UBIQUITOUS SOLAR ERUPTIONS DRIVEN BY MAGNETIZED VORTEX TUBES

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Received 2013 January 6; accepted 2013 April 21; published 2013 May 22

ABSTRACT

The solar surface is covered by high-speed jets transporting mass and energy into the solar corona and feeding the solar wind. The most prominent of these jets have been known as spicules. However, the mechanism initiating these eruption events is still unknown. Using realistic numerical simulations we find that small-scale eruptions are produced by ubiquitous magnetized vortex tubes generated by the Sun’s turbulent convection in subsurface layers. The swirling vortex tubes (resembling tornadoes) penetrate into the solar atmosphere, capture and stretch background magnetic field, and push the surrounding material up, generating shocks. Our simulations reveal complicated high-speed flow patterns and thermodynamic and magnetic structure in the erupting vortex tubes. The main new results are: (1) the eruptions are initiated in the subsurface layers and are driven by high-pressure gradients in the subphotosphere and photosphere and by the Lorentz force in the higher atmosphere layers; (2) the fluctuations in the vortex tubes penetrating into the chromosphere are quasi-periodic with a characteristic period of 2–5 minutes; and (3) the eruptions are highly non-uniform: the flows are predominantly downward in the vortex tube cores and upward in their surroundings; the plasma density and temperature vary significantly across the eruptions.

Key words: magnetic fields – magnetohydrodynamics (MHD) – methods: numerical – plasmas – Sun: chromosphere – Sun: photosphere – turbulence

Online-only material: color figures

1. INTRODUCTION

One of the most frequently observed phenomena of dynamical coupling between the solar convective and atmospheric layers are plasma eruptions on different scales, such as spicules and jets. Rapid increases in the observational power of new instruments, e.g., HMI/SDO (Scherrer et al. 2012), SOT/Hinode (Tsuneta et al. 2008), NST/BBSO (Goode et al. 2010), and IMAX/SUNRISE (Solanki et al. 2010), allow us to detect various features on smaller and smaller scales and measure their properties. Realistic numerical simulations, based on “ab initio” physical principles (e.g., Stein & Nordlund 1998; Wedemeyer et al. 2004; Vogler et al. 2005; Jacoutot et al. 2008a; Gudiksen et al. 2011; Kitiashvili et al. 2012b), have been able to reproduce the physics of the observed phenomena and allow the prediction of new effects difficult to detect in observations. In this paper, we present new results of radiative magnetohydrodynamics (MHD) simulations that shed light on the mechanism of small-scale eruptions in the solar atmosphere and link it to the dynamics of turbulent magnetized vortex tubes.

Previously, it was shown, through both simulations (e.g., Zirker 1993; Steiner et al. 2010; Moll et al. 2011; Shelyag et al. 2011; Kitiashvili et al. 2010, 2011, 2012b) and observations (e.g., Stenflo 1975; Wedemeyer-Böhm & Rouppe van der Voort 2009; Balmaceda et al. 2010; Cao et al. 2010; Goode et al. 2010; Yurchyshyn et al. 2011; Fedun et al. 2011; Ji et al. 2012; Wedemeyer-Böhm et al. 2012), that an important role in the dynamics of the turbulent convective layers and the low atmosphere, and also in chromospheric heating, is played by small-scale, spontaneously generated vortex motions. In particular, the numerical simulations revealed the existence of vortex tubes and their complicated dynamics. It is found that despite preferentially strong downflows in the vortex tube cores, strong upflows may occur around the cores, pushing material into the atmospheric layers (see Figure 5 in Kitiashvili et al. 2012b). Dynamical links between photospheric dynamics and the atmosphere and corona were previously considered by many authors, but mostly by introducing various photospheric perturbations, for instance, large-scale vortices (e.g., van Hoven et al. 1995), twisted magnetic flux tubes (e.g., Martinez-Sykora et al. 2008; Fang et al. 2012), or a strong (100–200 G) uniform vertical magnetic field superimposed on a snapshot of hydrodynamic convection, which led to formation of large-scale vortical structures (Kitiashvili et al. 2010; Wedemeyer-Böhm et al. 2012). An exception is the calculations of Wedemeyer-Böhm et al. (2012) which starts from a uniform vertical magnetic field superimposed on a snapshot of hydrodynamic convection as is done in the results reported here.

In this paper, we focus on small-scale flow dynamics from the subsurface layers to 1 Mm above the photosphere and demonstrate that spontaneously initiated quasi-periodic upflows associated with the vortex tube dynamics, in the presence of magnetic field, produce small-scale jet-like ejections of plasma generating shocks in the atmosphere. We discuss the origin and properties of these eruptions and their potential role in the spicule mechanism.

2. COMPUTATIONAL SETUP

To simulate the coupled dynamics of the top layers of the turbulent convective zone, the photosphere, and the low atmosphere of the Sun we use the three-dimensional radiative MHD
"SolarBox" code developed at the Stanford Center for Turbulence Research and NASA Ames Research Center (Jacoutot et al. 2008a). The code implements LES turbulence models, a real-gas equation of state, astrophysical opacity tables (Rogers et al. 2008a). The code implements LES turbulence models, a real-gas equation of state, astrophysical opacity tables (Rogers et al. 2008a) and uses a standard model of the solar interior for initial conditions (Christensen-Dalsgaard et al. 1996). Radiative transfer between fluid elements is calculated using a three-dimensional multi-spectral bin method with long characteristics, assuming local thermodynamic equilibrium.

The physical description of the dynamical properties of solar convection is improved through the implementation of sub-grid scale LES turbulence models, which can effectively increase the Reynolds number and provide representation of small-scale motions closer to reality (Jacoutot et al. 2008a). Here we used a Smagorinsky eddy-viscosity model (Smagorinsky 1963), in which the compressible Reynolds stresses were calculated in the form (Moin et al. 1991): 

\[ \tau_{ij} = -2C_S \Delta^2 \left( S_{ij} - u_i u_j / 3 \right) + 2C_C \Delta^2 \left| S \right|^2 / 3, \]

where the Smagorinsky coefficients are \( C_S = 0.001 \), \( S_{ij} \) is the large-scale stress tensor, and \( \Delta \equiv \left( dx \times dy \times dz \right) / 3 \) with \( dx, dy, \) and \( dz \) being the grid-cell dimensions.

The presented simulation results are obtained for a computational domain of \( 6.4 \times 6.4 \times 6.2 \) Mm\(^3\), with a 1 Mm layer above the photosphere and a 5.2 Mm layer below, using 12.5\(^2\) × 12 km grid cells. We model the conditions of a quiet-Sun region with an initially introduced uniform vertical magnetic field \( B_{z0} = 10 \) G, and, for comparison, also consider a pure hydrodynamic case \( (B = 0) \). The lateral boundary conditions are periodic. The top boundary is open to mass, momentum, and energy fluxes, and also to the radiation flux. The bottom boundary is open only for radiation, and simulates the energy input from the interior of the Sun. The simulation results previously were compared with a similar type code by Nordlund & Stein (2001) for some test cases and with photospheric observations (Jacoutot et al. 2008a, 2008b; Kitiashvili et al. 2013). Extending the computational domain into the atmosphere allows us to model effects of the intensive energy exchange between the photosphere and the chromosphere and to investigate some of the most energetic phenomena in the quiet Sun: spontaneous high-speed flow eruptions along magnetic flux tubes.

3. FLOW EJECTION DUE TO VORTEX TUBE DYNAMICS

The highly turbulent subsurface layers are the place of origin of numerous vortex tubes (see Kitiashvili et al. 2012a, and references therein). The turbulent vortex tubes are usually located in the intergranular lanes; they often become vertically oriented, penetrate above the solar surface, and can be stable for longer than a typical granulation lifetime. High-speed flows associated with the vortex tubes are accompanied by sharp variations of temperature, density, and gas pressure, and can strongly affect the dynamics of their environment. According to the previous numerical simulations, the vortex tubes penetrate into the chromospheric layers in both magnetic and non-magnetic cases. In the quiet-Sun region, the magnetic field effects reveal themselves mostly in the higher atmosphere as a magnification of hydrodynamic effects which play the dominant role in the turbulent surface and subsurface layers. Thus, the contribution of vortex tubes to the chromospheric dynamics and energetics is more significant than in the purely hydrodynamic case, considered in our previous paper (Kitiashvili et al. 2012b).

Our simulations show that upward vortex tube penetration into the solar atmosphere is often quasi-periodic and accompanied by spontaneous flow ejections. A time sequence of various vortex tube properties with a cadence of 15 s for a strong event is illustrated in Figure 1, where panels (a)–(c) show horizontal snapshots of temperature, vertical velocity, and density at height \( h = 625 \) km, and panel (d) shows vertical cuts of \( \log(p) \) taken along the \( x \)-axis through the region marked by short white lines in panels (a)–(c). Figure 1 shows a complicated structure and dynamics of the eruptions, with downflows in the vortex core and upward eruption flows in the surrounding region. As seen in the temperature distribution plots in panel (a), these eruptions are hotter than the surrounding plasma and can provide extra chromospheric heating in addition to the heating through the vortex core. The shape of the flow ejections in the vortex tubes is not completely circular due to the non-vertical vortex tube orientation and interaction with surrounding flows (Figures 1(c) and (d)).

The vortex tube causes strong swirling motions of the subsurface and atmospheric layers around the vortex core. Figure 2 illustrates various stages of a flow ejection, where the streamlines show the general behavior of the velocity field; yellow–blue isosurfaces represent the pressure gradient, normalized by density, of \( 5 \times 10^4 \) cm s\(^{-2}\) (yellow) and \( -5 \times 10^4 \) cm s\(^{-2}\) (blue), and the gray isosurfaces correspond to \( T = 6400 \) K. In the atmosphere layers, the flow ejection starts with the formation of a vertically oriented vortex tube, as described in Kitiashvili et al. (2012a) and Porter & Woodward (2000). This creates strong vertical pressure gradients, negative in the vortex core and positive at the vortex periphery (Figure 2(a)). The swirling motions become concentrated at a height of about 500 km (which corresponds to the temperature minimum region, panels (b) and (c)), and then erupt (panel (d)).

Because of the strong concentration of magnetic field in the vortex core \( (~1.2 \) kG in the photosphere layer), it is of interest to consider the dynamics in terms of the evolution of electric currents. Figure 3 shows that the vortex tube penetration for the same event is accompanied by formation of an electric current sheet in the surrounding area of the intergranular lane (blue isosurface), which expands together with the vortex tube (the yellow isosurface represents entrophy) into the atmosphere and relaxes during the ejection. The current sheet can be a source of Lorentz force (Section 5) and also, perhaps, additional heating.

4. DYNAMICS OF FLOW EJECTIONS

Generally, the flow structure during the eruption phase remains twisted: the material around the vortex core moves up from the subsurface layers, and also toward the vortex from the surrounding region, and collects near the vortex edge. The plasma is moved up by the twisting flows into the higher atmospheric layers, and, at the same time, in the lower layers the plasma flows down through the vortex core (Figure 4(a)). The magnetic field lines are weakly twisted opposite to the flow direction (Figure 4(b)). Because the dynamics of eruptions is associated with the flows surrounding a relatively narrow vortex core, we track the vortex core and analyze the data in cylindrical coordinates centered on the vortex core. For this analysis, we choose a typical vortex tube and divide the vortex region into 125 km “rings” (or “zones”), where “zone 0” includes the vortex core and its edge (Figure 5).

Figure 6 shows the mean vertical velocity variations with time at different heights, from \(-300 \) km to \( 780 \) km, for two zones: (a) vortex core (“zone 0”) and (b) surrounding region (“zone 1”). These diagrams show that the velocity...
perturbations are initiated at depths of ∼60–120 km below the surface (superadiabatic zone), and then propagate in both directions, upward and downward. Such perturbations are quasi-periodic with a period of 2–5 minutes, which can be related to the characteristic oscillation properties of the near-surface plasma, where the vortex tube is rooted. The period is also similar to the oscillations of large-scale acoustic (p) modes excited in the domain. However, these oscillations do not show correlation in phase with the vortex tube oscillations, and their amplitude is essentially smaller. The mean vertical velocity of the perturbations increases up to 5–8 km s$^{-1}$ at ∼800 km above the solar surface. These upflows can be identified as small-scale flow ejections. The amplitude and quasi-period of the eruptions vary with the vortex tube properties and their evolution (e.g., changes in their size, shape, and height penetration), or/and interactions with other vortices, as a result of which the ejections can be magnified or suppressed.

Comparison of the vertical velocity variations (Figure 6) in the vortex core (panel (a)) and the surrounding region (panel (b), as indicated in Figure 5 zones “0” and “1”) shows that in the vortex core the velocity perturbations have stronger amplitude. In the core, the upward speed of the velocity perturbations increases with height from 6 km s$^{-1}$ in the near-surface layers to more than 12 km s$^{-1}$ above 700 km. The downward perturbations propagate much more slowly, with a speed of 3–3.5 km s$^{-1}$, and their amplitudes apparently increase as they descend, but more analysis is needed. In the vortex-surrounding region (Figure 6(b)), the velocity shows a similar behavior. The time shift of the vertical velocity variations between different zones allows us to estimate the speed of the flow expansion during the eruption, which is about 20–25 km s$^{-1}$ in the vortex core area and decelerates to ∼15 km s$^{-1}$ at about 500 km from the vortex. For each individual ejection event, these numbers can vary due to the interaction of the perturbations with shocks from other eruptions.

The transformation of the velocity perturbations into shock waves is an additional interesting feature associated with flow ejection (Figures 1(c) and (d)). This effect is identified in both the hydrodynamic and magnetic simulations and in both cases is associated with the vortex tube dynamics. In the next section,
Figure 2. Different stages of the flow ejection: (a) vortex tube penetration into the atmosphere layers, (b) intensification of the swirling motions, (c) concentration of the swirling motion in a ring-like structure, and (d) flow ejection along the vortex tube. Black streamlines illustrate the velocity field in the vicinity of the vortex tube. Semitransparent light gray surface corresponds to a constant temperature of 6400 K. Yellow and blue isosurfaces correspond to the normalized-by-density vertical pressure gradient $(-\nabla p/\rho)$ for the values of $5 \times 10^4$ cm s$^{-2}$ (yellow color) and $-5 \times 10^4$ cm s$^{-2}$ (blue color).

(A color version of this figure is available in the online journal.)

we consider in more detail the process of flow ejection and magnetic field effects.

5. SOURCE AND DRIVERS OF SPONTANEOUS FLOW ERUPTIONS

The complicated dynamics of strong swirling flows in the presence of magnetic field across many pressure scale heights represents an interesting interplay of hydro- and magnetic effects. In general, there are two type of forces that are responsible for driving the flow eruptions: hydrodynamic, due to pressure excess; and magnetic, caused by the Lorentz force. A comparison of the contributions from the hydrodynamic and magnetic effects can be done by estimating the various terms of a modified momentum equation:

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} = \frac{\mathbf{J} \times \mathbf{B}}{c \rho} - \frac{\nabla p}{\rho} - g. \quad (1)$$

where $\mathbf{v}$ is the velocity vector, $\mathbf{J}$ is the electric current density, $\mathbf{B}$ is the magnetic field vector, $\rho$ is the gas pressure, $\rho$ is the density, and $g$ and $c$ are the gravitational acceleration and the speed of light. In this form, Equation (1) describes the flow acceleration on the left-hand side, and, on the right-hand side, the contributions of the Lorentz force (first term) and the pressure...
Evolution of the electric current sheet during the vortex tube eruption, which drags it into the higher atmospheric layers ((a)–(d)) followed by the current relaxation during the flow ejection ((e) and (f)). Blue isosurfaces correspond to the value of electric current $|J| = 8 \times 10^4$ and yellow isosurfaces show the enstrophy distribution for $\Omega = |\text{curl}v|^2 = 0.35 \text{ cm}^{-2}$. Black streamlines show selected flow trajectories. (A color version of this figure is available in the online journal.)

Figure 3. Evolution of the electric current sheet during the vortex tube eruption, which drags it into the higher atmospheric layers ((a)–(d)) followed by the current relaxation during the flow ejection ((e) and (f)). Blue isosurfaces correspond to the value of electric current $|J| = 8 \times 10^4$ and yellow isosurfaces show the enstrophy distribution for $\Omega = |\text{curl}v|^2 = 0.35 \text{ cm}^{-2}$. Black streamlines show selected flow trajectories. (A color version of this figure is available in the online journal.)

Gradient and gravity. In the initial equilibrium state the pressure gradient and gravity are balanced.

Figures 7 and 8 show a comparison of the pressure gradient excess and the Lorentz force in the vortex core (zone “0,” panels (a)) and the surrounding region (zone “1,” panels (b)). The profiles of both non-magnetic and magnetic forces reveal a clear connection with the upward and downward velocity perturbations associated with the flow ejection, showing a similar decrease in the perturbation amplitude in the vortex surrounding regions, and also a time lag with height. Propagation of the perturbations is better visible in the Lorentz force (Figure 8), with a clear indication of acceleration in higher layers of the atmosphere, indicating a strong increase of magnetic field effects at a height $h \geq 700 \text{ km}$. The propagation of the Lorentz force perturbations upward and downward along the vortex tube (Figure 8(a)) gives us an additional estimate for the depth of the initialization source, which varies for different events from the photosphere to $\sim 120 \text{ km}$ below surface. This process corresponds to the non-magnetic case, where the primary source of the vortex eruptions is hydrodynamic. Magnetic field effects become important above the temperature minimum region, where the plasma upflows are accelerated by the Lorentz force.

Figure 9 shows the contributions of the magnetic (blue curves) and non-magnetic acceleration (red curves) in four layers: 780 km and 300 km above the solar surface (panels (a) and (b)), in the photosphere layer (panel (c)), and 240 km below the surface (panel (d)). Dashed curves represent the vertical velocity for these same layers, given for comparison. The results show that the Lorentz force is most important for the flow acceleration in the higher layers, where strong Lorentz force fluctuations are correlated with strong flow acceleration (e.g., at $t = 9 \text{ minutes}$). The flow eruption is much weaker for those events in which the most contribution comes from hydrodynamic forces (e.g., $t = 3 \text{ minutes}$). Nevertheless, close to the surface and in the subsurface layers hydrodynamic effects are significantly more important (Figures 9(b)–(d)) than the Lorentz force.

As we have discussed above, the initial perturbations of the flow velocity and the hydrodynamic and magnetic forces associated with the vortex eruption are generated just below the surface, where the effect of the pressure gradient force is dominant. The subsurface layers in the vicinity of the vortex core
Figure 4. Topology of the flow streamlines and magnetic field lines during the flow ejection. The vortex is visualized by a constant temperature isosurface, $T = 6000$ K. The color scale on this surface shows the distribution of the magnetic field strength from 50 G or less (gray) to 1.2 kG (red). Streamlines in panel (a) illustrate the topology of flows, with helical upward ejection flows and downflows in the narrow vortex core. In panel (b) black lines show the topology of the magnetic field lines. (A color version of this figure is available in the online journal.)

Figure 5. Schematic representation of the analysis on zones with 125 km width around the vortex core. Background image illustrates the density distribution at height of 625 km above the solar surface for $t = 7$ minutes. For the analysis, presented in Figures 6–9, the vortex core is tracked in time for the subsurface and atmosphere layers.

6. SUMMARY AND DISCUSSION

High-resolution ground-based and space observations have revealed an intense and very dynamic interaction between the surface layers and the low atmosphere in quiet-Sun regions with relatively weak mean magnetic field. Radiative MHD simulations can reproduce some basic features of observed phenomena and provide an important complementary tool for investigation of the underlying physical processes. However, one has to keep in mind that despite their realistic character, the simulations have certain limitations, and the results are therefore mostly qualitative, revealing the basic physical processes rather than reproducing the exact physical properties. In particular, because the solar plasma is characterized by extremely high Reynolds numbers, the numerical simulations depend on subgrid turbulence models for dissipation. However, increasing the numerical resolution allows us to resolve essential scales of the solar turbulence in the photosphere (Kitiashvili et al. 2013). Another limitation is in the use of the LTE approximation, which, however, mostly affects the radiative transfer in spectral lines, and is not expected to significantly affect the qualitative properties of vortex tube dynamics and flow ejections, but potentially can be a source of quantitative deviations of our results from observations.
Our numerical simulations with an initial mean 10 G vertical magnetic field show a complicated mixture of hydrodynamic and magnetic effects associated with spontaneous quasi-periodic (with period 2–5 minutes) flow ejections from the subsurface layers into the higher atmosphere along magnetized vortex tubes, in which the magnetic field strength on the surface is typically ∼1 kG (Figure 6). The quasi-periodic character of the eruptions reflects vortex tube interaction with the environment at different dynamical scales. The mean period of the flow ejections along the same vortex tube corresponds to the well-known 5 minute oscillations. However, we did not do a correlation with the $p$-modes excited in our simulation domain. The quasi-periodic behavior affects interactions among the vortex tubes and with surrounding turbulent flows and thus is rather irregular. The eruptions have a complicated dynamical structure with mostly continuous swirling downflows, decreasing density and heating in the vortex core, and spontaneous upflows mostly propagating along the vortex core periphery (Figures 1 and 2), forming shock waves in the higher atmosphere (Figures 1(c) and (d)). Schematically, the flow pattern of the eruptions, which resembles the mass circulation in tornados, is illustrated in Figure 11. The plasma flow in the eruptions accelerate in the higher (mid-chromospheric) layers from 6 to 12–15 km s$^{-1}$. Also, the perturbations associated with the flow ejection propagate into the solar interior along the vortex tube core with a speed of about 3–3.5 km s$^{-1}$ and increasing amplitude.

The process of flow ejection originates in a subsurface layer about 100 km deep, where vortex compression by converging
**Figure 8.** Temporal profiles of the mean variations of the Lorentz force normalized by density ($F_L/\rho$) for (a) vortex core region “0” (range 0–125 km) and (b) surrounding region “1” (range 125–250 km) at different levels below the surface and in the atmosphere. The thick black curve shows the variations in the photosphere layer. The height difference between the curves is 60 km. (A color version of this figure is available in the online journal.)

**Figure 9.** Comparison of the contributions to the flow ejection of the hydrodynamic ($-\nabla p/\rho - g/g\rho$, red curves) and magnetic (Lorentz force, $F_L/\rho g$, blue curves) vertical accelerations (normalized by the gravity acceleration) at different altitudes: (a) $h = 780$ km, (b) $h = 300$ km, (c) $h = 0$ km (photosphere), and (d) $h = -240$ km. The dashed curves correspond to the vertical velocity, $V_z$, given for reference at the same layers. All curves correspond to the vortex core region “0.” (A color version of this figure is available in the online journal.)
flows increases the pressure gradient and accelerates swirling flows (the evolution of a strong event is shown in Figures 1–3). This compressed vortex tube starts penetrating into the low-atmosphere layers, and induces the surrounding atmospheric plasma into swirling motion. Accumulation of the swirling flows at a height of \( \sim 500 \) km (the temperature minimum region) forms a ring-like structure which propels the swirling flows into higher layers along the vortex tube. The flows are mostly accelerated by the pressure gradient in the subsurface and near-surface layers, and by the Lorentz force in the higher layers (\( \geq 700 \) km).

The described mechanism of flow ejection in vortex tubes works also in the purely hydrodynamic case, but in this case the velocity perturbations are much smaller and the eruptions almost immediately fall back to the photosphere. Nevertheless, in this case the vortex tube eruptions also generate shocks in the low-density atmospheric layers. Previously, jet-like behavior was found in three-dimensional simulations extending into the corona in which a twisted magnetic flux tube was prescribed at the bottom boundary (1.4 Mm below surface) with strength \( \sim 1–4.5 \) kG for different cases (Martinez-Sykora et al. 2008). Perturbations generated by the flux emergence became shock waves in the chromosphere which, according to Martinez-Sykora et al. (2009), drive the jets. Our simulations demonstrate that the shock generation in the chromosphere can be also due to spontaneous vortex tube dynamics.

It is quite possible that the described flow eruptions represent a mechanism for spicules observed on the solar limb and other small-scale jet-like eruptions, which have puzzled solar astronomers for more than a century since their discovery by Secchi (1877; for a recent review and references see Tsiropoula et al. 2012). The possible mechanism that follows from our numerical simulations, and schematically illustrated in Figure 11, requires further detailed investigation. However, it seems that it is capable of solving a number of puzzling features of solar spicules, such as the regions of lower temperature and temperature gradients perpendicular to the spicule axis (Athay 1961), disparity between spicule velocities measured in different lines (Krat & Krat 1961; Socas-Navarro & Elmore 2005), the double-thread structure (Suematsu et al. 2008), the apparent rotation of spicules around their axis (Beckers 1968), the quasi-periodic behavior (Pasachoff et al. 1968), and apparent fading away of some spicules without the material falling back (Mouradian 1967; because it can be drained down in the vortex core).

According to our simulation results, the magnetic field captured in the vortex tubes plays an important role, magnifying the initial hydrodynamic perturbations and accelerating them along the vortex tubes by the Lorentz force in the higher atmosphere, producing ubiquitous spontaneous flow eruptions in the chromosphere. Our next step is to investigate the propagation of these eruptions into the upper chromosphere and corona.

The simulation results were obtained on the NASA’s Pleiades supercomputer at the NASA Ames Research Center. This work was partially supported by the NASA grant NNX10AC55G,
Figure 11. Schematic illustration of the flow pattern in eruptions driven by magnetized vortex tubes. The red arrows illustrate downdraft in the low-density, relatively cool vortex tube core (gray area); blue lines and arrows show swirling upflows around the vortex core. The vortex tube is rooted below the surface, and the flow eruptions are initiated by a pressure excess 60–120 km below the surface, and further accelerated by the Lorentz force in the mid-chromosphere. (A color version of this figure is available in the online journal.)

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(A color version of this figure is available in the online journal.)