Surface Convection

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Abstract. What are supergranules? Why do they stand out? Preliminary results from realistic simulations of solar convection on supergranule scales (96 Mm wide by 20 Mm deep) are presented. The solar surface velocity amplitude is a decreasing power law from the scale of granules up to giant cells with a slight enhancement at supergranule scales. The simulations show that the size of the horizontal convective cells increases gradually and continuously with increasing depth. Without magnetic fields present there is (as yet) no enhancement at supergranule scales at the surface. A hypothesis is presented that it is the balance between the rate of magnetic flux emergence and the horizontal sweeping of magnetic flux by convective motions that determines the size of the magnetic network and produces the extra power at supergranulation scales.

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INTRODUCTION

The nature and origin of supergranulation remains one of the outstanding questions in our understanding of solar convection. One approach to increasing our knowledge has been to simulate the behavior of the solar convection zone. Increases in computational power have enabled corresponding increases in the sophistication of convection simulations. These started with the idealized, two dimensional simulations of Graham (1975); Hurlburt et al. (1984). Now there are spherical, magneto-convection simulations of the interior of the solar convection zone (Miesch, 2005; Brun et al., 2004). The first realistic surface convection simulations were by Nordlund (1982). Now there are realistic, high resolution simulations of surface magneto-convection (Keller et al., 2004; Carlsson et al., 2004; Vögler et al., 2005; Stein & Nordlund, 2006), simulations of the surface convection plus the chromosphere (Schaffenberger et al., 2005, 2006) and even including the corona (Hansteen et al., 2007). The required physics to make realistic models of solar surface convection is: three-dimension, non-linear, compressible flows, inclusion of ionization energy in the equation of state (2/3 of the energy flux is ionization energy near the surface), and non-grey radiation transport (radiative cooling produces the low entropy dense plasma who's buoyancy work drives the convection). Currently there are three different codes that can be used to perform realistic stellar convection simulations – the MURAM code of Vogler, the CO^{5}BOLD code, and our stagger-code. Here we report on some preliminary results from simulations of surface convection on supergranulation scales.

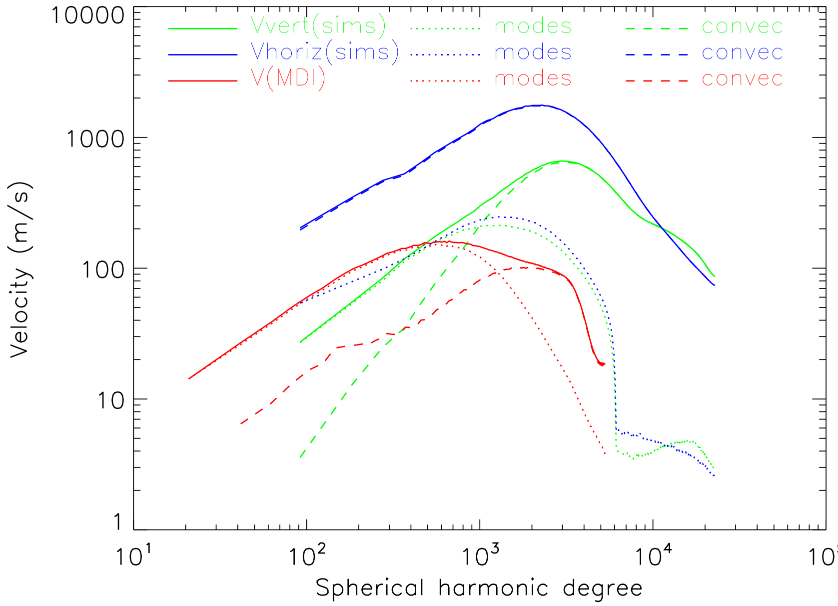

FIGURE 1. The velocity amplitude from high resolution MDI observations (red) and supergranulation scale convection simulations (horizontal blue and vertical green). The spectrum is a power law for scales larger than granulation. The velocity is separated into convective (dashed) and oscillatory (dotted) components. Horizontal motions are almost entirely convective. Vertical motions are convective at granular scales and oscillatory modes at larger scales. There is an enhancement in the observed convective velocity at supergranule scales ($\ell \sim 150$).

VELOCITY SPECTRUM

Granulation is the only distinct scale of solar convection, the scale on which radiative losses from the surface drive the convective motions. Convection motions on scales larger than granulation are self-similar. The velocity amplitude, $\sqrt{kP(k)}$, where $P(k)$ is the velocity power and k the wave vector, at the surface is very nearly a power law from granules up to giant cells. It decreases inversely as the horizontal size increases. The horizontal velocity is almost entirely due to convective motions, while the vertical velocity is primarily of convective origin at granular scales but is primarily due to the p-mode oscillations at larger scales 1. These can be separated by filtering in Fourier space. The MDI high resolution observations show a slight enhancement at supergranule scales, which has not yet been seen in the non-magnetic simulations. What is supergranulation?

CONVECTION SIMULATIONS

To investigate the nature and origin of supergranulation we have started a simulation of surface convection in a domain 96 Mm wide by 20 Mm deep. We solve the equations of mass, momentum and internal energy conservations in conservative form on a staggered grid using 6$^{\text{th}}$ order finite difference spatial derivatives and a third order, Runge-Kutta

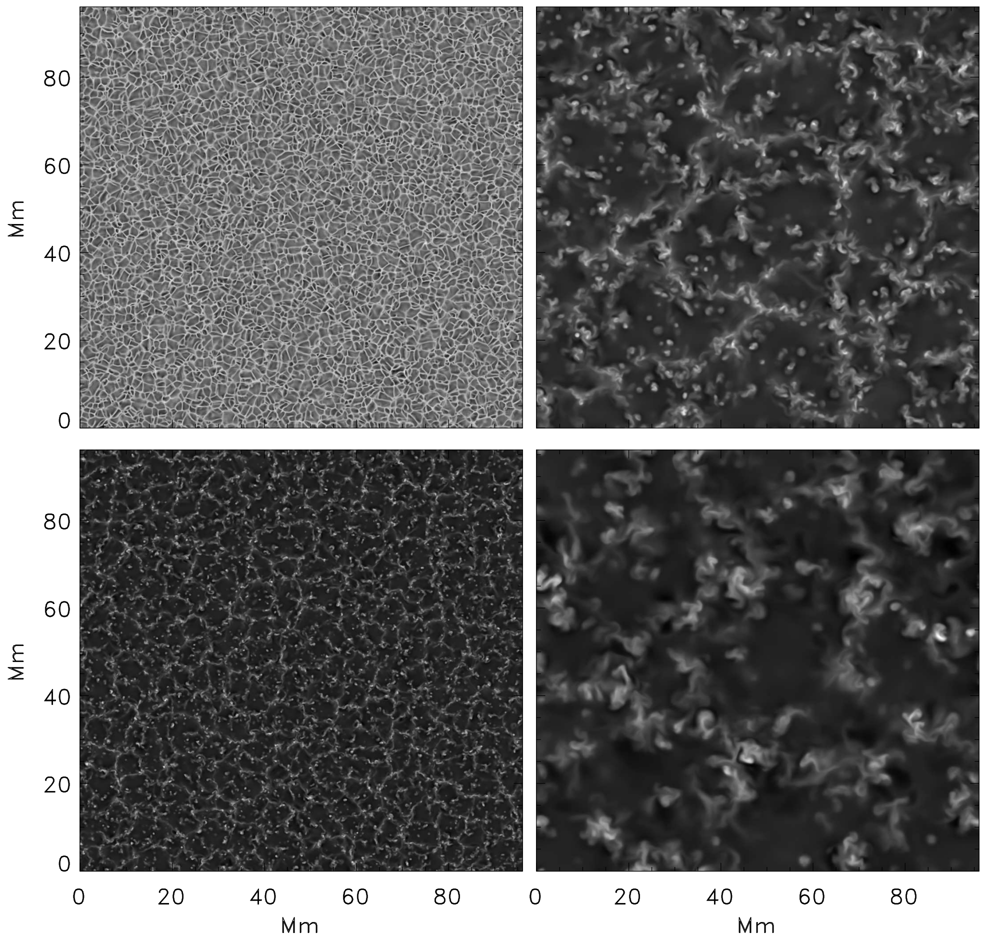

FIGURE 2. Vertical velocity on horizontal slices at the surface and depths of 2, 8, and 16 Mm. Horizontal width is 96 Mm. Darker is upflows of increasing velocity. Lighter is downflows of increasing velocity. The range is 6.1 km/s down to 5.6 km/s up at the surface, 8.7 km/s down to 2 km/s up at 2 Mm, 3 km/s down to 1 km/s up at 8 Mm and 2 km/s down to 0.5 km/s up at 16 Mm depth. Each slice has been separately scaled between its minimum and maximum values. As the depth increases the size of the horizontal flow pattern also increases.

time advance. Realism is achieved by using a tabular equation of state the includes ionization and excitation of hydrogen, helium and the other abundant elements and by calculating the radiative heating and cooling by solving for the intensity along one vertical and four slanted rays assuming local thermodynamic equilibrium and a muti-group frequency binning of the opacities and source functions into four bins according to their opacity at optical depth one. The slanted rays are rotated about the vertical by an incommensurable angle each time iteration. The starting solution was bootstrapped from narrower domains. So far 5.5 turnover times have been simulated. The thermal structure is well relaxed, but the dynamic structure at large depths is still changing.

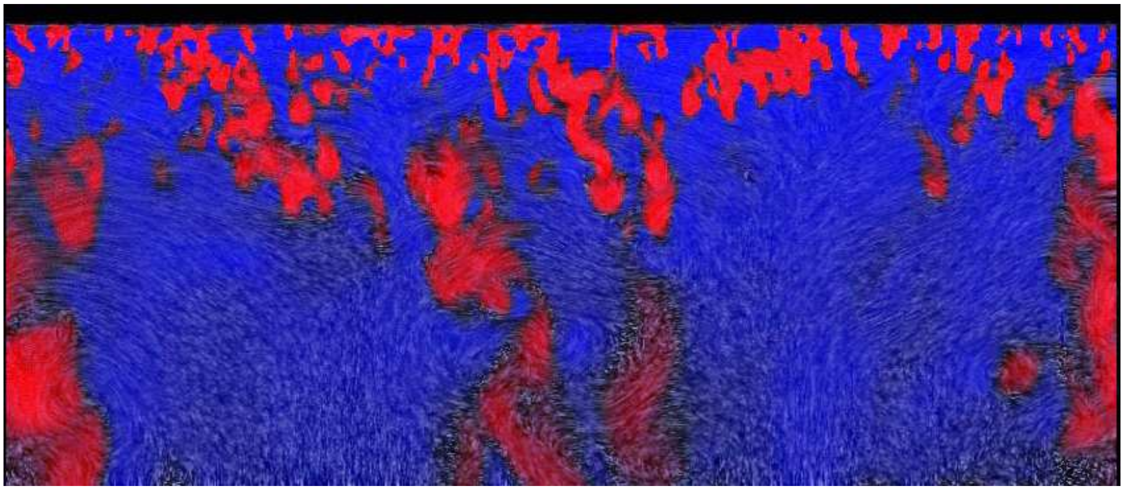

FIGURE 3. Velocity in a vertical slice. Red is downward and blue upward motion. Near the surface granulation is the dominant scale. With increasing depth both the horizontal spacing and the vertical extent of the flow pattern increases.

Convection has a cellular pattern in horizontal planes, with compact upflows surrounded by more or less continuous downflow lanes. The size of the upflows increases with depth due to mass conservation (Fig. 2). Most of the fluid moving upward at any depth diverges and heads downward within a scale height. It flows back down converging into the boundaries of the large cells at depth. Upflows at the surface come from a small region in the interior of the large upflow cells at depth. Only a small fraction of the plasma reaches the surface to cool and become the low entropy dense plasma which gravity pulls down to drive the convection. This diverging flow is driven by slightly higher pressure in the upflows than the downflows. The diverging upflows sweep the the smaller scale downflows above sideways, merging them into larger, more widely spaced downflows (Fig. 3). The strongest upflows also decelerate, halt and disperse weaker downflows from above that are trying to beat their way down against them. The increasing scale height with increasing temperature at larger depths leads to larger horizontal sizes of the upflows with increasing depth (Stein & Nordlund, 1998). The pressure fluctuations associated with the larger cellular patterns at larger depths imprints itself at higher levels and drives flows on large scales although at reduced amplitude. Further, above the boundaries of the larger cells at depth, where the fluid is moving downward, there is less resistance to downflows from above, so it is here that downflows collect and penetrate to large depths.

The results of these simulations are being stored in the HMI archive and will be available for all to use.

ORIGIN OF SUPERGRANULATION

The simulations posses supergranule size upflows at large depths (Fig. 2). However, there is no enhancement in the velocity power at the surface at supergranule scales as is observed in the MDI data (Fig. 1). Recall that all scales of motion from giant cells to granules are visible at the surface, but with amplitude decreasing inversely with size. I propose that supergranules stand out because magnetic fields pile up in the network due to the rate of flux emergence balancing the rate of horizontal sweeping at the scale of supergranulation. How could this idea be tested? First, will enhanced power or visibility at supergranule scales develop when magneto-convection when we introduce magnetic fields into the simulation. Second, does supergranulation vary over the solar cycle and if so how?.

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