EXCITATION OF ACOUSTIC WAVES BY VORTICES IN THE QUIET SUN

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ABSTRACT

The five-minute oscillations are one of the basic properties of solar convection. Observations show a mixture of a large number of acoustic wave fronts propagating from their sources. We investigate the process of acoustic waves excitation from the point of view of individual events, by using a realistic three-dimensional radiative hydrodynamic simulation of the quiet Sun. The results show that the excitation events are related to the dynamics of vortex tubes (or swirls) in intergranular lanes of solar convection. These whirlpool-like flows are characterized by very strong horizontal velocities (7–11 km s⁻¹) and downflows (≈7 km s⁻¹), and are accompanied by strong decreases of temperature, density, and pressure at the surface and 0.5–1 Mm below the surface. High-speed whirlpool flows can attract and capture other vortices. According to our simulation results the processes of vortex interaction, such as vortex annihilation, can cause excitation of acoustic waves on the Sun.

Key words: hydrodynamics – methods: numerical – Sun: granulation – Sun: oscillations – turbulence – waves

1. INTRODUCTION

Oscillatory behavior is one of the basic properties of the solar surface. Stochastic wave excitation in the turbulent convective medium and frequent interference of acoustic wave fronts make the problem of understanding the mechanism of solar oscillations very complicated. In observational data individual wave excitation events are overlapped with other waves. Nevertheless, individual impulsive events generating acoustic waves have been detected with the Dunn Solar Telescope (Sacramento Peak Observatory; Stebbins & Goode 1987). According to the data analysis and numerical simulations, the source of solar acoustic waves with a typical period of 5 minutes is located in the turbulent convection layer approximately 200 km below the solar surface (Goode et al. 1992). Such impulsive events usually occur in intergranular lanes of the granulation pattern and are associated with strong local cooling (Rimmele et al. 1995; Goode et al. 1998).

At the present time, there is no clear explanation of the mechanism of acoustic wave sources on the Sun. In turbulence theory, the wave excitation process was initially studied for waves generated in air flow by Lighthill (1952) and in stratified convective atmosphere by Stein (1967). According to the Lighthill’s theory, transfer of the flow kinetic energy to the acoustic energy can be caused by short-time deformation of fluid elements by shear flows (Lighthill 1954). The importance of turbulence as a source of wave generation on the Sun was confirmed by numerical simulations. In particular, the numerical results of Stein & Nordlund (2001) supported the observations that strong acoustic sources are located near the solar surface (Goode et al. 1992). The simulations also supported the observation that these sources are located at the intergranular lanes or in their vicinity, where wave excitation is related to occasional, high-pressure fluctuations associated with initiation of turbulent downdrafts and, sometimes, with the intergranular lane formation. Current numerical simulations cannot resolve turbulent scales in the solar conditions. Accurate sub-grid scale modeling of turbulence is therefore important when the events of interest are a part of the turbulent scales. In particular, Jacoutot et al. (2008a) studied several turbulence models and found that the best agreement of the synthetic (simulated) oscillation power spectrum with observational data is given by a dynamic formulation of the Smagorinsky model (Germano et al. 1991; Moin et al. 1991).

The problem of resolving small-scale turbulent eddies is also evident in the current observing capabilities. Observations were able to resolve relatively large, ~3 Mm in diameter, vortex flows in the photosphere (Brandt et al. 1988). Then, an evidence for vortex motions was found from an example of two bright points rotating around each other (Wang et al. 1995). Other observations of vortices showed a connection of vortices to strong downflows (Pötzi & Brandt 2005). Recent observations were able to detect a number of vortical flows in a quiet-Sun region near the solar disk center, by tracing magnetic bright points (Bonet et al. 2008), which followed a logarithmic spiral trajectory and were engulfed by a downdraft. Such whirlpools are less than 0.5 Mm in size, and their lifetime varies from 5 minutes to greater than 20 minutes (Bonet et al. 2008, 2010). The distribution of vortices shows a strong preference for concentration in regions of convective downflows, particularly, at the mesogranular scale (Pötzi & Brandt 2005). Also, the detection of horizontal vortex tubes (along the solar surface) was reported (Steiner et al. 2010).

In this Letter, we present new results of numerical simulations of three-dimensional (3D) radiative hydrodynamics of a quiet-Sun region without magnetic field. By analyzing these results, we identify the process of excitation of acoustic waves and study their propagation in the convective medium. Our results reveal an interesting connection between interactions of vortex tubes that are distributed in the near-surface layer of the Sun and the generation of acoustic waves.

2. REALISTIC SIMULATIONS OF THE QUIET-SUN TURBULENT CONVECTION: NUMERICAL SETUP

We use the 3D radiative MHD simulation code “SolarBox” (developed by A. Wray). It is based on a large eddy simulation formulation that includes various sub-grid scale turbulence models (Jacoutot et al. 2008a). The code takes into account several physical phenomena: compressible fluid flow in a highly stratified medium, 3D multi-bin radiative energy transfer between fluid elements, real-gas equation of state, and...
The simulation results are obtained for two different computational domains: $6.4 \times 6.4 \times 5.5$ Mm$^3$ and $12 \times 12 \times 5.5$ Mm$^3$, and various grid resolutions: $50^2 \times 43$ km$^3$, $25^2 \times 21.7$ km$^3$, and $12.5^2 \times 11$ km$^3$. The domains include a 5 Mm deep layer of the upper convective zone and a 0.5 Mm high layer of the low atmosphere. The lateral boundary conditions are periodic. The top and bottom boundaries are closed to mass, momentum, and energy transfer (apart from radiative fluxes).

3. VORTEX STRUCTURES IN THE SIMULATED QUIET SUN

Vortical motions in the intergranular lanes (“inverted tornadoes”) initially were predicted by numerical simulations (Nordlund 1985; Stein & Nordlund 2000; Nordlund et al. 2009). Figure 1 shows snapshots of our simulations of the surface layer (optical depth in blue continuum $\tau \sim 1$) for temperature, density, vertical velocity, and the magnitude of horizontal velocity at the same moment of time. Several vortex structures (whirlpools) are indicated by white squares. The figure illustrates that small vortices are easier to detect in the density distribution than in the temperature and vertical velocity distributions. The detailed structure of a single vortex is shown in the bottom left corner of each panel in Figure 1. The vortices have a complicated surface structure that has the following properties: (1) a low-temperature core, in which the temperature can decrease by approximately 20%; (2) a sharp drop in density and gas pressure (up to 60% in strongest vortices); (3) strong downflows (up to 7 km s$^{-1}$); and (4) high-speed, often supersonic, horizontal velocities that reach up to 11 km s$^{-1}$.

4. ANNIHILATION OF VORTICES AS A SOURCE OF THE ACOUSTIC WAVES

The dynamics of vortices in the intergranular lanes resembles an inverse “tornado” behavior. An accurate tracking of individual vortices reveals the generation of concentric waves, excited approximately at the center of vortex cores (see Figure 2). The waves are best seen in density perturbations, and often are a result of interaction of two or more vortices. The wave fronts form a circle or a sector of a circle, depending on the source structure, interference with waves from other sources, and on the dynamics of surrounding flows. The wave propagation can also be observed in the movies of the vertical velocity, temperature, and intensity variations at the surface. Figure 2 shows the process of the acoustic wave excitation in a sequence of the density difference, $\rho(t_{i+1}) - \rho(t_i)$, with the time lag of 30 s, in a horizontal slice corresponding to the solar surface. Yellow circles
Figure 2. Temporal evolution of density fluctuations (calculated as $\rho(t_{i+1}) - \rho(t_i)$) at the solar surface ($\tau \sim 1$) with cadence 30 s shows an example of acoustic wave excitation and radial propagation from a vortex source, representing the interaction of two vortices with the opposite-sign vertical component of vorticity, $\Omega_z$. Overplotted yellow circles indicate the approximate position of the wave front. Red and blue contours correspond to the magnitude of the positive (clockwise) and negative (counterclockwise) vertical vorticity.

indicate the approximate positions of the wave front. The wave originated from a place of collision of two vortices, the vertical component of vorticity which had opposite signs (indicated by red and blue contours).

This process of acoustic wave excitation is common in these simulations. However, identification of individual events is often difficult because the wave amplitude is of the same order as the amplitude of noise coming from other acoustic waves and turbulent convection. Nevertheless, we have identified and examined many excitation events with the circular-shaped wave fronts, similar to the one shown in Figure 2.

The propagating wave fronts can be shown in time–distance diagrams, obtained by plotting the density perturbations averaged over a range of angles for different distances from the vortex locations. Figure 3 shows three examples of the acoustic wave propagation in such time–distance diagrams. The diagrams show normalized density variations. The light inclined ridges correspond to the acoustic waves. The wave speed is 7–14 km s$^{-1}$ on average, but it may vary, probably due the background convective flows. In some cases, we see sequences of acoustic waves (Figures 3(a) and (c)), when several wave fronts are produced with $\simeq 2$–2.5 minute intervals. Our analysis shows that the frequency of the excitation events depends mostly on the distribution of vortices and their dynamics.

The vertical vorticity distribution reveals a correlation between the acoustic excitation events and the interaction of vortices with the opposite-sign vorticity, similar to the case shown in Figure 2. In this particular example, two local concentrations of the vertical vorticity component with opposite signs move close to each other and partially merge (annihilate) under the surface, resulting in a partial cancellation (reduction of the magnitude) of the negative vorticity. This process produces a strong negative density perturbation at the surface (Figure 2) and in the subsurface layers. Figure 4 shows different stages of the process of the subsurface interaction of these vortices. In this process, two vortices that rotate in the opposite directions (panel (a)) move closer to each other (panel (b)) and merge (panel (c)). The annihilation of vortices is often partial, without complete
vanishing of the smaller vortex. The interaction of vortices is quite complex: turbulent flows deform the shape of swirls, and smaller vortices get stretched around bigger “main” vortices. The annihilation process can lead to strong local density perturbations. Figure 5 illustrates the propagation of an acoustic wave front through the subsurface layers, which is similar to the wave fronts from point source, obtained in linear wave simulations (e.g., Parchevsky & Kosovichev 2007), but has a less regular structure.

The depth of the wave excitation events is within the top 0.5 Mm layer of the convection zone. However, more detailed investigation of the depth structure is needed, because of the complicated dynamics of the vortex tubes and wave fronts.

5. DISCUSSION AND CONCLUSION

There is no doubt that the solar oscillations are a result of highly turbulent convective flows in the stratified subsurface layers. The results of our simulations reveal that strong interacting vortices in the top layers of the convection zone may play an important role in excitation of solar acoustic oscillations. The vortices are often characterized by supersonic horizontal flows and strong downflows in the vortex cores (Figure 1). The simulation results do not show a preference in directions of the vortex rotation. The vortices are formed in the intergranular lanes. They are numerous and interact with each other. Therefore, these vortex interactions in the subsurface layers are very common.

Figure 3. Time–distance diagrams of normalized density fluctuations show inclined (bright) ridges, corresponding to acoustic waves. Panel (a) shows the time–distance diagram for the event in Figure 2. The slope of the wave ridges corresponds to a mean speed of 7–14 km s$^{-1}$.

Figure 4. Different stages of a subsurface vortex interaction shown in vertical cuts of the magnitude of the positive and negative vertical vorticities (s$^{-1}$): (a) the initial structure of the vortices, (b) the closing-up stage, and (c) the state after annihilation.

Figure 5. Acoustic waves propagation through the subsurface layers. The grayscale background shows the density difference, revealing a wave front (a dark diffuse region at $\sim 3$ Mm) propagating into the interior. Solid and dashed isolines are positive and negative vertical vorticity contours.
We have found that the process of interaction of the vortices with opposite-sign vorticity can lead to their partial annihilation, and that this can result in strong density perturbations and excitation of acoustic waves. The dynamics of vortices is complicated and mostly depends on the structure of surrounding convective motions. Our future plan is to investigate the physical properties of the acoustic sources in more detail and compare with helioseismology observations.

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