortening and lengthening of the evolving current sheets which results from the oscillatory reconnection mechanism. This displacement gives the vertical outflow jets a swaying nature and explains the transverse nature of the oscillations. This was further confirmed by analyzing v, (−2.5 Mm, 7 Mm, t), which clearly demonstrated the transverse behavior (Figure 5(a)).

In order to quantitatively estimate the vertical outflows, we measured the vertical velocity at a fixed point: v, (−2.5 Mm, 7 Mm, t). Here, the positive (material ejected from the end of the current sheet) and negative (inflow into the reconnection region) vertical flows were visible as well as the periodic nature of the oscillations (Figure 5(b)). Only a few complete periods were observed, and so we labeled this quasi-periodic behavior. We fit the damped oscillations with exponential envelopes and found that there was a preference for positive velocity over negative, i.e., evidence of a positively directed vertical net flow in the model. Note that the generation of this positively directed vertical net flow is tightly localized.
to the upper ends of the (evolving) current sheet and so similar results are obtained only for other choices of fixed points located around (−2.5 Mm, 7 Mm) and within the same domain of connectivity.

By tracking the vector potential, $A_z$, at the center of the (moving) current sheet, we quantitatively measure the period of oscillation, allowing us to measure a period of 195 s (3.25 minutes) for an initial magnetic flux tube strength of $B_0 = 3.25 \times 10^3$ G ($B_0^2 = 2.5$).

We also perform a parameter study varying the initial magnetic strength of the buoyant flux tube, i.e., $B_0$. We find that for a range of parameters applicable to the solar atmosphere, $2.6 \times 10^3 G \leq B_0 \leq 3.9 \times 10^3$ G, we observed similar flux emergence and oscillatory reconnection behavior, with each $B_0$ corresponding to its own period of oscillation in the range 1.75 minutes $\leq$ period $\leq$ 3.5 minutes. Essentially, the stronger the initial flux tube strength, the longer the period of oscillation.

However, for $B_0 \lesssim 2.47 \times 10^3$ G, we do not observe successful flux emergence and thus, obviously, there is no subsequent oscillatory motion. This is in agreement with Murray et al. (2006) who found that for low initial magnetic field strengths, the tube cannot fully emerge into the atmosphere since the buoyancy instability criterion is not satisfied, i.e., “failed” flux emergence. Further details of the buoyancy instability criterion can be found in Newcomb (1961), Yu (1965), Thomas & Nye (1975), Acheson (1979), and Archontis et al. (2004). Thus, it is the buoyancy instability criterion that dictates the lower limit in our model, given our choices of parameters. For different parameters, e.g., a stronger/weaker equilibrium unidirectional magnetic field, the buoyancy instability criterion will have a higher/lower threshold, although a full investigation must be undertaken to investigate the true behavior.

We also investigate larger values, i.e., $B_0 \geq 4.55 \times 10^3$ G. Here, unlike for $2.6 \times 10^3 G \leq B_0 \leq 3.9 \times 10^3$ G, we observe the formation of plasmoids ejecting from the ends of our current sheet. These ejected plasmoids change the properties of the X-point, e.g., taking magnetic flux with them. Thus, even though we still have oscillatory behavior, seen in the evolution of $A_z$, this represents a fundamentally different regime than that of $2.6 \times 10^3 G \leq B_0 \leq 3.9 \times 10^3 G$. The exact reason for plasmoid formation above a particular threshold strength is uncertain, and will be investigated in future work.

Finally, we investigated how the final location of the X-point depends upon our choice of $B_0$. We found that the location X-point at $t = 100$ minutes, i.e., the final/resting location, was displaced both higher and further to the left for stronger values of $B_0$ (we restricted our records to $2.6 \times 10^3 G \leq B_0 \leq 3.9 \times 10^3 G$). Both the longer duration periods of oscillation and increased displacement/height of the X-point can be fully explained since stronger $B_0$ tubes have larger emergence velocities and thus greater momenta. Thus, the larger momentum flux tubes are able to compress the X-point to a greater extent (resulting in a stronger/longer current sheet and thus longer periods for the subsequent oscillatory reconnection, which explains Figure 8(a)) and, second, higher $B_0$ flux tubes with larger momenta carry the tube higher and farther into the atmosphere (explaining Figure 8(b)).

Thus, we have presented numerical simulations that naturally generate quasi-periodic flows with a characteristic transverse/swaying aspect. Such outputs result from the oscillatory reconnection physical mechanism, i.e., in a self-consistent manner since no periodic driver is imposed on our system. The vertical speeds of the outflows, 20–60 km s$^{-1}$, are comparable to those reported in recent observations. By varying the initial strength of our submerged flux tube, we recover periodicities in the range of 1.75–3.5 minutes. Thus, the mechanism of oscillatory reconnection may provide a physical explanation for the generation of some of the recent quasi-periodic, transverse, vertical motions/jets/outflows reported by a multitude of authors (see Section 1 for details). In particular, the oscillatory reconnection mechanism presented here may explain the observations and simulations by Nishizuka et al. (2008, 2011) and He et al. (2009a, 2009b), who detail Hinode/SOT observations and simulations of transverse motions on a spicule, originating from the cusp of an inverted Y-shaped structure, as well as more recent work by Ding et al. (2011) and Harra et al. (2011).

The oscillatory mechanism presented here may also partially explain quasi-periodic pulsations (see reviews by Aschwanden 2003; Nakariakov & Melnikov 2009). Such oscillatory behavior has been observed in a number of solar and stellar flares (Mathioudakis et al. 2003, 2006; McAteer et al. 2005; Inglis et al. 2008; Inglis & Nakariakov 2009; Nakariakov et al. 2010; Nakariakov & Zimovets 2011) but the true physical mechanism responsible remains uncertain.

Finally, it should also be noted that the mechanism generates both $v_x$ and $v_y$ motions together (one cannot exist without the other), and such motions are exponentially damped. Thus, if such signals are detected, then they may be decaying, not due to a damping mechanism, but due to the generation mechanism itself. This is not surprising given that flux emergence injects a finite amount of energy into the (oscillatory reconnection) mechanism, and so it is expected that the phenomena and outputs will also only be of a finite duration, i.e., this is a dynamic reconnection phenomenon as opposed to the classical steady-state (time-independent) reconnection models.

Although we have only presented a specific example of reconnection initiated by flux emergence, we believe the oscillatory reconnection mechanism described in this paper is a robust, general phenomenon that may be observed in other systems that demonstrate finite-duration reconnection. Further studies should focus on the inclusion of heat conduction (e.g., Miyagoshi & Yokoyama 2003, 2004) which is expected to reduce the temperature of the outflow jets. However, the density of outflows will also be increased by heat conduction, i.e., to ensure force balance in the current sheet, which may make the outflow jet more observable (e.g., Shiota et al. 2005). Finally, the oscillatory reconnection mechanism itself should be investigated further (e.g., Gruzscek et al. 2011) and extended to fully three-dimensional studies. Evidence of oscillatory reconnection in three-dimensional flux emergence simulations was recently reported by Archontis et al. (2010).

J.M. thanks M. Murray, V. Archontis, and A. Hood for helpful and insightful discussions and suggestions. R.E. acknowledges M. Kéray for patient encouragement and is also grateful to STFC (UK) and NSF, Hungary (OTKA, Ref. No. K83133). The authors also acknowledge IDL support provided by STFC. The computational work for this paper was carried out on the joint STFC and SPC (SRIF) funded cluster at the University of St Andrews (Scotland, UK).

REFERENCES

Acheson, D. J. 1979, Sol. Phys., 62, 23
Arber, T. D., Longbottom, A. W., Gerrard, C. L., & Milne, A. M. 2001, J. Comput. Phys., 171, 151
