NUMERICAL SIMULATION OF THE SOLAR GRANULATION

Lawrence D. Cloutman
Theoretical Division, Group T-3
University of California
Los Alamos Scientific Laboratory
Los Alamos, NM 87545

Abstract. The solar granulation has been simulated by numerical solution of the multidimensional, time-dependent, nonlinear Navier-Stokes equations applied to the solar atmosphere. Granules may be explained as buoyantly rising bubbles created at the level where T = 8000 K, and which have collapsed into vortex rings. The calculation is in quantitative agreement with observations and has a number of implications for solar physics and convection theory.

With the advent of large, fast computers, such as the CDC-7600 and Cray-1, it has become feasible to apply the techniques of numerical fluid dynamics to modeling solar phenomena such as the granulation. Indeed, the multidimensional, unsteady, nonlinear nature of the granulation almost dictates the use of such an approach. My granule simulation uses a hydrostatic model solar atmosphere as the initial condition for a finite-difference solution of the full two-dimensional Navier-Stokes equations. Radiative transfer is treated by gray diffusion, and the influence of turbulence is modeled by a standard large eddy simulation. The gas physics package was taken from the stellar envelope program by Paczynski (1969). Cloutman (1979a) fully describes the input physics and numerical method.

The initial condition is a solar model computed with Paczynski's envelope program. Figure 1 shows some results from this program. The most notable feature of these solutions is the appearance of a density inversion when the ratio of mixing length to pressure scale height $L/H < 1.5$. This feature is caused by the steep temperature gradient found in the region where T = 8000 K. The steep gradient, in turn, is caused by a combination of short photon mean free path and inefficient convection. Approximately one per cent of the hydrogen is ionized in the inversion zone. The solution for $L/H = 1$ is used as the initial condition in the hydrodynamics program (which, incidentally, makes no use of the mixing length theory).

Figure 2 shows velocity vectors and isopycnics approximately three minutes into the calculation. The mesh is 450 km wide and 173 km deep,

Space Science Reviews 27 (1980) 293–299. 0038–6308/80/0273–293 $01.05.

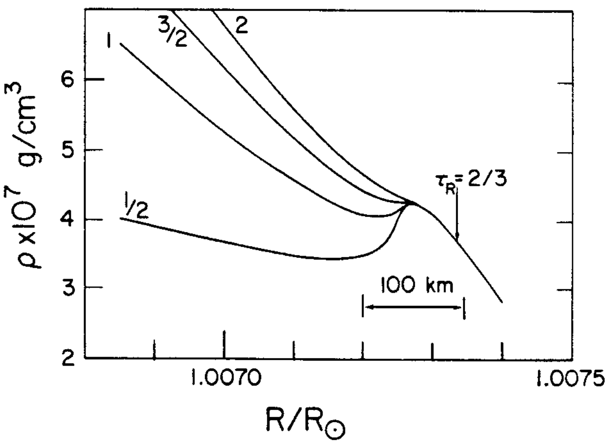

Figure 1. One-dimensional hydrostatic solar density profiles labeled with the ratio of mixing length to pressure scale height.

and the material in the upper third of the mesh is optically thin. The initial motion is produced by a Rayleigh-Taylor instability. However, the convective heat flux is so small that heat is trapped near the lower boundary, creating two low-density bubbles labeled B and C, each representing a granule. Granule C is 340 km wide and has a central upflow velocity of 3 km/s. There is a weak, narrow density inversion rising with the top edge of the bubbles. Shear between a buoyantly rising bubble and the ambient atmosphere causes the bubble to collapse into a vor-

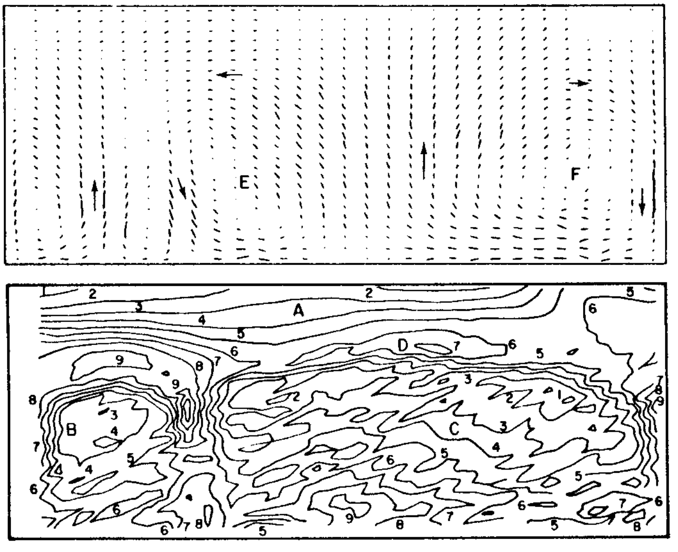

Figure 2. Velocity vectors and isopycnics. The density ranges from 2.03×10^{-7} to 6.07×10^{-7} g cm^{-3}. Contour values are evenly spaced.

https://doi.org/10.1017/S0252921100081677 Published online by Cambridge University Press

tex ring, a phenomenon seen in both granules. The centers of vorticity for granule C are labeled E and F.

Figure 3 shows the flow 13 s later. The larger granule has penetrated well into the optically thin layer. Vortex center F has risen slightly, but the rise of E has been inhibited by interaction with the smaller granule.

Figure 4 shows the flow 10 s later. Upflow has effectively ceased in the larger granule, and the cooled material at the top is descending as a pair of dense jets in the intergranular lanes H and I.

Figure 5 shows the flow after another 7.5 s. There is relatively little motion in the radiative zone A. The dense jets have dissipated, and the material in the original granule C has returned to a simple stratified configuration.

Figure 6 shows the solution 12.5 s later. A new granule has appeared, replacing the original granule C. The new granule begins entraining the smaller granule B. This quasi-periodic behavior was followed through the formation, buoyant rise, and dissipation of three granules.

All things considered, the agreement between the calculation and observations is quite good. The calculated granule has a diameter of 340 km, near the lower end of the observed range of 300 to 2000 km. The small calculated size is undoubtedly influenced by the small size of the computational mesh. Upflow velocities in the simulation are typically 1.5 km/s with a dispersion of ± 1.5 km/s, while observational values re-

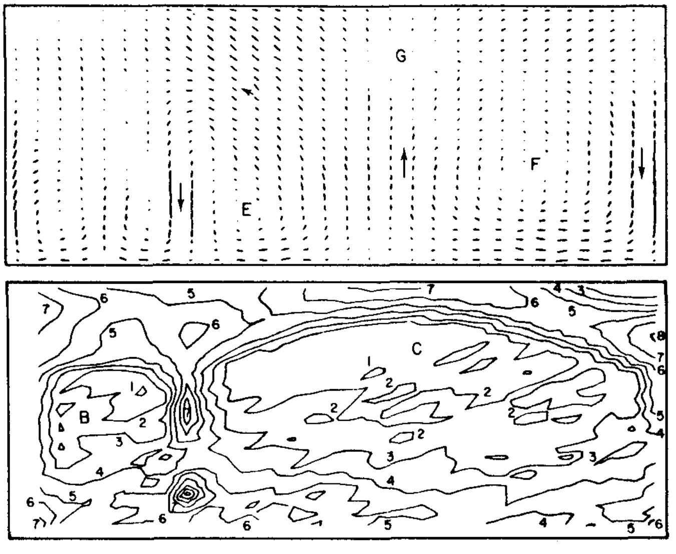

Figure 3. Velocity vectors and isopycnics 13.0 s after Figure 2. Density ranges from 2.15×10^{-7} to 7.42×10^{-7} g cm^{-3}.

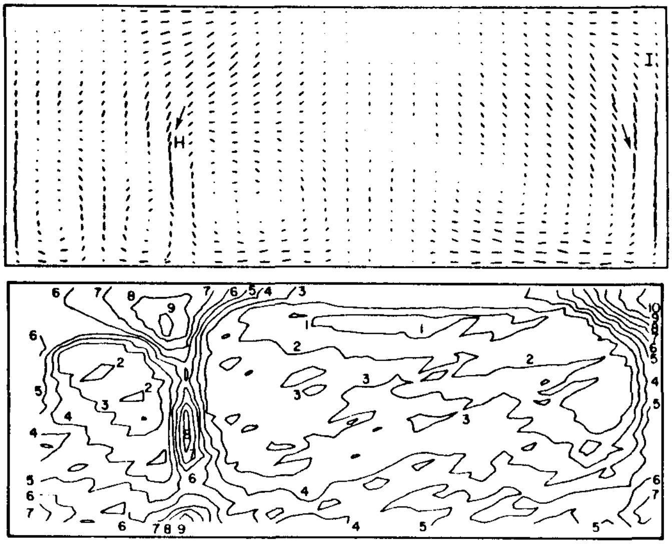

Figure 4. Velocity vectors and isopycnics 23.0 s after Figure 2. Density ranges from 2.11×10^{-7} to 7.55×10^{-7} g cm^{-3}.

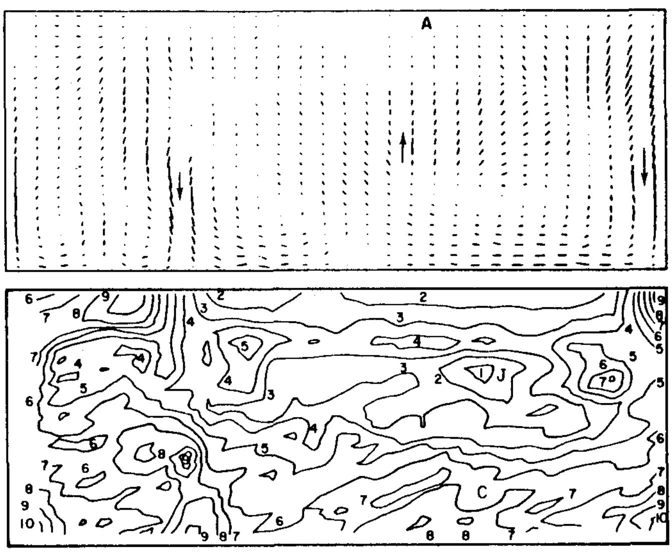

Figure 5. Velocity vectors and isopycnics 30.5 s after Figure 2. Density ranges from 1.52×10^{-7} to 6.82×10^{-7} g cm^{-3}.

ported by various authors range from 0.3 to 3.0 km/s. Here we see one complication in making the comparison: the observed values of upflow velocity are averaged over many granules, whereas my large eddy simulation produces individual granules. The computed center-to-edge temperature difference is 300 to 400 K. The observed average values range from 92 K to over 1000 K. The poorest agreement is for the granule lifetime.

https://doi.org/10.1017/S0252921100081677 Published online by Cambridge University Press

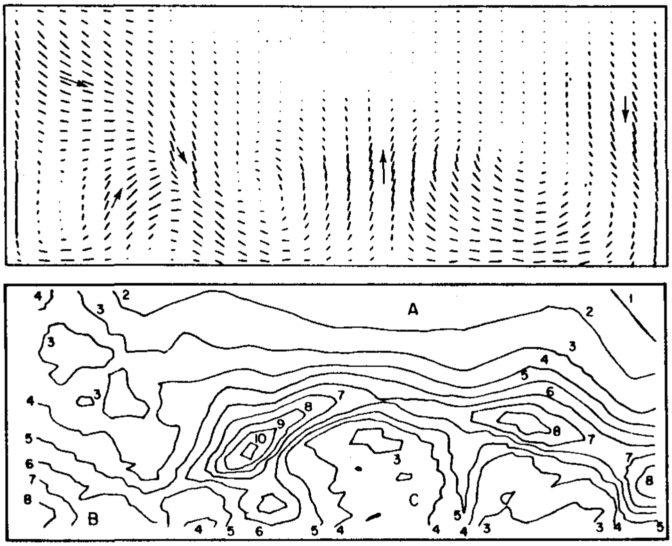

Figure 6. Velocity vectors and isopycnics 43.0 s after Figure 2. Density ranges from 4.9×10^{-8} to 1.011×10^{-6} g cm^{-3}.

The calculation is ambiguous, giving values of one minute and four minutes. The observed average is eight to ten minutes, although there is observational evidence that small granules have shorter lifetimes. The small depth of the mesh and truncation errors in the differencing of the radiation diffusion terms of the energy equation artificially decreased the computed lifetime.

The computed lifetime ambiguity was suggested by a marker particle movie of the numerical solution. New bubbles appeared every minute, splitting the one above it. However, the bubble created after four minutes was much more energetic than the previous ones. It is not clear which would appear to be the birth of a new granule when viewed from above at poor resolution. The calculated granule behavior could match any of the observed patterns. Most granules first appear as fragments of an old one. The calculated bubble splitting could easily have this appearance when viewed from the surface of the earth. Most granules die by splitting, fading, or merging with another granule, all of which were seen in the calculation. Cloutman (1979a) discusses these points in more detail.

A number of conclusions and implications may be drawn from this calculation. First, we may draw a physical picture of the mechanism of the granulation. It is a network of buoyantly rising bubbles/vortex rings produced near T = 8000 K. The vortex ring structure causes the upwelling of hot fluid in the center of each granule. Buoyant rise detaches each bubbles from its heat source, causing the finite lifetime. At most, one per cent of the hydrogen was ionized in any computational cell, so hydrogen ionization contributes at most ten per cent to the internal energy in any cell. The buoyant rise mechanism does not require hydrogen ionization as an energy source, but it does make the granules more energetic. The ionization is more important as an opacity source.

The observed range of diameters can also be explained. Bubbles smaller than 300 km radiatively cool in a matter of seconds, disappearing quickly if they ever form. The upper limit of 2000 km is imposed by geometrical effects. To be recognizable as a granule, the circular vortices must have radii less than the distance from optical depth 2/3 to T = 8000 K. Granules are integral scale features of the turbulent solar atmosphere. It is interesting that the thermal microscale is at the lower limit of granule diameters, not much smaller than the integral scale. The Kolmogorov (velocity) microscale is one centimeter, eight orders of magnitude smaller.

Linear and/or steady-state models have been notable for their lack of success in elucidating the physics of the granulation because it is both highly nonlinear and quasi-periodic. Discovery of the time-dependent buoyant rise of individual granules was crucial for understanding their dynamics. Multidimensional ensemble-averaged models (in contrast to large eddy simulations) are also suspect because the averaging procedure may suppress the buoyant rise or other time-dependent behavior of the mean flow, obscuring important physics.

Another implication is that the granulation is strictly a surface phenomenon, and therefore its use to calibrate phenomenological theories of convection cannot be justified. In particular, the fact that granules are approximately one pressure scale height in diameter is fortuitous and lends no support to the commonly-used specious arguments that turbulent eddies can be no larger than approximately one scale height. Nothing in the present calculation suggests any connection between scale heights and turbulence length scales.

A final implication suggested by this model requires the reader to ignore all the traditional beliefs about the supergranulation's origin. There is not one shred of firm evidence, either observational or theoretical, that supergranules are thermally-driven convection cells caused by some unknown agent (frequently speculated to be He ionization). The calculated granules lift material above them much as an elevator would. This suggests that the granulation behaves as a giant bubble plume, lifting a small net amount of matter over the entire surface of the sun. This matter eventually sinks back into the photosphere in the observed small downdrafts between supergranules. The flow is analogous to terrestrial rip currents, an idea developed in more detail by Cloutman (1979b).

References

Cloutman, L. D.: 1979a, Ap. J. 227, pp. 614-628.
Cloutman, L. D.: 1979b, Astron. Astrophys. 74, pp. L1-L3.
Paczynski, B.: 1969, Acta Astr. 19, pp. 1-22.

DISCUSSION

KEELEY: Did you do a calculation with no density inversion but with a substantially superadiabatic temperature gradient?

CLOUTMAN: Not a complete calculation. One of the very first things that happens in density inverted atmospheres is that it begins rising and destroys the inversion.

KEELEY: How can you distinguish between the Rayleigh-Taylor phenomenon and convection?

CLOUTMAN: In the calculation with an initial density inversion, the original motions are undoubtedly Rayleigh-Taylor. Later it is more a matter of heat being trapped and creating a bubble.

KEELEY: If you took a horizontal density average at some depth, would it still be inverted relative to the surface once the motions have developed?

CLOUTMAN: I have not yet done this calculation.

COLGATE: What is the density contrast which is related to the magnetic field concentration?

CLOUTMAN: There are density variations of a factor of two typically.

M. SMITH: If the driving for granulation is the high hydrogen opacity, perhaps the cooler stars would not have any overshooting and granulation as we see it on the sun. True or false?

CLOUTMAN: I would have to look at some cooler model atmospheres to answer that question.