CONSTRAINTS IMPOSED BY VERY HIGH RESOLUTION SPECTRA AND IMAGES ON THEORETICAL SIMULATIONS OF GRANULAR CONVECTION

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Abstract

We have obtained a sequence of simultaneous granulation spectra of the line Fe I 6302.5 Å and narrow band slit-jaw images using the Swedish Vacuum Solar Telescope (SVST) on La Palma, Canary Islands, Spain. Simultaneous 0.02s CCD exposures of both the spectrum and the slit-jaw image effectively ‘freeze’ the atmospheric seeing motions and permit unambiguous identification of the spectral features with the corresponding structures of the granular convection.

The unique combination of simultaneous images and high resolution spectra places significant constraints on theoretical simulations of compressible granular convection. These observational constraints have led to the following comparisons: 1) The simulations predict spatially averaged line widths very close to that observed, thereby validating the mean vertical velocity amplitudes of the numerical simulations. 2) The ratio σ_1rms/σ_vrms in the simulated granulation is in agreement with that inferred from the observations. However, the observed intensity and velocity fluctuations are systematically less than in the simulations, suggesting a substantial level of “scattering” from both the seeing and the telescope. We are able to give quantitative estimates of the effects of seeing by using the fact that the total velocity amplitude is known (from the broadening of spatially unresolved spectral lines). 3) Comparison of the observed and simulated granular images reveal the size of convective elements to be systematically larger in the simulations. Reduction of the size of these simulated convective elements was accomplished through a decrease in the adopted value of numerical viscosity. However, even with this reduced viscosity, small scale structures are more prevalent in the observations.

1 Data Acquisition and Analysis

Shown in Figure 1 is a spectrum of Fe I 6302.5 Å obtained at about local noon on 1987

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Figure 1: A slit-jaw image (left), the corresponding spectrum (right) of Fe I 6302.5 Å are shown for measurements of a quiet region near disk center at 11h51m17s UT on 1987 October 29. The apparent slit width is greater than its actual width. The length along the slit corresponds to 19.3 Mm at the surface of the Sun. This image had the highest rms intensity fluctuation (0.68 km/sec) of any of the spectra analyzed. However, the rms intensity contrast (0.056) for the slit jaw image is about average.

September 29 in a quiet region near disk center. The slit-jaw image on the left is recorded simultaneously with the accompanying spectrum. The very short exposure time (0.02 sec) of this digital image, the excellent optical quality of the telescope, the high efficiency of the spectrograph, and the excellent seeing conditions of the La Palma site permit the acquisition of highly dispersed spectra with angular resolution approaching that of the telescope itself (0.3°). The spectrograph has a measured FWHM of 0.025 Å at this wavelength. The observed range of intensity fluctuations (0.066 ≤ σ_{I rms} ≤ 0.091) and vertical Doppler velocities (0.42 ≤ σ_{V rms} ≤ 0.68 km/sec after removal of most of the p-mode oscillatory signal) attest to the exceptional quality of these observations.

Video synchronization of two CCD cameras assured simultaneity of both the spectrum and slit-jaw images. The video signals from each of the cameras were combined with a video signal mixer, and the resultant video signal was 'grabbed' and processed by the image processing system (Scharmer 1987). In the present analysis we consider 11 individual frames (of high rms intensity contrast in the slit-jaw images) from 8 bursts of four images each. In these bursts, the time interval between the starts of the video scans of the successive images is 0.04 sec.
The digital images were corrected for dark-level offset. Observations of a defocused quiet Sun provided the basis for flat-field corrections (c.f. Lites and Scharmer 1988). These corrections greatly reduce the wavelength-dependent fringing in the CCD device used to record the spectrum. After Thomas et al. (1987), we adopt the centroid method of determining Doppler shifts for this line.

2 Fully Compressible Simulations of Granular Convection

The method of numerical simulation of the granular convection (as well as p-mode resonant oscillation of the subsurface cavity), is being described by Stein et al. (1989) and Nordlund & Stein (1989) in papers presented at this symposium. These simulations allow a time history of monochromatic images (including, for example, selected wavelengths within an absorption line) to be generated. The convection is computed for a 6 × 6 Mm area of the surface, with periodic boundary conditions. Figure 2 presents three such images. The simulated continuum images at 6300 Å are shown beside the simulated spectrum of Fe I 6302.5 Å. These images denote: (left) the unsmoothed image with the resolution of the numerical model (0.097 Mm/pixel), (middle) the image smoothed to mimic the diffraction-limited resolution of the SVST, and (right) the image smoothed with both the telescope and a seeing modulation transfer function (MTF) of exponential form (e.g. Nordlund 1984). It should be noted that this exponential form is not unlike that adopted by Schmidt, Knölker, and Schröter (1981) for small wavenumber k; but, unlike their theoretical telescope MTF, it does not vanish at a finite k. The Doppler shifts inferred from the unsmoothed and smoothed spectra are shown in Figure 3, along with Doppler shifts from the observed spectrum of Figure 1. An identical analysis procedure was used to extract Doppler shifts from the simulated and observed spectra. The oscillatory component of the Doppler shift has been removed from the curves. Note the discontinuities in simulated Doppler shift due to the image boundaries at 6 and 12 Mm. For the lower curve, Doppler shifts are presented relative to average shift with redshift positive, the two lowest spatial frequencies representing p-modes with wavelengths of ≈ 20 and 10 Mm have been filtered, high frequency noise has also been removed, and 1.5 Mm on each end of this curve has been apodized. One feature in the spectrum (labeled "a") shows a particularly large shear in the vertical velocity. It is associated with the border of the large granule nearly bisected by the slit near the center of the image in Figure 1.

The combined telescope and atmospheric MTFs adopted for the image on the right of Figure 2 yield rms velocities (after removing the average Doppler shifts due to p-mode oscillations) approximately equal to the average for the observed spectra. The derived exponent (see caption, Figure 2) increases the half-width of the telescope point-spread function (PSF) by about 15%, although it contributes a significant "scattered light" component to the PSF. The effect of this smoothing is to decrease the contrast of the features, yet allow visibility of small features down to the diffraction limit (as also seen in the observed image of Figure 1). The contrast and physical dimensions are identical in all images of Figures 1, 2, and 5.

The main uncertainty in the simulations is probably the one due to the approximate
Figure 2: Simulated continuum images at 6300 Å and adjoining spectra of Fe I 6302.5 Å are shown. Each vertical granulation image is a mosaic of three time steps of a convection sequence, separated from each other by 4 minutes. The sequential images are stacked vertically (with the first image at the top) so as to simulate the longer slit sample of the observed spectra. A vertical line designating the artificial “slit” of width 0.19 Mm (approximately equal to the actual slit width of the observations) shows the locations from which the simulated spectra were derived. The image to the left is unsmoothed, the middle image has been smoothed with a diffraction pattern corresponding to the SVST, and the image to the right has been convolved with both the telescope diffraction MTF and an exponential function of the form $\exp(-0.13k/k_0)$, where $k_0 = 1.05 \text{ Mm}^{-1}$.

treatment of the non-gray radiative transfer, with the influence of millions of spectral lines approximated by averaging the source function into just four bins (representing the continuum, weak lines, intermediate lines, and strong lines). Care has been taken to use a good approximation to the true Rosseland mean in the continuum forming layers, while using an intensity weighted mean in the optically thin layers. However, the position of the “surface” (defined as the location of maximum radiative cooling) depends sensitively on the value of the continuum opacity, and therefore uncertainties in this opacity relative to the monochromatic opacity used when calculating the synthetic spectra do influence to what extent the temperature fluctuations are visible; i.e., the $\sigma_{rms}$. We have estimated the effect of a fairly drastic change of the continuum bin opacity (a factor of 100.2, probably an upper limit to the uncertainty), and we find that the ratio of velocity to intensity rms changes by about 10% (cf. Table below).
3 Results

3.1 Statistical Properties of Observed and Simulated Granular Convection

Table 1 summarizes the statistical properties of the granulation from both the observations and the simulations. For the observations we consider one frame from each of the 8 separate bursts. The rms intensity fluctuation $\sigma_{I\text{rms}}$ of the observations is given for both the slit-jaw images and the spectra. The observed vertical velocity fluctuations $\sigma_{V\text{rms}}$ are limited in sample to the area admitted by the slit, so that the variance of these measurements from frame to frame is much larger relative to that of the intensity fluctuation. In the simulations, the numerical diffusion was changed in such a way as to keep the numerical energy diffusion approximately constant, while decreasing the ratio of momentum to energy diffusion (the Prandtl number $P$). The simulated $\sigma_{rms}$ are derived from 10 solar minute averages over 16 different slit positions, except for the $P=1$ case, which is an average over 50 solar minutes. The simulations show a variance similar to
that of the observations for comparable "slit" widths.

Table 1

<table>
<thead>
<tr>
<th>Case</th>
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<th>Telescope and Seeing</th>
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<td>Irms Vrms</td>
<td>Irms Vrms</td>
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<tr>
<td>P=2 Modified Opac.</td>
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<tr>
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<tr>
<td>Slit Jaw Image</td>
<td>- -</td>
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<td>0.056 -</td>
</tr>
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</table>

3.2 Line Width Constraint on the rms Velocity of Granular Convection: Calibration of the Smoothing due to Seeing

The simultaneous observations of velocity and intensity fluctuations presented here place important constraints on the numerical models of solar granulation. Whereas interpretations of observed intensity fluctuations alone are always subject to uncertainties as well as to the amount of light scattered beyond a few arcseconds (Nordlund 1984), such ambiguities do not arise in the present analysis since, unlike the intensity fluctuation, the rms velocity fluctuation arising from granular convection is reasonably well-known from line widths of spatially averaged line profiles. Thus we have another independent parameter constraining the permissible amount of smoothing due to seeing.

Since the convection model yields approximately the observed average line width (FWHM = 0.118Å simulated, 0.114Å observed), we believe the velocity distribution at the levels of formation of the Fe I line in the simulations to be roughly correct. Figure 4 compares the FTS profile (Livingston 1987) with the average of the simulated profiles. However, since the width of this medium strong line depends sensitively on the (uncertain) Van der Waals damping, weaker lines should be used to put more stringent constraints on the velocity field amplitude.

3.3 Compatibility of the rms Intensity and velocity Fluctuations

The difference between measured $\sigma_{\text{rms}}$ of the slit-jaw image and that of the spectral continuum is of some concern. The slit-jaw reflection introduces some scattering, and the optics used in these measurements to relay the slit-jaw image to the camera are also known to introduce some scattering and degradation of the image. The rms granular contrast measured (at another occasion) with this telescope at 4700 Å without these relay optics show $\sigma_{\text{rms}} \approx 9 - 10\%$, which corresponds to an rms contrast of $\approx 7\%$ at 6300 Å. Thus, even though there remains some uncertainty in the dark level of the spectrum observations (Lites and Scharmer 1988), the $\sigma_{\text{rms}}$ from the spectral continuum probably represents a more accurate mean of the true intensity fluctuations.

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Figure 4: The spatial and temporal average of the Fe I 6302.5 Å line from the simulations (solid curve) is compared with disk-center FTS observations (dashed curve).

Using Wien's law, the simulated $\sigma_{rms}$ of 16.6% in Table 1 corresponds to $\approx 20\%$ at 5200 Å, which is in disagreement with the 13% contrast found by von der Lühe and Dunn (1987). If it can be shown that the atmosphere and telescope are not responsible for all of the "scattering" needed to bring our simulations and observations into agreement, a very special error would have to exist in our numerical model. This error would have to be such that its removal would preserve both the total velocity amplitude and the ratio of measured velocity and intensity amplitudes, while at the same time decreasing the measured intensity $rms$ by a sizeable factor. Even if we disregard the difficulty of finding any possible physical or numerical cause for such an error, it would seem to be hard to adjust two quantities (velocity and intensity fluctuation) in such a way as to preserve the amplitude of one quantity, the observed ratio between them, while still reducing the other by a large factor.

3.4 Observed Size of Granules: Constraints on Numerical Viscosity

The improvement of the correspondence between the size of the largest granules in the observations and simulations upon reducing the numerical viscosity indicates that a numerical viscosity of some $3 \times 10^{12} \text{ cm}^2\text{s}^{-1}$ is marginally small enough to represent
Figure 5: Granulation images are compared after 20 minutes of simulated solar time for the cases of large \((\approx 9 \times 10^{12} \text{ cm}^2\text{s}^{-1})\), left) and small \((\approx 3.5 \times 10^{12} \text{ cm}^2\text{s}^{-1})\), right) numerical viscosity. Each \(12 \times 12 \text{ Mm}\) image is a mosaic of four identical \(6 \times 6 \text{ Mm}\) images with periodic structure. Note the significant reduction of the size of the convective cells upon reduction of the numerical viscosity.

large granules well. The actual diffusivities in our numerical simulations are functions of the local velocity and velocity differences, so we cannot provide more accurate limits. In order to improve the similarity between observations and numerical models on smaller scales, the effective numerical viscosity needs to be further reduced. This might perhaps be accomplished by using a pseudo-spectral representation (as in Nordlund 1982), instead of finite differences.

4 Conclusions

Comparison of Observations and Simulations:

1. The average width and central depth of the simulated Fe I 6302.5 Å line agree remarkably well with the FTS observations. This is evidence that the average vertical velocity in the simulations is nearly correct.

2. The ratio of the intensity to the velocity fluctuations agrees in the simulations and observations. Both the intensity and velocity fluctuations of the simulated granulation are larger than observed. By smearing the simulated images with the theoretical telescope modulation transfer function, and an exponential MTF similar in shape to empirically determined seeing MTFs (Nordlund 1984), the simulated fluctuations can be reduced so as to agree with the observed ones. The atmospheric smearing is dominant. It allows one to see features near the diffraction limit of the telescope, but it greatly reduces the contrast of those features. The simulated contrast of 17% disagrees with the 13% contrast found by von der Lühe and Dunn (1987).
3. There is apparently more power in the real granulation at small size scales than in the simulations, even with the numerical viscosity reduced to the lowest value permitted.

Future Work:

1. Spectral observations covering a larger area of the solar surface, and comprising weaker spectral lines (less affected by damping) from both neutral and ionized species, will help to constrain further the thermodynamics and vertical motions of solar granulation.

2. The question of the amount of "scattering" caused by atmospheric seeing will be further investigated. In particular, the central intensity observed in small sunspots and pores might be used to check the level of "scattering" present in the observed $\sigma_{\text{rms}}$.

3. Numerical experiments with the viscosity will continue in order to improve the resolution of small scale features of the granulation.

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