TWISTED FLUX TUBE EMERGENCE FROM THE CONVECTION ZONE TO THE CORONA

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ABSTRACT

Three-dimensional numerical simulations of a horizontal magnetic flux tube emergence with different twist are carried out in a computational domain spanning the upper layers of the convection zone to the lower corona. We use the Oslo Stagger Code to solve the full MHD equations with non-gray, non-LTE radiative transfer and thermal conduction along the magnetic lines. A magnetic flux tube is input at the bottom boundary into a weakly magnetized atmosphere. The photospheric and chromospheric response is described with magnetograms and synthetic continuum as well as Ca II H line images and velocity field distributions. In the photosphere the granular size decreases when the flux tube approaches from below, as has been reported previously in the literature. In the convective overshoot region, some 200 km above the photosphere, adiabatic expansion produces cooling, darker regions with the structure of granulation cells. We also find evidence of collapsed granulation at the boundaries of the rising flux tube. Once the flux tube has crossed the photosphere, bright points related to concentrated magnetic field, vorticity, high vertical velocities, and heating by compressed material are found at heights up to 500 km above the photosphere. At greater heights, in the magnetized chromosphere, the rising flux tube produces a large, cool, magnetized bubble that tends to expel the usual chromospheric oscillations. In addition, the rising flux tube dramatically increases the chromospheric scale height, pushing the transition region and corona aside, such that the chromosphere extends up to 6 Mm above the photosphere. We find flux tube emergence through the photosphere to the lower corona to be a relatively slow process, taking of order 1 hr.

Subject headings: MHD — methods: numerical — radiative transfer — Sun: atmosphere — Sun: magnetic fields

1. INTRODUCTION

One of the stated goals of the newly launched Hinode satellite is to follow the evolution of magnetic flux from the moment of emergence through the photosphere and into the chromosphere and corona. Such observations come at a timely moment, as they should prove a fertile testing ground for the three-dimensional (3D) numerical models of flux emergence that are now becoming available through the technological development of massively parallel computers and algorithms to make use of them.

A great variety of simplified simulations have been developed in order to study the different phases of flux emergence. Originally, early simulations were performed in 1D due to computational limitations. Studies of rising flux tubes were carried out to gain an understanding of the emergence latitudes of active regions, their tilt angles, and the asymmetry between leading and following polarities and magnetic forces such as tension (Moreno-Insertis 1986; Fan et al. 1993; Caligari et al. 1995). The early 1980s saw the appearance of 2D simulations, in which Schüssler (1979) and Longcope et al. (1996) found that an emerging magnetic flux tube without twist is fragmented. Moreno-Insertis & Emonet (1996) investigated the effect of the surrounding flows on the flux tube’s rise to the surface and demonstrated that a minimum twist in the tube was required in order to suppress the conversion of the tube into vortex pairs (Lites et al. 1995). Emonet et al. (2001) studied the Von Kármán vortex street generated in the boundary layer of the tube (Dorch & Nordlund 1998). In the 1990s, 2D simulations were extended to 3D. Fan et al. (1998) investigated flux tubes moving through an adiabatic stratification, and found that the degree of twist must be large enough to avoid fragmentation yet small enough to avoid the kink instability. There are also other 3D emergence models that, while not including radiative transfer, nor any detailed treatment of convection cells below the photosphere, have added schematic descriptions of the chromosphere and corona (Matsumoto et al. 1998; Fan 2001; Magara 2004, 2006; Manchester et al. 2004; Archontis et al. 2004) in order to gain a handle on the effects to be expected.

On the other hand, in the last decade more realistic 3D MHD models of active region flux emergence have been developed up to the photosphere. Cheung et al. 2007a consider flux emergence through a convective layer, including detailed photospheric radiative transfer, but excluding the layers above the photosphere. Other simulations involve solar surface magnetoconvection (Stein & Nordlund 2002, 2006; Stein et al. 2003; Vogler et al. 2005), but do not consider flux emergence from below.

The description of the outer layers of the solar atmosphere are also growing in sophistication. Gudiksen & Nordlund (2005) recently performed realistic simulations of the solar corona driven by a stochastic approximation of granulation. Hansteen (2004), Hansteen et al. (2007a), and Abbett (2007) studied 3D MHD simulations for a convective layer below the photosphere and included the upper atmosphere (chromosphere, transition region, and lower corona) with the radiative losses in the quiet Sun and conduction along the magnetic field treated in detail.

In this paper our goal is to study horizontal flux tube emergence from the upper convection zone to the lower corona in a realistic 3D MHD model. The model is designed to have a corona driven by magnetoconvection. The radiative losses from the photosphere and lower chromosphere are computed in a nongray manner, and scattering in the chromosphere is handled to a certain approximation (Nordlund 1982; Skartlien 2000). For the upper chromosphere and corona we assume effectively thin radiative losses. A flux tube is injected into the bottom boundary of an atmosphere that contains a preexisting but weak magnetic field. We follow the evolution of the flux tube as it rises through the various atmospheric layers, and address the questions: How much flux enters the differing regions? When do we see observational signatures of flux emergence? Where and how does the reconnection process
happen? and How does this affect chromospheric and coronal dynamics and structure?
In § 2 we summarize how the MHD equations with radiative transfer, thermal conduction, viscosity, and resistivity are solved by the Oslo Stagger Code. Section 3 shows the initial and boundary conditions of our numerical box for the different simulations. We describe in more detail how the magnetic flux tube is input in the bottom boundary. The results of our simulations are described in § 4, centered on the different events observed in the different layers of the simulation box. We start with the photosphere, then treat the reverse granulation layer, the end of the overshooting and boundaries of the simulation box. We start with the photosphere, then x in the bottom boundary. The results of our simulations are described by the Oslo Stagger Code. Section 3 shows the initial and boundary conditions of our numerical simulation box. We start with the photosphere, then treat the reverse granulation layer, the end of the overshooting and boundaries of the simulation box. The results of our simulations are described by the Oslo Stagger Code. Section 3 shows the initial and boundary conditions of our numerical

2. EQUATIONS AND NUMERICAL METHOD

In order to model the rise of magnetic flux tubes through the upper convection layer and their emergence through the photosphere and into the chromosphere and corona, we solve the equations of MHD using the Oslo Stagger Code (OSC):

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

\[
\frac{\partial u}{\partial t} + (u \nabla) u + \frac{1}{\rho} \nabla (P + \tau) = \frac{J \times B}{\rho} + g.
\]

\[
\frac{\partial (\varepsilon e)}{\partial t} + \nabla (e u) + u \nabla P = \nabla F_r + \nabla F_c + Q_{\text{Joule}} + Q_{\text{visc}},
\]

\[
\frac{\partial B}{\partial t} = \nabla \times (u \times B) - \nabla \times (\eta J),
\]

where \( \rho \) represents the mass density, \( u \) is the fluid velocity, \( P \) is the gas pressure, \( J \) is the current density, \( B \) is the magnetic field, \( g \) is gravitational acceleration, and \( \varepsilon \) is the internal energy. The viscous stress tensor is written \( \tau \) and the resistivity \( \eta \). The term \( F_r \) represents the radiative flux, \( F_c \) represents the conductive flux, and \( Q_{\text{Joule}} \) and \( Q_{\text{visc}} \) are the joule heating and viscous heating, respectively.

These equations are solved using an extended version of the numerical code described in Dorch & Nordlund (1998) and Mackay & Galsgaard (2001) and in more detail by Å. Nordlund & K. Galsgaard (http://www.astro.ku.dk/~kg) and Hansteen et al. (2007a). Extended in this case means the inclusion of thermal conduction along the magnetic field, nongray, non-LTE radiative transfer and characteristic boundary conditions on the upper and lower boundaries. The latter allow the passage of waves out of the computational box, while at the same time allowing the specification of an input magnetic field and entropy at the lower boundary.

In short, the code functions as follows. The variables are represented on staggered meshes, such that the density and the internal energy are volume centered, the magnetic field components and the momentum densities \( p = \rho u \) are face-centered, while the electric field \( E \) and the current density are edge-centered. A sixth order accurate method involving the three nearest neighbor points on each side is used for determining the partial spatial derivatives. In the cases where variables are needed at positions other than their defined positions, a fifth order interpolation scheme is used. The equations are stepped forward in time using the explicit third order predictor-corrector procedure defined by Hyman et al. (1979), modified for variable time steps. In order to suppress numerical noise, high-order artificial diffusion is added in the form of both viscosity and magnetic diffusivity.

The radiative flux divergence from the photosphere and lower chromosphere is obtained by angle and wavelength integration of the transport equation. Assuming isotropic opacities \( \chi_{\lambda} \) and emissivities, we find

\[
\nabla F_r = 4\pi \int \varepsilon_\lambda \chi_{\lambda} (B_\lambda - J_\lambda) \, d\lambda,
\]

where \( \varepsilon_\lambda \) is the photon destruction probability. The method of solving the transport equation assumes that opacities are in LTE and coherent scattering. Nordlund (1982) devised a solution technique based on group mean opacities, in which the spectrum is divided into four bins representing strong, medium, and weak lines in addition to the continuum. The transfer equation is formulated for these bins, and a group mean source function is calculated for each bin. These source functions contain an approximate scattering term and an exact contribution from thermal emissivity. The resulting 3D scattering problems are solved by iteration based on a one-ray approximation in the angle integral for the mean intensity as developed by Skartlien (2000).

For the upper chromosphere and corona, we assume optically thin radiative losses such that

\[
\nabla F_r \propto \rho^2 f(T)e^{-\tau},
\]

where \( f(T) \) is the optically thin radiative loss function based on the coronal approximation and atomic data collected in the HAO spectral diagnostics package (Judge & Meiners 1994); \( f(T) \) is based on the elements hydrogen, helium, carbon, oxygen, neon and iron. The \( e^{-\tau} \) term prevents this term from having an effective contribution from thermal emissivity. The resulting 3D scattering problems are solved by iteration based on a one-ray approximation in the angle integral for the mean intensity as developed by Skartlien (2000).

In the mid and upper chromosphere we include non-LTE radiative losses from hydrogen continua, hydrogen lines, and lines from singly ionized calcium. These losses are calculated from

\[
\nabla F_r \propto N_e f_\lambda(T) e(T_e(m_e)),
\]

where \( N_e \) is the electron density, \( f_\lambda(T) \) is a precalculated function based on collisional excitation and radiative deexcitation, separate for hydrogen and calcium, and \( e(T_e(m_e)) \) is the non-LTE escape probability as a function of column mass \( m_e \). This escape probability function is calculated from 1D dynamical chromospheric models in which the radiative losses are computed in detail (Carlsson & Stein 1992, 1995, 1997, 2002). In addition to these optically thin losses in the upper atmosphere, we have added an ad hoc heating term to prevent the atmosphere from cooling much below 2000 K in the upper chromosphere.

The Courant condition for a diffusive operator such as that describing thermal conduction scales with the square of the grid size \( \Delta x^2 \), instead of with \( \Delta x \) as applies to the magnetohydrodynamic operator. This severely limits the time step \( \Delta t \) at which the code can be stably run. Our solution to this problem is to proceed by operator splitting, such that the operator advancing the variables in time is \( L = L_{\text{hydro}} + L_{\text{conduction}} \). Thus the conductive part of the energy equation is solved by discretizing

\[
\frac{\partial e}{\partial t} = \nabla F_c = -\nabla \kappa_{\lambda} \nabla T
\]

using the Crank-Nicholson method and solving the resulting implicit problem using a multigrid solver. The formulation used in the code described here is based on the method used by Malagoli,
Dubey, and Cattaneo, but extended to 3D and confining conduction to follow the magnetic field lines.

The units employed in this work are in SI. Sometimes we refer the distance in Mm (10^6 m) and the time in hs (10^2 s).

3. INITIAL AND BOUNDARY CONDITIONS

The five models described here are run on a nonuniform grid of 128 x 128 x 160 points spanning 8 x 4 x 16 Mm^3. The nonuniform grid ensures that the vertical resolution is good enough to resolve the photosphere and the transition region with a grid spacing of 32.5 km, while becoming larger at coronal heights. At these resolutions the models have been run for roughly 1 hour solar time.

The average temperature at the bottom boundary is maintained by setting the entropy of the fluid entering the computational domain. The bottom boundary is otherwise open, allowing fluid to enter and leave as required. The upper boundary is set so that the temperature gradient is zero; no conductive heat flux enters or leaves the computational domain through the top boundary.

Of course, without coronal heating the corona would cool on a timescale of roughly an hour (depending on the magnetic field topology), when no heat flux enters the model through the upper boundary. We have therefore seeded the initial model with a magnetic field in which sufficient stresses can be built up to maintain coronal temperatures in the upper part of the computational domain, as previously shown to be feasible by Gudiksen & Nordlund (2004). The initial field was obtained by semi-randomly spreading some 20–30 positive and negative patches of vertical field at the bottom boundary, then calculating the potential field that arises from this distribution in the remainder of the domain. Stresses sufficient to maintain a minimal corona are built up by photospheric motions after roughly 20 minutes solar time.

At the top boundary the hydrodynamic variables (aside from the temperature) and the magnetic field are set by characteristic extrapolations. This method hinders most of the reflections that are due to the presence of the upper boundary. No joule heating is added in the top five computational zones.

3.1. Initial Model

The initial atmosphere, into which magnetic field is injected, includes the upper convection zone, the photosphere, chromosphere, transition region, and corona. In the left panel of Figure 1 we show the lower 12 Mm (of 16 Mm) minimum, maximum, and horizontally averaged temperatures and densities as a function of height z. At the base of the model, 1.4 Mm below the photosphere, the average temperature is ~16,200 K, with average density $6.7 \times 10^{-3}$ kg m$^{-3}$. With increasing height the temperature falls close to adiabatically up to the photosphere, which is located at z ~ 0 Mm, where the temperature gradient becomes much steeper and the average temperature falls to 6,000 K. The average density falls roughly 1.5 orders of magnitude to $2.5 \times 10^{-4}$ kg m$^{-3}$ in the same height range. Quantities vary much more in the chromosphere, which extends from the top of the photosphere up to a height of some 4 Mm in some locations. The chromospheric temperature varies from a low of 2000 K up to almost 10,000 K in the strongest shocks and in regions of strong magnetic field. The density also has a high horizontal contrast in the chromosphere, while at the same time falling by 7–8 orders of magnitude vertically. The location of the transition region varies from 1.5 to 4 Mm above the photosphere. In this region the temperature rises rapidly to coronal values of roughly 1 MK, while coronal densities are of order $10^{-12}$ kg m$^{-3}$ in this model.

In the right panel of Figure 1 we plot the minimum, maximum, and horizontally averaged gas and magnetic pressures as a function of height. The average gas pressure is $8.7 \times 10^5$ Pa at the bottom boundary, while the average magnetic pressure at the same depth is much smaller, at $1.6 \times 10^3$ Pa. The ratio between these is still large in the photosphere, but note that the maximum magnetic pressure is as large as the maximum gas pressure here; photospheric motions can concentrate the magnetic field to pressures that equal or exceed photospheric pressure in intergranular lanes. The average plasma $\beta$ (ratio of gas pressure to magnetic pressure) remains >1 up to ~600 km above the photosphere, but the $\beta = 1$ plane is quite corrugated and can extend up to z ~ 1000 km. This means that the upper chromosphere, transition region, and lower corona all are low-$\beta$ regions. In the initial model, there is little net magnetic flux and the field is small at great heights; we therefore find some high-$\beta$ regions at heights greater than $z = 8$ Mm or so.

The numerical box and the axes used are shown in Figure 2. The color scale represents the temperature. The red lines are the magnetic field lines in the initial background field. Note that field lines extending into the corona are mainly rooted in regions that cover all y values and around x = 7 and 14 Mm. We also show planes of temperature at four heights: in the photosphere z = 10 km, in the reverse granulation z = 234 km, at the layer z = 458 km, and in the chromosphere at z = 900 km. We will show

\[\text{as shown at http://astro.uchicago.edu/Computing/OnLine/cfe95/carnells.html.}\]
The black lines at the left and right side show the heights of the four layers. The green lines show the magnetic field lines of the flux tube coming in from the bottom these heights later in this paper. The green lines show the details of how the initial atmosphere reacts to flux emergence at different heights, shown in the figure as partial planes with the temperature (gray-scale coded); at heights $z = 10 \text{ km}$ (photosphere), $z = 234 \text{ km}$ (reverse granulation), $z = 458 \text{ km}$ (photosphere-chromosphere), and $z = 906 \text{ km}$ (mid-chromosphere). The black lines at the left and right side show the heights of the four layers.

Fig. 2.—Computational box from the convection zone to the corona. The color table is the temperature. The magnetic flux tube coming from the bottom boundary is shown by green lines, and the initial (weak) background magnetic field lines by red lines. The $z$ axis runs from the corona ($z = 14 \text{ Mm}$, top boundary) to the convection zone ($z = -1.4 \text{ Mm}$, bottom boundary). We center our attention on four different heights, shown in the figure as partial planes with the temperature (gray-scale coded); at heights $z = 10 \text{ km}$ (photosphere), $z = 234 \text{ km}$ (reverse granulation), $z = 458 \text{ km}$ (photosphere-chromosphere), and $z = 906 \text{ km}$ (mid-chromosphere). The black lines at the left and right side show the heights of the four layers.

3.2. Injection of Magnetic Flux

We introduce a magnetic sheet or magnetic flux tubes into the lower boundary of the model described in §3.1. The OSC uses a numerical method that, in principle, does not change $\nabla \cdot B$ in time. The solenoidal condition must be enforced on the boundary to ensure that no magnetic monopoles are introduced. This is implemented by applying the boundary condition to the electric field; the staggered mesh will then enforce $\nabla \cdot B = 0$ to the numerical accuracy of the operators at the boundary.

The magnetic field variation at the boundary is defined by

$$\frac{\partial B}{\partial t} = -\nabla \times E, \quad (9)$$

where, for example, for the $x$ component of the electric field we have

$$E^x = E_x = \frac{\Delta(B_y)}{\tau} \Delta x, \quad (10)$$

where $E^x$ is the new $x$ component of the electric field at the boundary, $\tau$ is the time step size, $\Delta x$ is the vertical cell size, and $\Delta(B_y) = B_y^\text{new} - B_y^\text{old}$ is the difference between the value of the magnetic field we would like to impose at the boundary, $B_y^\text{new}$, and the current boundary field, $B_y^\text{old}$.

We have run models in which a constant horizontal field in the $y$ direction has been injected, and several models where a flux tube is introduced. The flux tube is horizontally rectilinear, with twisted magnetic fields lines. The expression for the magnetic field has a structure given by

$$B_{\text{long}} = B_0 \exp\left(-\frac{r^2}{R^2}\right) e_z, \quad (11)$$

$$B_{\text{trans}} = B_{\text{long}}q e_y, \quad (12)$$

where $r = \sqrt{(x - x_0)^2 + (z - z_0)^2}$ is the radial distance to the center of the tube that has radius $R$, and $B_{\text{long}}$ and $B_{\text{trans}}$ are the longitudinal and transversal magnetic fields in cylindrical coordinates, respectively. The total longitudinal flux of the tube is $\int B_{\text{long}} dA = 0.98 \pi R^2 B_0$. The radius is the same for all simulations ($450 \text{ km}$). The parameter $q$ is used by Linton et al. (1996) and Fan et al. (1998) to define the twist of the magnetic field. Following Cheung et al. (2006), we define a new twist parameter, $\lambda$, as

$$\lambda \equiv qR. \quad (13)$$

As the flux tube enters the computational box, the height of the center of the tube ($z_0$) changes in time. The speed of flux tube, $(dz_0/dt)$, is set to the average of the velocity of plasma inflow at the boundary in the region where the magnetic flux tube is located at each time step. We choose an average inflow instead of the local vertical velocity for two reasons: (1) it allows us to describe the shape of the tube analytically, and (2) it ensures that the tube is horizontal when crossing the boundary. While we find small flux variations along the tube axis, these variations are consistent with the gas pressure oscillations and velocities in the convection zone.

The field defined by equations (11) and (12) is easily seen to be a horizontal axisymmetric magnetic flux tube in which the longitudinal field has a Gaussian profile in the radial direction.

### Table 1

| Name     | Twist | $B_0$ (G) | Size (Mm$^3$) | Comment                | Time (s) |
|----------|-------|-----------|---------------|------------------------|----------|
| A1........ | 0.1   | 4484      | $8 \times 4 \times 16$ | Flux tube in $y$ direction | 2200     |
| A2........ | 0.2   | 3363      | $8 \times 4 \times 16$ | Flux tube in $y$ direction | 2100     |
| A3........ | 0.3   | 4484      | $8 \times 4 \times 16$ | Flux tube in $y$ direction | 2500     |
| A4........ | 0.6   | 4484      | $8 \times 4 \times 16$ | Flux tube in $y$ direction | 3200     |
| B1........ | 0.0   | 1121      | $16 \times 8 \times 16$ | Flux sheet in $y$ direction | 4500     |

4. RESULTS

We have carried out five simulations with different twist and magnetic field strength in order to study the effects of flux emergence in the photosphere and in the chromosphere. A summary of the runs completed is shown in Table 1. In describing the reaction of the atmosphere to the introduction of new magnetic flux, we will specifically concentrate on four layers placed at heights of $z = 10, 235, 450,$ and $900 \text{ km}$, represented in the Figure 2.

We find that all runs show a similar series of events after the emerging magnetic flux pierces the photosphere. These events, which occur at roughly the same time in all models, are summarized in Table 2, which shows the processes observed in the simulations ordered in time. These processes are described in the following sections according to where they happen.

In the following sections all the figures shown correspond to simulation A4 unless otherwise noted, both because it has run for
a long solar time \((T = 3200 \text{ s})\) and because it has the most pronounced processes as a result of flux tube emergence.

4.1. Photosphere

The photosphere is located at \(z \approx 0 \text{ Mm}\) and is, up to the time when the emerging flux penetrates, as described in § 3.1, with a cellular temperature structure similar to that shown in the upper left panel of Figure 3. As the flux tube approaches the photosphere from below, the cells immediately above the flux tube expand as seen in the upper right panel of Figure 3. Eventually, horizontal field pierces the photospheric surface in the granular cell centers, as seen in the second right panel of Figure 4. The horizontal field is rapidly moved to the intergranular lanes as a result of the granular flow (Fig. 4, third row). The granular cells where the field penetrates remain larger than in the undisturbed state as the flux tube passes through the photosphere. At some point, the expansion lowers the temperature of the expanding cells through adiabatic cooling. At later stages a small amount of the magnetic flux that pierces the photosphere is returned to the convection zone. The photospheric evolution of emerging flux as described above has already been extensively studied previously and reported in the literature (e.g., Cheung et al. 2007a and references therein).

In all the simulations we find that approximately 2100 s passes from the time the magnetic flux tube crosses the photosphere until the time the photosphere again appears to regain its “normal” state, i.e., until the photospheric again is similar to the initial state before the flux tube passes through (see Fig. 3). Let us study the figures in more detail.

In Figure 5 we show two 3D images of the A4 simulation from two different viewpoints, from above and below the photosphere as seen at time \(t = 1700 \text{ s}\). The figure shows how the temperature

| Process                                                                 | Time (s) |
|------------------------------------------------------------------------|----------|
| Expansion of granular cells in the photosphere                         | 900      |
| Expansion of the reverse granulation                                    | 920      |
| Cooling of the center of granular cells in the photosphere              | 1160     |
| Tube crosses the photosphere                                            | 1300     |
| Tube crosses the chromospheric height forming reverse granulation      | 1380     |
| Magnetic field moved to the intergranular lanes in the photosphere      | 1550     |
| Reverse granulation cooling with expansion                             | 1560     |
| Tube crosses the layer \(z = 450 \text{ km}\)                          | 1660     |
| The cells return to “normal” size in the photosphere                   | 2100     |
| Upper chromosphere vertical expansion and cooling                       | 2900     |

from below, the cells immediately above the flux tube expand as seen in the upper right panel of Figure 3. Eventually, horizontal field pierces the photospheric surface in the granular cell centers, as seen in the second right panel of Figure 4. The horizontal field is rapidly moved to the intergranular lanes as a result of the granular flow (Fig. 4, third row). The granular cells where the field penetrates remain larger than in the undisturbed state as the flux tube passes through the photosphere. At some point, the expansion lowers the temperature of the expanding cells through adiabatic cooling. At later stages a small amount of the magnetic flux that pierces the photosphere is returned to the convection zone. The photospheric evolution of emerging flux as described above has already been extensively studied previously and reported in the literature (e.g., Cheung et al. 2007a and references therein).

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The structure of the granular cells has been changed by the presence of the flux tube, and in addition how the structure of the flux tube itself has been modified. The tube has suffered an expansion and splitting, gaining an irregular structure due to the movements of the convective cells.

The magnetic field evolution in the photosphere is shown in Figure 4. The maximum magnetic field strength in the photosphere varies between 850 and 1060 G. From 1700 s until the simulation ends the maximum field strength increases, in some instants rising to 1700 G. The magnetic field is almost horizontal...
and centered in the cells when the flux tube starts to cross the photosphere. The field is confined by the fluid and displaced to cell edges, at which time its orientation becomes vertical. After most of the original tube has crossed the photosphere, some remaining magnetic flux that has remained below the photosphere appears. This remaining flux is small compared to the main tube’s emergence and appears far away on either side of the central tube axis. The emergence process for this remaining flux is similar to the main tube’s emergence, in that almost horizontal field rises in the cell center, to be subsequently transported to the intergranular lanes, where it becomes vertical, as also reported earlier by Cheung et al. (2007a; see the last row of Fig. 4).

The intensity in the opacity bin with smallest opacity, designed to mimic the continuum, is shown in Figure 3, along with contours of the magnetic field strength at height $z = 10 \text{ km}$ at six different instants in time; at 600, 1100, 1210, 1660, 2200, and 3220 s. The evolution of the intensity is very similar to that of the temperature; granular cells, located where the flux tube emerges, become larger and darker as they expand. These large cells cool as their size increases, due to both radiative losses and adiabatic expansion. After the tube has crossed the photosphere, the granulation pattern returns to normal, roughly at times greater than 2100 s.

It is worth remarking that we see several examples of collapsed cells (see Skartlien et al. 2000) visible near the boundary of the flux tube as it crosses the photosphere (see the top right at time 1100 s and bottom left at time 1210 s panels at $x \approx 3 \text{ Mm}$ and $x \approx 5 \text{ Mm}$, the blue line in Fig. 3). Squeezing of the granule occurs as the adjacent plasma expands during the rise of the flux tube and by the tendency for downflows surrounding a small granule to merge in the boundary layers. There are also bright points visible after the tube crosses the photosphere, as seen in the lower left panel of Figure 3 at position $(x, y) \approx (6.5, 2.7) \text{ Mm}$ at time 2200 s, or the bottom right panel at the position $(7, 3.8) \text{ Mm}$. At that position the tube is low at photospheric height, but the magnetic field is strong and the decreased gas density (and thus photospheric opacity) allows us to see deeper into the atmosphere, where the temperature is higher (see also Shelyag et al. 2004; Carlsson et al. 2004).

In Figure 6 we show the evolution of the mean of magnetic flux of simulations A1, A2, A3, and A4 by area. We define the mean of the magnetic flux per unit of area between 2 heights by

$$\langle \phi \rangle = \frac{\int_0^L \left( \int_0^{L_z} \int_0^u B \, dS \right) \, dn}{(L[S])},$$

(14)

where $\phi$ is the mean of magnetic flux integrated in the area in the vertical plane between $z = l$ and $z = u$ in the vertical component of $S$, i.e., $L_z = u - l$ and along the whole horizontal component of $S$, from 0 to $L_h$. The mean is carried out along the perpendicular component of $S$, i.e., it is defined as the integral over the line perpendicular to the surface $S$ divided by the length in that direction of the box domain. We are interested in measuring the flux in the $y$ direction; then expression (14) simplifies to

$$\langle \phi \rangle = \frac{\int_0^{L_z} \left( \int_0^u \int_0 B \, dz \, dx \right) \, dy}{(L[S])} / (L[L_x,L_y,L_z]),$$

(15)

where $L_x$ is the length of the box in the $x$ direction, $L_y$ is the length in the $y$ direction, and the integration in $z$ goes from $z = l$ to $z = u$. We consider two different integrated regions in Figure 6, one below the photosphere ($z < 0.01 \text{ Mm}$), i.e., from $l = -1.5 \text{ Mm}$ to $u = 0.01 \text{ Mm}$, plotted in red, and the second from $l = 0.01 \text{ Mm}$ to $u = 245 \text{ km}$, plotted in black. The figure shows that the greater the twist, the greater the amount of magnetic flux that crosses the photosphere. On the other hand, the time needed for the tube to cross the photosphere is similar in all simulations. (It should be kept in mind that there is also magnetic flux being lost through the bottom boundary of the simulation box, in addition to that rising beyond the photosphere into the upper atmosphere.) Simulation A2 (with weaker injected field $B_0$) has a smaller total flux, and the slope $(d\langle \phi \rangle/dt)$ is much smaller than in the other simulations. When the tube has finished crossing the photosphere ($t > 2000 \text{ s}$), the flux retained above the photosphere is in quasi-equilibrium and oscillates with a period of roughly 5 minutes. This oscillation is due in part to the magnetic field that is returned to the photosphere and in part because the direction of the tube changes in time. The oscillation in flux strength coincides with oscillations in maximum downward velocity variation with time, but there is a small delay of around 30 s between the flux and the velocity variation. We find the same phenomenon in the upper layers (see §§ 4.2 and 4.3).

The average amount of magnetic flux in the convection zone is greater than in the photosphere, which means not all of the flux tube crosses into the photosphere. The only portion of the magnetic tube that reaches the photosphere is the part that has a steeply decreasing field strength with height. Cheung et al. (2007a) have pointed out that the higher the level of twist in the initial flux tube, the larger the fraction of magnetic flux that can pass into the regions above the photosphere. This can be explained as a consequence of the magnetic tension of the transverse fields tending to keep the tube coherent, as shown by Moreno-Insertis & Emonet (1996). Following the linear stability analysis of Acheson (1979), we find that the photosphere has a superadiabatic excess profile, defined by $\delta_T = \nabla - \nabla_s$, that is shaped like a Gaussian with height. In this case the magnetic buoyancy instability sees a barrier in the photosphere, and the emerging tube velocity decreases as it comes closer to the photosphere. Only the portion of the flux tube where the gradient of the magnetic field strength is larger than the superadiabatic excess in the photosphere can reach the layers above the photosphere. The relation between the buoyancy instability and the superadiabatic excess has been studied by several authors (Acheson 1979; Magara & Longcope 2001; Archontis et al. 2004).

The field left behind after the tube has passed is more vertical than it was before the tube passes through a given particular height. This behavior is more evident near the end of the simulation,
where the magnetic field is more vertical in the chromosphere. The ratio between $B_\parallel$ and $|B|$ oscillates in time in much the same manner as does the maximum downward velocity in the photosphere between $z = 0$ and 458 km.

4.2. Reverse Granulation

Intensities originating a few hundred kilometers above the granulation show a pattern that is the reverse of that of the granulation, with low intensity above granules and higher intensity above intergranular lanes (Evans & Catalano 1972; Suemoto et al. 1987, 1990; Rutten & Krijger 2003; Cheung et al. 2007b). The reason for the inverse contrast is the cooling from a divergent velocity field above granules and heating from a convergent velocity field above the intergranular lanes. The radiative heating of fluid rising above granules is also important. The final intensity pattern from this layer may also be influenced by internal gravity waves, but does not appear to be related to the magnetic field (Rutten et al. 2004; Leenaarts & Wedemeyer-Böhm 2005). However, as we discuss below, when the magnetic flux crosses this region, the contrast and the structure of the reverse granulation is modified.

Figure 7 shows 3D images in two different views at $t = 1900$ s, as seen from above and from below the reverse-granulation layer at $z = 234$ km. The figure shows how the reverse granulation has been changed by the presence of the rising magnetic flux tube and is colder inside than outside the reverse granulation cells in regions where the tube is located. At this height we can also see how the structure of the tube has been disrupted as it has passed through the atmosphere. In fact, the structure of the tube is even more split and fragmented than seen at lower heights (Fig. 5).

At this height we see expansion of the cells beginning at time 920 s. The flux tube starts to go through the reverse-granulation layer some 80 s after it crosses the photosphere, i.e., at time 1380 s. As in the photosphere, the reversed granules increase in size as the flux tube approaches. The magnetic field lines of the tube are seen in Figure 7 to go from one side of the expanded cells to the other.

The maximum magnetic field strength at $z = 234$ km, before the flux tube reaches the reverse granulation, is of order 500 G. When the tube starts to cross the height 234 km, the maximum rises to 600 G. At later times, but while parts of the tube are still to be found at this height, the remaining magnetic field is confined to downflow regions, and the maximum field strength rises to 650 G. After the tube has passed, some remaining confined flux rises to a maximum of up to 800 G. During the last 500 s of the simulation, the maximum field strength oscillates around 700 G. Again, as in the photosphere, the magnetic field is initially horizontal and appears in the center of the granular cells. The magnetic field is then confined and moves with the fluid to the edges of the cells, where it becomes vertical. At the cell edges a great number of bipoles form by $t = 2100$ s. However, at later times the bipoles are canceled by magnetic diffusion.

The top row of Figure 8 shows the continuum intensity at 170 nm as calculated from the simulation at times 1620 s (left) and 3220 s (right). The continuum opacity at this wavelength is dominated by Fe bound-free opacity, and the monochromatic optical depth unity is around 250 km height in the simulation. Note that real observations around this wavelength (such as the TRACE 170 nm bandpass) are dominated by line opacity, with the intensity thus coming from higher layers. The intensity images shown here are, however, typical of a diagnostic formed in the reverse granulation layer (like the inner wings of the resonance lines from ionized calcium). The figure also shows the vertical velocity in the second row with the same gray-scale values, i.e., from 2.6 km s$^{-1}$ (white) to −4.1 km s$^{-1}$ (black), the divergence of the velocity in the third row, and the vertical vorticity in the fourth row, all these variables at height 234 km. The synthetic 170 nm intensities show reverse granulation, and it is clear that at $t = 1620$ s the granular cells have expanded in regions cospatial with the flux tube. The same pattern is also found in plots of the temperature and the vertical velocity. Larger cells grow dimmer and colder due to the expansion, as can be verified by considering the velocity divergence. While cool, dim regions are due to expansion, the hotter bright network points are seen to be related to contraction of the fluid at this height. At the end of simulation we find several bright points. This is seen clearest at time $t = 3220$ s in the regions where we find concentrated vertical magnetic field (see second column of Fig. 8 at the position [6.7, 3.7] Mm). These bright points in intensity are related to large vertical velocities, but also to high temperatures compared to the surroundings, a large vertical vorticity, and compression of material (black color in the divergence of the velocity plots). The heating process for these bright points is clearly related to the high velocity convergence and high vorticity. We will find similar bright points at greater heights in the atmosphere, although with larger horizontal extent.

There are no large changes in the upward maximum velocity with time before, during, or after the tube crosses the layer 234 km height; it is found to be around 2.5 km s$^{-1}$. The maximum downward velocity does not change until after $t = 1400$ s, when it has a small increase for 200 s. The maximum downward velocity then returns to normal before increasing from 3 to 5 km s$^{-1}$ starting at $t = 2200$ s. These large downflow velocities are found to correspond to the small regions with a strongly confined
magnetic field in the intergranular lanes. Examples of such regions are found in the second row, right column, of Figure 8 at position \([x, y] = [4.1, 0.2] \text{ Mm}\) and also at \([7.1, 3.6] \text{ Mm}\). Towards the end of the simulation, at time 3100 s, the maximum downward velocity has returned to 3 km s\(^{-1}\). The maximum horizontal velocity oscillates around 5.5 km s\(^{-1}\). However, it has a peak at 1480 s with a maximum velocity of 8 km s\(^{-1}\) as the tube is crossing the layer 234 km height.

The expansion of the cells is observed at time \(t = 900\) s in the photosphere \((z = 10 \text{ km})\) and roughly 25 s later in the reverse-granulation layer 234 km height. The separation between these two layers is 224 km. The propagation speed of the tube itself is much slower, as Table 2 shows, it spends 250 s in moving from the layer at 10 km to the layer at 234 km height. Another possibility for explaining the expansion of the cells at the layer at 234 km height is by the propagation of Alfvén waves, but again, the time such waves need to propagate from the layer at 10 km to the layer at 234 km height is too long, because the mean Alfvén speed is very small in that region \((<100 \text{ m s}^{-1})\). On the other hand, the average sound speed between 10 and 234 km height is 8.5 km s\(^{-1}\), which gives a travel time close to 25 s, which fits with the time to move the horizontal expansion of the cells outward. In other words, we see the expansion of the granular cells some 400 s before the magnetic tube actually emerges through the photosphere, when the tube is situated 182 km below the photosphere. The speed of sound below the photosphere is on average 10 km s\(^{-1}\), which means that the expansion wave is produced roughly 420 s before the tube reaches the photosphere, i.e.,

![Figure 8](image-url)
when the tube is roughly at $-246$ km. The average tube velocity from $-246$ to 10 km is $0.5$ km s$^{-1}$. However, the tube decelerates when it approaches the photosphere, as explained in § 4.1. The cells’ average horizontal expansion velocity is roughly 2.5 km s$^{-1}$ before the tube reaches the photosphere.

Figure 9 shows the mean magnetic flux in the same manner as in Figure 6, but here the regions considered are from the layers $z = 10$ to $z = 234$ km (red) and from the layers $z = 234$ to $z = 458$ km (black). Each of the four displayed simulations conserve magnetic flux in the sense that when the magnetic flux tube crosses these regions, no flux is lost or retained in the region, as opposed to what happens in the convection zone. The biggest difference between the two regions is seen to be in the slope of the flux $d\langle \phi \rangle / dt$ as the tube moves through the region. The slope of the flux is much smaller than that found in Figure 6 when the tube crosses those layers, i.e., more time is spent in crossing each region. The oscillation of the mean magnetic flux occurs more or less at the same time, when the tube crosses the corresponding region, but the amplitude of the variation is greater in higher regions.

4.3. End of the Photosphere–Beginning of the Chromosphere

The top of the convection zone, photosphere, and lower chromosphere are the regions where acoustic waves are excited by convective motions. While the waves propagate upward, they steepen into shocks, dissipate, and deposit their mechanical energy as heat in the chromosphere. In studying the quiet non-magnetic chromosphere, Wedemeyer et al. (2004) corroborates in 3D models the finding by Carlsson & Stein (1994) that the chromospheric temperature rise derived from semiempirical modeling of the time average intensity does not necessarily imply an increase in the average gas temperature, but rather can be explained by the presence of substantial spatial and temporal temperature inhomogeneities, such as those caused by nonlinear waves.

We are interested in finding out how the rise of a flux tube affects chromospheric dynamics and energetics, i.e., if there are other energy sinks or sources that become active with the appearance of new magnetic flux, or if the new flux modifies the propagation of acoustic waves into the middle and high chromosphere.

In our simulations the magnetic flux tube enters the height $z = 458$ km some 300 s after it has crossed the photosphere. At this height the atmosphere suffers various perturbations in response to the appearance of the flux tube.

Figure 10 shows two 3D images of the A4 simulation at $t = 1980$ s from above and below a temperature slice made at height $z = 458$ km above the photosphere. The temperature structure at this height has been changed by the presence of the tube, and is much cooler in regions where the tube is located. However, on the borders of the rising tube we find regions with higher temperatures. As in the previous 3D images, featuring lower heights, we see how the structure of the magnetic flux tube has been perturbed as a result of rising through the atmosphere; comparison with these figures shows the structure of the tube at this late time is even more splintered and fragmented than at earlier times (see Figs. 5 and 7).

The vertical magnetic field is shown in the left column of Figure 11 and the horizontal magnetic field in the right column, for two different instants at height $z = 458$ km. The maximum magnetic field strength before the magnetic flux tube reaches this height is 170 G. During the flux emergence process, the maximum field strength increases to 270 G, and at later times, as the magnetic flux is compressed and confined to smaller regions, the field strength at some points increases to 350 G. At this height there is a cellular structure at any given time, but the cells do not directly correspond to the photospheric granular cells, but rather to patterns in the velocity field that change from instant to instant. The vertical magnetic field is mostly confined to downflow regions and dominates the field. However, as the flux tube crosses the layer at 458 km height, the horizontal magnetic field is strongest and fills the upflow cells. There are some regions or “points” with strong vertical magnetic field, for instance at position [7, 4] Mm in the bottom left panel of Figure 11. These points have increasing
maximum magnetic field strength with time after the flux tube has passed through the layer, and they move around with the fluid.

Figure 12 shows the calculated continuum intensity at 160 and 130 nm for two snapshots of the simulation. These images show what could be observed in the TRACE 160 nm filter and in a SUMER raster at 130 nm. At both wavelengths the continuum opacity is dominated by bound-free opacity from silicon: at 160 nm from the first excited level and at 130 nm from the ground state. The monochromatic optical depth unity is on average around 480 and 790 km height in the simulation at 160 and 130 nm, respectively (in the VALC model atmosphere the corresponding heights are 456 and 735 km, respectively). The intensity at $t = 1620$ s shows expansion of the plasma with subsequent dimming, somewhat more clearly at 160 nm. At 3220 s both the continua show a bright point at position [7, 3.8] Mm.

The vertical velocity is shown in Figure 13 in the first row of panels using the same gray-scale intensity, from $1.5 \text{ km s}^{-1}$ (white) to $-5.88 \text{ km s}^{-1}$ (black), with the divergence of the velocity in the second row and the vertical vorticity in the last row of panels, all at time 1620 s in the first column and at time 3220 s in the second column. We find similar structure to those found in the synthetic
observations (Fig. 12) before the tube crosses the layer at 458 km height. The structure of the cells is strongly modified as the tube goes through that layer. We find that the cell expansion is related to the divergence of the velocity, also at this height, but that the correspondence between temperature/continuum emission and velocity divergence is not as clear as in the lower layers. There are large vertical velocities (first row of Fig. 13), both up or down (see the left panels of Fig. 13 at position [2.1, 0.8] Mm and right panels at position [7, 3.7] Mm), which correspond to the bright points in the synthetic observations and also fit with the large concentration of magnetic flux and vertical vorticity.

After the magnetic flux tube has crossed the layer at 458 km height, the structure of the plasma no longer appears granular. The magnetic field, shown in Figure 11, is almost horizontal, and only in the boundary layer of the tube can one see any vertical component. With greater initial twist the tube remains more horizontal in the chromosphere compared to the cases with less initial twist, i.e., the ratio of the horizontal magnetic field component to the vertical magnetic field component, in regions where the tube is located, increases with increasing twist.

Figure 13 also shows the expansion of the fluid as the tube crosses the layer at 458 km height. The centers of these cells are colder than the edges as the tube expands. However, as the tube crosses this layer, the small cells seen in the initial model disappear and, cold larger zones form near the center of the tube. This is presumably due to expansion (second row of Fig. 13), but the velocity divergence does not fit as well with the temperature or intensity maps as found in the lower layers. This suggests that at this height (458 km) other processes could also be active in cooling the chromosphere. We will go into more detail on these alternate processes in the next section, as they become steadily more important with increasing height into the chromosphere.

At the boundary layer of the magnetic flux tube, the temperature rises. This heating could be due to a wave, compression of the plasma, or reconnection where the magnetic field is almost vertical. Once the tube has disappeared from the layer at 458 km, at time $t = 2300$ s, the temperature displays an irregular structure with some high temperature points. These points are coincident with a high vertical vorticity and strong vertical magnetic field (e.g., at position [7, 3.8] Mm at time 3220 s; see Figs. 11–13). Note that the temperature structure has not returned to its pre-emergence state. This could be due to the fact that the magnetic structure of the atmosphere has changed: before the tube appeared, the energy density of the magnetic field was low and $\beta > 1$, but around $t = 2200$ s we find several regions where $\beta \approx 0.5$ and the field dominates the chromospheric structure.

Bright points are seen to occur in the synthetic observations (Fig. 12). In the layer at height 458 km, the bright points have greater contrast than found in the regions below and also much greater temperature than in the surrounding plasma. The bright
point in the top right panel of Figure 12 at the position \([7, 4]\) Mm has a temperature at this height of 6500 K, compared with the surrounding temperature of 5100 K. At the same position at height 234 km (see Fig. 8), the temperature is 5700 K compared with 5200 K in the surroundings. As explained earlier for the lower layers, bright points are related to strong magnetic field, vertical velocity, and vertical vorticity, and to a larger compression than in the surroundings. The heating seems to come primarily from the convergence of the velocity field, as we find the most important heating term is the advection term; it is an order of magnitude greater than the joule and viscous heating terms.

Figure 14 shows the mean magnetic flux for the regions from \(z = 234\) to \(z = 458\) km (red), and from \(z = 458\) to \(z = 905\) km (black). The biggest difference between behavior at different heights (Figs. 6, 9, and 14) is the slope of the flux with time \((d\phi/dt)\). The mean magnetic flux entering the chromosphere is much smaller than that at lower heights shown in Figures 6 and 9, because the tube spends more time in crossing the upper regions, presumably due to the horizontal expansion of the magnetic flux tube. After the initial large rise, when the tube crosses the corresponding section, the curve shows an oscillation (see Fig. 14) that is quite similar to that seen in the layers below (see Figs. 6 and 9). However, by comparing each curve it is possible to see that there is a phase delay. This phase difference between the different layers is what we would expect from a wave that propagates in the sound...
Fig. 16.—Continuum intensity of the C i to the power of 0.4 (equivalent to a $\gamma$ of 0.4 for an image) to better bring out the structure at 109.9 nm at times 1620 s (top left) and 3220 s (top right). The synthetic Ca ii H line intensity is plotted at times (from left to right and top to bottom): 600 s, before the flux tube goes through the chromosphere; 1620 s, when the tube starts to cross; 2110 s, as the tube is crossing; and 3220 s, when the tube has crossed the chromosphere.

Fig. 17.—Vertical velocity at $z = 906$ km at times: 600 s, before the flux tube goes through the chromosphere (top left); 2110 s, when the flux tube is close to the chromosphere (top right); 2800 s, when the big cells are cooling through expansion (bottom left); and 3220 s, after the tube has passed through the chromosphere (bottom right).
speed between each layer. The variation of the mean magnetic flux increases with increasing height, twist, and/or magnetic field strength. The oscillations seem related to the oscillations in the downward maximum velocity with time and also to oscillations in the ratio between the vertical and horizontal magnetic field.

Finally, we find that the slope of the flux with time, \( \frac{d\phi}{dt} \), at the time the tube crosses into the chromosphere, is larger, with greater values of the twist parameter and larger magnetic field strength. This effect is clearer in the chromosphere than in the photosphere. Previous 2D flux emergence simulations by Shibata et al. (1989) and Magara & Longcope (2001) have also identified magnetic buoyancy instabilities as important in the rise of magnetic field to the chromosphere and coronal layers.

### 4.4. Chromosphere, Transition Region, and Corona

Let us finally discuss the effects of the magnetic flux tube as it reaches the upper chromosphere, transition region, and lower corona. The variation of the magnetic field in the chromosphere, at \( z = 906 \) km, is shown in Figure 15, with the vertical field in the left column and the horizontal field in the right column, both at three instants, times 600 s, 2800 s, and 3220 s. The first signs of the magnetic flux tube reaching this layer are evident at time

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**Fig. 18.**—Temperature, shown with gray scale, in a vertical plane at 3220 s for the simulations A4 (left) and B1 at time 3370 s (right). Note the different scales.

**Fig. 19.**—Synthetic Ca ii H line Hinode intensity to the power of 0.25 (equivalent to a \( \gamma \) of 0.25 in an image) is plotted to better bring out the structure of the bubble from simulation A4 at time 600 s, before the flux tube goes through the chromosphere (top left), and at 3220 s, when it has crossed the chromosphere (top right), and from simulation B1 at time 3370 s (bottom).
$t = 2100$ s. However, the tube does not appear uniformly in the region from $x = 2$ to 6 Mm as it does in the levels below. Rather, patches of magnetic flux rise into different places randomly along the tube region at different times. The maximum absolute magnetic field strength before the tube reaches the layer is 43 G. This value increases to 80 G after the tube comes into the chromosphere. During the flux emergence into this level and after the tube has passed, the average of the maximum field strength is of the order of 65 G. At this height the magnetic field does not have any singular isolated points with strong amplitude. The field becomes generally more horizontal once the tube crosses this layer, and has a smoother structure than in the layers below.

In Figure 16 we show the intensity of the C i continuum at 109.9 nm (as could be observed with SUMER). We have calculated intensities at $t = 1620$ s before the emerging magnetic flux has entered the chromosphere and at $t = 3220$ s, some 15 minutes after the emerging flux first appears. The mean monochromatic optical depth unity is around 1100 km height in the simulation of the C i continuum at 109.9 nm (in the VALC atmosphere model it is at $z \approx 975$ km). We also show synthetic Hinode observations of the Ca ii H line at times 600, 1620, 2110, and 3220 s. Note that while the carbon continuum is formed mainly in the chromosphere, the Ca ii as observed with the 0.22 nm wide Hinode filter has contributions from the entire atmosphere, stretching from the upper photosphere to the chromosphere (Carlsson et al. 2007). The structure of the intensity formed at this height shows large changes before and after the magnetic flux tube reaches the chromosphere. The temperature range in the chromosphere at height 906 km before the tube reaches this level is 2.2–7.2 kK, while after the tube has reached this height the range is 2.0–7.0 kK. However, note especially the large dim (and cold) zones that become evident after the tube crosses into the chromosphere at time 3000 s. These dim, cold, regions are much larger than in the lower layers (see §4.2 and 4.3).

It is worth remarking that we do not find the concentrated bright points that appear in the lower lying layers. This is presumably because the magnetic field is mainly horizontal, and we do not observe the confinement of the magnetic field that occurs in the regions below due to plasma motions. On the other hand, the chromosphere and corona suffer large changes in size, structure, and temperature after the tube enters this zone. The cooling in the layers between 234 and 458 km height is due to radiative losses and superadiabatic expansion, but in these layers of the chromosphere the big cold regions do not fit as well with the local plasma expansion as in the lower layers.

The vertical velocity in the chromosphere at height 906 km is shown in Figure 17 at four different instants, 600, 2110, 2800 and 3220 s. The maximum downward velocity is around 10 km s$^{-1}$, and the maximum upward velocity is around 7 km s$^{-1}$ throughout the whole simulation. It is difficult to see any effects due the emergence of flux in the maximum horizontal velocity, as these have large changes with time. The average maximum horizontal velocity is 13 km s$^{-1}$ and varies between 7 and 20 km s$^{-1}$. On the other hand, the structure of the velocities change radically, as is evident by comparing the pre- and postemergent panels of Figure 17. Shock waves dominate the upper chromosphere before the tube crosses the chromosphere ($t = 600$ s). However, while the tube crosses the chromosphere the velocity pattern is much smoother in the regions where the field strength increases due to the rise of the flux tube into the upper chromosphere. At late stages (lower right panel) the velocity structure is clearly influenced by the magnetic field and appears filamentary.

That the chromosphere and overlying transition region and lower corona suffer large structural changes as a result of flux emergence is driven home by considering a vertical slice of the atmosphere, as shown in the left panel of Figure 18. The transition region has been pushed by the emerging flux from a height that varies with chromospheric dynamics from around 2 Mm to almost 6 Mm. This panel also shows that the flux tube has grown in horizontal extent and almost fills the computational box. We therefore also present the equivalent vertical temperature slice from simulation B1, which has a computational domain that is twice as large in the horizontal directions. It is also evident in this model that the rising flux sheet has pushed the transition region and lower corona aside and has lifted chromospheric plasma to heights of roughly 6 Mm. These cool, Lorentz force supported bubbles are long lived, and the simulation that has run the longest, B1 to 4500 s, maintains an extended chromosphere for almost 2000 s and is still doing so at the end of the simulation. The gas in the extended chromospheric bubble is quite cool, down toward a uniform 2000 K, and shows no sign of reheating at heights greater than 1 Mm. The big bubbles can also be seen in the synthetic Hinode Ca ii H limb images as shown in Figure 19. Toward the end of the B1 simulation, the emerging magnetic flux shows signs of having begun fragmentation as it reconnects with the previously present field. This looks to have interesting implications for transition region and coronal observables, but the process is not complete in any of our simulations, and we will refrain from discussing it until the next paper in this series.

Further insight into this phenomena can be found by considering vertical slices of the B1 simulation at earlier times, as the flux tube bubble rises through the chromosphere, such as the slices of logarithmic temperature, vertical velocity, and logarithmic pressure we show in Figure 20. We find that a small, low-$\beta$ region
forms just above the photosphere, centrally placed over the (partly stalled) rising flux tube. As plasma forms just above the photosphere, centrally placed over the (partly excluded from the bubble. Acoustic waves seem to have diffused throughout the otherwise all-pervasive chromospheric oscillations. The appearance of the extended chromospheric bubble and its surrounding regions described in detail is strongly related to the twist parameter and also to the original magnetic field strength injected at the bottom boundary. We find that with greater twist and/or greater field strength, more flux crosses the photosphere into the chromosphere. The photosphere is the region where most of the flux is retained. The flux that eventually enters the lower chromosphere rises through the various heights we have recorded at less than 10 km s$^{-1}$, and does not halt until reaching the transition region/lower corona.

As previously reported in the literature, we find that an emerging flux tube produces an expansion of the granulation cells in the photosphere. This expansion begins some 400 s before the flux tube itself reaches the photosphere. The simulations show that the chromospheric plasma also expands as the emerging flux tube rises. As in the photosphere, we find a delay between cell expansion and the arrival of magnetic flux in the lower layers of the chromosphere. As a result of the expansion, the tube plasma is colder than its surroundings, and emission from the central parts of the chromosphere is dimmed successively at all heights of the atmosphere. Such successive dimming has been observed by the SOT and EIS instruments aboard the Hinode spacecraft (Hansteen et al. 2007b) for lines up to and including Fe xii 19.5 nm, which is formed at a temperature of $\sim$1.2 MK, but further observations are certainly required to search for confirmation or discrepancies with the models described here.

In addition to dimming of the central portion of the flux tube, the expansion produces other important effects; for instance, in the photosphere, the boundary layer of the rising flux tube is a region that is conducive in producing granular collapse.

We also find that chromospheric structure is substantially altered by the rise and expansion of the flux tube. The chromosphere is pushed upward by the magnetic field, and cool chromospheric material is found at heights up to 6 Mm above the photosphere, in contrast to the 2–3 Mm extent of the preemergence chromosphere. In expanding, the transition region and corona above the flux tube are pushed aside by the chromospheric plasma. However, the preexisting coronal magnetic field and transition region and coronal emission are remarkably little changed at the times reached by our simulations. Only in simulation B1 do we see some initial signs of reconnection between the preexisting coronal field and the rising bubble of emerging flux. This reconfiguration, with attendant changes in transition region and coronal emission, occurs $\sim$30–40 minutes after the flux tube initially pierces the photosphere. Since the flux tube also expands dramatically in the horizontal direction, reaching widths almost equal to the simulation dimensions.
box for simulations A1–A4, discussion of transition region and coronal effects will be postponed to a later paper, when simulations contained in a larger box are completed. It is also possible that the tube expansion could be affected by the finite horizontal size of the computational domain. On the other hand, the (limited number of) models we have run with a larger box, 16 × 8 × 16 Mm³, do not show a fundamentally different behavior, so we believe the effects of limited simulation size are minor.

While the cooling process in the photosphere and at the lower chromospheric heights (234 and 458 km) is dominated by adiabatic cooling, we find that at higher layers where β < 1 other processes also come into play. The acoustic waves that are generated as a result of convective overshoot and/or granular dynamics and that permeate the nonmagnetic chromosphere are expelled from the rising cooling flux tube. Thus, the temperature variations that are due to compressive shock waves propagating up through the chromosphere are absent in the plasma rising with the flux tube, which maintains a much lower temperature than its surroundings for the duration of our simulations. Toward the end of the simulations, the magnetic bubble does begin to oscillate with the same vertical velocity as the rest of the atmosphere, but the modes penetrating the bubble are still noncompressive at the time of the completion of the simulation, and the temperature remains fairly constant.

Another interesting effect is the increase of magnetic field strength in small regions or “points” in the atmosphere near the edges of the rising flux tube. We find both “classical” photospheric bright points and bright features in the chromosphere. In the case of the higher lying regions, the bright points are regions of concentrated high magnetic field strength, high up- or downflowing velocity, high velocity convergence and high vorticity. They are bright in the various spectral bands describing these heights, as a result of high gas temperature due to the compression of the fluid in these regions.

There are several interesting and important effects that we have not reported extensively in this paper, among which are the effects of joule heating and transition region and coronal diagnostics of flux emergence. This is mainly due to the finding that the flux emergence process is a quite slow one: it takes on the order of 1 hour solar time from the time the magnetic field pierces the photosphere until it reaches and begins to reconnect with the pre-existing coronal field. We are currently undertaking simulations that have run long enough and that have a large enough computational box to study these phenomena.

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