DYNAMICS OF MAGNETIZED VORTEX TUBES IN THE SOLAR CHROMOSPHERE

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ABSTRACT

We use three-dimensional radiative MHD simulations to investigate the formation and dynamics of small-scale (less than 0.5 Mm in diameter) vortex tubes spontaneously generated by turbulent convection in quiet-Sun regions with an initially weak (10 G) mean magnetic field. The results show that the vortex tubes penetrate into the chromosphere and substantially affect the structure and dynamics of the solar atmosphere. The vortex tubes are mostly concentrated in intergranular lanes and are characterized by strong (near sonic) downflows and swirling motions that capture and twist magnetic field lines, forming magnetic flux tubes that expand with height and attain magnetic field strengths ranging from 200 G in the chromosphere to more than 1 kG in the photosphere. We investigate in detail the physical properties of these vortex tubes, including thermodynamic properties, flow dynamics, and kinetic and current helicities, and conclude that magnetized vortex tubes provide an important path for energy and momentum transfer from the convection zone into the chromosphere.

Key words: Sun: chromosphere – Sun: magnetic topology – Sun: photosphere – Sun: surface magnetism

1. INTRODUCTION

Interest in vortex tube dynamics of the quiet Sun was recently initiated by the detection of ubiquitous small-scale swirling motions in the photosphere (Wang et al. 1995; Pötzi & Brandt 2005; Bonet et al. 2008, 2010; Balmaceda et al. 2010; Steiner et al. 2010) and the chromosphere (Wedemeyer-Böhm & Rouppe van der Voort 2009) with high-resolution solar telescopes. Vortex tubes on the Sun were studied by theoretical models (e.g., Stenflo 1975) and numerical simulations (e.g., Brandenburg et al. 1996; Stein & Nordlund 2000a; Kitiashvili et al. 2010, 2011; Antolin & Verwichte 2011; Fedun et al. 2011; Vasheghani Farahani et al. 2011). Both observations and numerical simulations show concentrations of vortex tubes in the intergranular lanes. According to recent radiative hydrodynamic simulations, vertical motions can also form inside granules (Kitiashvili et al. 2012). These simulations have also shown that vortex tube formation in the near-surface layers can be caused by two basic mechanisms associated with: (1) small-scale convective instability developing inside granules, and (2) the Kelvin–Helmholtz instability of shearing flows. Converging downflows in the intergranular lanes make the vortex tubes more stable, with characteristic lifetimes up to 40 minutes, whereas inside granules the lifetime is less than 10 minutes. These processes can explain why the observed vortex tubes are predominantly concentrated in the intergranular lanes.

In this Letter, we present new numerical simulations that demonstrate important links between the turbulent subsurface layers and the solar atmosphere through the dynamics of penetrating vortex tubes.

2. COMPUTATIONAL SETUP

Numerical simulations of the quiet Sun are performed by using a three-dimensional (3D) radiative MHD code (“SolarBox”) developed at the NASA Ames Research Center and the Stanford Center for Turbulence Research by Alan Wray and his colleagues (Jacoutot et al. 2008) for modeling the outer part of the solar convection zone and lower atmosphere in a Cartesian geometry. The code was developed for realistic-type numerical simulations of the Sun. Radiative energy transfer is calculated with a 3D multi-spectral-bin method between fluid elements, assuming local thermodynamic equilibrium (LTE). At this stage, our simulation code does not include non-LTE (NLTE) effects because full 3D NLTE MHD modeling is currently computationally prohibiting. The one-dimensional and two-dimensional simulations (Carlsson & Stein 2002; Carlsson & Leenaarts 2012) showed that the NLTE effects result in longer relaxation time for ionization/recombination processes, affecting the structure of chromospheric shocks, and also causing additional heating of cool chromospheric plasma “pockets,” but the principal plasma dynamics does not change.

The physical description of the dynamical properties of solar convection was improved through the implementation of subgrid-scale turbulence models, which effectively increase the Reynolds number and allow better resolution of essential turbulent scales.

In the current study, the simulation results were obtained for a computational domain of 6.4 × 6.4 × 6.2 Mm3, including a 1 Mm high layer of the atmosphere, with a grid spacing of \(dx = dy = 12.5\) km and \(dz = 10\) km. The lateral boundary conditions are periodic. The top boundary is open to mass, momentum, and energy transfers and also to radiative flux. The bottom boundary is open for radiation and flows, and simulates energy input from the interior of the Sun. We focus mostly on a case with an initially uniform vertical magnetic field, \(B_{z0} = 10\) G, representing quiet-Sun conditions (far from sunspots and active regions).

3. FORMATION OF VORTEX TUBES BY TURBULENT CONVECTION

Vortex tubes are formed by turbulent convection in near-surface layers of the convective zone (e.g., Stein & Nordlund 2000a; Kitiashvili et al. 2012). The vortex tubes represent compact low-density structures up to 0.5 Mm in diameter and with high-speed swirling motion reaching up to 12 km s\(^{-1}\). The vortex cores are characterized by strong downflows (up to
Figure 1. Snapshots of vertical velocity $V_z$ and enstrophy $\omega^2 = (\nabla \times \mathbf{u})^2$ on the solar surface for two simulation cases: without a magnetic field (panels (a) and (c)) and with an initial uniform weak vertical magnetic field, $B_z = 10$ G (panels (b) and (d)). Examples of small-scale vortex tubes are indicated by white and black squares. Contours in panel (b) indicate magnetic field strength from 200 G (outer contour) to 1.2 kG. The contours are plotted every 200 G. Panels (e) and (f) show the enstrophy distribution at different heights for the non-magnetic and magnetic cases.

8 km s$^{-1}$) and lower temperature. Large vortex tubes can extend deeper than 300 km below the surface.

Our previous simulations (Kitiashvili et al. 2012) revealed two basic mechanisms of vortex tube formation: one is due to a granular instability (vortex sheet overturning), and another is due to the Kelvin–Helmholtz instability in shearing flows. Vortex tubes can form in intergranular lanes and inside granules, but are mostly concentrated in the intergranular lanes (Figures 1(a) and (c)). For example, the vortex tube marked by the square in Figures 1(a) and (c) is formed due to convective granule instability which started inside a granule and led to the formation of a vortex sheet. The vortex tube is a result of overturning of the initially formed vortex sheet. During this process the vortex tube moved into the intergranular lane and became vertical due to convective downdrafts (for illustrations and more details, see Kitiashvili et al. 2012).

These physical mechanisms of vortex tube formation in subphotospheric and photospheric layers of the Sun are hydrodynamic, but in the real Sun, vortices are expected to strongly interact with ubiquitous magnetic fields. However, neither simulations nor observations have shown a clear correlation between vortex motions and magnetic field concentrations, that is, not every vortex is accompanied by a strong magnetic field concentration. This fact has also been shown in simulations using a shallow domain (1.4 Mm in total height; Shelyag et al. 2011; Moll et al. 2012).

In weak magnetic field regions, magnetic patches follow convective motions. Concentration and magnification of the magnetic field by swirling motions can stabilize the vortex tube structure and decrease the influence of surrounding turbulent flows. In our simulation case, we introduce a 10 G, initially uniform, vertical magnetic field. This field gets quickly concentrated, mostly in intergranular lanes, and we find that the strongest magnetic field ($\sim$1 kG) concentrations are often associated with vortices (Figures 1(b) and (d)). The influence of magnetic field on the enstrophy distribution on the surface
200 and 500 km above the surface is illustrated by histograms (Figures 1(e) and (f)) obtained for 29 minute data sets. In the surface layers the enstrophy distributions are similar with and without a magnetic field, but in the magnetic case the contribution of high enstrophy values, $0.3 \text{ s}^{-2}$ and greater, is larger. In the higher atmospheric layers, the enstrophy distribution declines steeper in the magnetic case, because the influence of the magnetic field increases with height, and this suppresses turbulent motions.

4. DYNAMICS AND PROPERTIES OF VORTEX TUBES IN THE CHROMOSPHERE

A new interesting result of our simulations is the extension of turbulent vortex tubes from the convection zone into the convectively stable atmospheric layers. Figure 2 illustrates a snapshot of enstrophy distribution showing vortex tube structures (yellow isosurfaces) above the photosphere (the horizontal wavy light surface shows the 6400 K near-surface layer). These vortex tubes are mostly concentrated in the intergranular lanes and often form arc-shaped structures above the surface. Other vortices penetrate almost vertically into the higher chromospheric layers (an example of such an extended vortex tube is indicated by the arrow; we will consider its structure in detail below). Local upflows (orange color on vertical slices, Figure 2) cause stretching of the vortex arcs, and nearby vortices can destroy them. The overall chromospheric dynamics driven by turbulent convection is thus very complicated. The effect of vortex penetration into the chromosphere is observed in simulations with and without a magnetic field. However, the magnetic field tends to be captured and concentrated in the vortex tubes, causing new dynamical effects. The effects are plasma heating inside the vortex core and flow ejection. While the effect of vortex penetration exists in the non-magnetic case, it is much stronger in the magnetic case. The local heating inside of the vortex core is also stronger in the presence of a magnetic field, whereas without a magnetic field the local heating is very weak and often not detectable.

The structure of the vortex tube indicated by the arrow in Figure 2 is illustrated in Figure 3 at different heights: 200 km, 500 km, and 650 km above the surface. The temperature distribution (Figure 3, row a) shows local heating of the vortex core region, whereas in the subphotospheric layers the core vortex temperature is lower than in the surrounding plasma. For this moment of time, the swirling motions in the vortex region are characterized mostly by highly turbulent downflows (Figure 3(b)), but some upflows are noticeable near the edge of the vortex tube, the size of which is expanding with height. The current helicity, calculated in Alfvén units as $\chi_m = (1/4\pi\rho)B \cdot (\nabla \times B)$, forms a sheet-like structure oriented along the intergranular lane near the photospheric layers (Figure 3(c)). The current sheet structure gradually changes orientation in the higher layers and becomes more circular (Figure 3(c)). The current helicity structure is more diffuse than the kinetic helicity, $\chi_k = u \cdot (\nabla \times u)$. The density distribution in the lower atmosphere is similar to the surface layers, but the vortex tube structure becomes more complicated with height, forming a ring-like structure at $\sim 800$ km above the surface.

Figure 4 shows the time evolution of the velocity streamlines (panels (a)–(c)), magnetic field lines (panels (d)–(f)), and the ratio of the gas pressure to magnetic pressure (plasma $\beta \equiv 8\pi\rho p / B^2$) for three moments separated by 3 minutes. The structure of the vortex tube in the middle column is shown in more detail in Figure 5(a). In Figure 4, the gray–yellow isosurface corresponds to a temperature of 5800 K. Color patches on this surface indicate variations of magnetic field strength as indicated in the right color bar. The strongest magnetic field concentrations ($\sim 1.2$ kG) are associated with the vortex tubes in the photospheric layer, and the field strength decreases to $\sim 200$ G in the upper layers of our domain ($\sim 1$ Mm above the photosphere).

The numerical simulations show the penetration and dynamics of the vortex tube into the chromosphere. The vortex core contains very compact helical downflows, and we observe that the vortex pulls granular fluid upward which then reverses into the downflows (Figure 4(a)). The magnetic field at this stage of vortex evolution continues to concentrate in the vicinity of the vortex by following the swirling turbulent motions (Figure 4(d)). These strong helical flows capture and twist the magnetic field lines. Also, the helical magnetic loops formed by vortex tubes have a tendency to move upward due to local upflows near the vortex core. Three minutes later, the helical downflows have become more compact and stronger (Figure 4(b)), but the vortex is...
affecting a larger surrounding area. We begin to see evidence of vortex decay when this vortex starts interacting with others by sharing with them a part of the downflow (Figure 4(b)). Finally, during the next 3 minutes, the photospheric and chromospheric parts of the vortex tube become disconnected but still continue to evolve. Figure 4(c) shows remnants of the initially strong helical flows in the atmosphere. At this moment, they are still weakly helical and become captured by another growing vortex. The magnetic field lines also keep their helical topology and start to diffuse (Figure 4). We show the plasma parameter, $\beta = 3$, level as blue isosurfaces in Figures 4(g)–(i); the value $\beta = 1$ is reached only in a small region of the vortex core. This parameter shows that the magnetic effects play a significant, but not dominant, role in the photospheric layers of the vortex tube and that the region of their influence rapidly expands with height. At the decay stage of the vortex tube (Figure 4(i)), magnetic effects are significant only in the upper layers.

The relative role of kinematic and magnetic effects of the swirling motions is illustrated by the kinetic, $\chi_k$, and magnetic, $\chi_m$, helicities. An example of relative distribution for both helicities is shown in Figure 5(a) (the kinetic helicity is in blue, and the current one is in pink) for the vortex tube that is indicated by the arrow in Figure 2. Blue and pink isosurfaces correspond to helicity values of $-5000 \text{ cm s}^{-2}$; the current helicity is calculated in Alfvén units and has the same dimension as the kinetic helicity. In Figure 5(a), we also plot the temperature isosurface for 5800 K, which has a very compact structure of a complicated chiralical shape, expanding into the higher layers of the atmosphere. The distribution of the kinetic helicity is more compact than the current helicity, meaning that the swirling flows in the vortex tube are more compact than the twisted magnetic field lines.

To investigate the properties of the magnetized vortex tube with height, we select a region inside the $-5000 \text{ cm s}^{-2}$
Figure 4. Evolution of the velocity field (streamlines in panels (a)–(c)), magnetic topology (streamlines in panels (d) and (e)), and plasma parameter $\beta$ (blue isosurface for $\beta = 3$ in panels (g)–(i)). Each column corresponds to simulation data 3 minutes apart. The gray isosurface shows $T = 5800$ K; additional coloring from light yellow to orange indicates variations of the magnetic field strength in the range from 0 to 1200 G. Coloring of the velocity streamlines in panels (a)–(c) corresponds to vertical velocities from $-7$ km s$^{-1}$ (blue) to $+7$ km s$^{-1}$ (red).

isosurface of the current helicity. In this region, we plot the mean values of temperature and density, vertical and horizontal velocities, magnetic field components, and kinetic and current helicities as a function of height for different moments of time with a cadence of 20 s (Figures 5(b)–(f)). The values of temperature and density are shown as perturbations from and normalized by the mean values: $(T_{\text{vortex}} - T)/T$ and $(\rho_{\text{vortex}} - \rho)/\rho$. The temperature distribution shows a deficit in the convective layers of the vortex tube. Above the photosphere, the temperature in the vortex tube increases, and we can see heating in the vortex core (Figure 5(b)). Temperature fluctuations above $\sim 500$ km reflect spontaneous flow ejections into the higher layers of the atmosphere (see the vertical velocity profiles shown by red curves in Figure 5(d)), and also are due to the oscillatory behavior of the vortex tube associated with the vortex penetration into the higher layers and decay. The relative density distribution (Figure 5) shows an increase below the surface due to mass concentration around the vortex core, which has significantly lower density. Above the surface, the mean density perturbation in the tube first decreases and then increases above 200 km (Figure 5(c)).

The vertical distribution of the mean velocity inside the vortex tube shows very different properties for the horizontal and vertical components. The mean horizontal speed (blue curves, Figure 5(d)) is almost constant along the vortex tube, with relatively small fluctuations in time around the mean speed of $\sim 3.5$ km s$^{-1}$. It is interesting that the mean horizontal speed, averaged over time and over the whole domain (thick dark blue curve), shows a decrease at 400–800 km above the surface, but inside the vortex tube there is no such decrease. In contrast to the horizontal speed, the vertical velocity component (red curves, Figure 5(d)) is very dynamic and is characterized by predominant downflows; however, local upflows can be detected inside the vortex tube.

The vertical component of the magnetic field is significantly stronger than the magnitude of the horizontal field (Figure 5(e)). Both vertical (red curves) and horizontal (blue curves) fields show a similar tendency to decrease in the atmospheric layers, which is reflected in the expanding topology of the flux tube. At a height of about 500 km, the magnitude of the vertical component of magnetic field is smaller than the horizontal component because the magnetic field lines become more twisted by the vortex. The mean kinetic helicity (blue curves, Figure 5(f)) is significantly greater than the mean current helicity (red curves) because swirling motions in the tube are accompanied by strong downflows, while the strongest magnetic field is only weakly twisted. Snapshots of the vertical fluxes of mass, kinetic energy, and Poynting vector (Figures 5(g)–(i)) show that these are mostly concentrated around the vortex tube cores, and are associated with the swirling motions.

5. DISCUSSION AND CONCLUSION

The dynamics of small-scale turbulent vortex tubes play key roles in various processes of the surface convection and the atmosphere of the quiet Sun. Vertically oriented vortex tubes studied in our numerical simulations are mostly of hydrodynamic nature. They are formed inside granules and intergranular lanes due to convective overturning or as a result of
the Kelvin–Helmholtz type instability (Kitiashvili et al. 2012). After the formation the vortex tubes are mostly concentrated in the intergranular lanes. They show complicated dynamics, can penetrate into the chromospheric layers, and also form arc-like structures. An initial indication of such a possibility was found in the simulations of Stein & Nordlund (2000b; Figure 13), with a thin atmosphere layer (500 km).

Our radiative hydrodynamic and MHD simulations revealed details of the penetration of vortex tubes, formed by turbulent convection, from the subphotospheric layers into the chromosphere. We investigated two cases: without a magnetic field and with a weak 10 G mean magnetic field corresponding to quiet-Sun regions. The statistical distribution of enstrophy is found to be similar in both cases in the near-surface layers (with a larger fraction of strongest vortices, $\omega^2 > 0.3 \, \text{s}^{-2}$, in the magnetic case). Above the surface, where the effects of magnetic field became stronger, the enstrophy distribution decreases more steeply due to suppression of vorticity by the magnetic field (Figures 1(e) and (f)). However, the vortex tube effects in the chromosphere are significantly stronger in the presence of a magnetic field. The simulation results showed that the vortex tubes cause significant qualitative changes in the atmospheric dynamics, leading to strong variations in the thermodynamic structure through local heating and density variations, generating twisted magnetic flux tubes, and creating local twisted upflows into the chromosphere. Temperature variations in the subsurface and surface regions show a strong temperature decrease in the vortex tube core, whereas above the surface, $z \gtrsim 200 \, \text{km}$, where the magnetic effects are more significant, the region inside the vortex core is significantly hotter than in surrounding regions (Figure 5(b)). A similar heating effect was recently found in simulations with a stronger mean magnetic field of $B_0 = 200 \, \text{G}$, corresponding to plage regions (Moll et al. 2012). In this case, they found a more distributed heating not specifically associated with the vortex cores.

Our simulations show that strong localized swirling motions occupy large areas around the vortex tubes, capturing and twisting magnetic field lines from nearby magnetic structures.
Such vortices can spontaneously produce flow ejections (see vertical velocity profiles at Figure 5(d)). Figures 5(g)–(i) show snapshots of the mass flux, $F_m$, kinetic energy flux, $F_k$, and Poynting flux, $F_p$, for one such ejection at a height of 500 km above the surface. The upward fluxes are caused by the swirling motions around the vortex cores.

These phenomena suggest that the magnetized vortex tubes generated by turbulent convective motions provide a very important link for energy and momentum exchange between the subsurface layers and the chromosphere.

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