Is Supergranulation on the Sun's Surface Convection?
J. S. Sands, M. P. Rast.

Significant Opportunities in Atmospheric Research and Science, High Altitude Observatory, National Center for Atmospheric Research, Boulder, CO, 80307-3000, U.S.A.

Abstract: We examined 177 supergranules to determine whether the temperature variations due to convection could be observed. Images in three wavelengths from the Precision Solar Photometric Telescope (PSPT) were used: Calcium K images, Blue continuum images and Red continuum images. Supergranules were identified in the Calcium K image. Since Calcium K is not an indicator of temperature, the Blue and Red continuum images of the same region were used to determine brightness variations within the supergranulation. The supergranule centers were found to be dimmer on average in the center and hotter towards the cell boundary unlike what one would expect from convection. The results of the supergranulation surrounded by active network are summarized separately from those surrounded by quiet network.

1. Introduction

Supergranulation is characterized by large-scale, horizontal flows in the chromosphere (Simon and Leighton, 1964). The lifetime of a supergranule is typically about one to one and a half days. Supergranulation cells measure between 20,000 km - 40,000 km. There are two ways to observe supergranulation. One method uses a Dopplergram of the Sun towards the limb of the disk. Supergranulation can also be observed as network in Calcium K images (Figure 1). Since another observed velocity flow on the Sun, granulation, was proven to be a convective phenomena (Richardson and Schwarzschild, 1950; Leighton, 1957) it was thought that supergranulation may be as well (Simon and Leighton, 1964). However, there has been some evidence supporting the idea that supergranulation is convection (Simon, 1966) and other evidence showing that it is not (Beckers, 1968; Frazier, 1970). Our motivation for this project was to find out whether or not, supergranulation is indeed convection.

2. Observations

The images came from the Precision Solar Photometric Telescope (PSPT) in Mauna Loa, Hawaii. The full-disk images are 2,048 x 2,048 pixels and they were taken at 393 nm (center of line Calcium II K), 409 nm (Blue continuum) and 607 nm (Red continuum). The algorithm of Kuhn et al. (1991) was used to 'flat-field' (correct variations in detector sensitivity) the images. Sixteen images of the Sun were taken from different parts of the detector and variations due to imperfections in the CCD detector were subtracted out. Limb darkening was also removed from the images as follows:

$$\frac{\delta I}{I_o} = \frac{(I - I_o)}{I_o},$$

where $I_o$ is the intensity of the quiet Sun as a function of distance from the center. Finally, the images at different wavelengths were aligned so that they exactly overlaid. We chose two images from the active region and one from the equator on two different dates. We sampled supergranules on two different dates from the areas shown in Figure 1 (the images were taken July 6, 1998 and December 21, 1998).
3. Technique

We first located the supergranules that were defined by the network in the **Calcium K** images (Figure 2). We applied a circular mask with different radius annuli until the best fit to the inner boundary of the supergranule was achieved. A Sobel filter was used to enhance the network boundary before making the fit. We selected only those supergranules which had a clearly defined dark center, a bright network and were generally small and circular (the average diameter we measured was 17.2 Mm). Supergranules are irregularly-shaped objects and some of the fits were poor. The poor fits to the supergranules were discarded. For example, there were a small number of supergranules which had a thin division through their centers, were very elongated, or had very incomplete network which were not used. When supergranules with highly active network compared to quieter network were found, a note was made to keep the data separate. Calcium K images were used only to locate the supergranules because it is a spectral line and a poor indicator of temperature. Therefore, we used images of Blue and Red continuum from identical regions of the Sun for intensity analysis. Images taken in continuum provide a direct relationship between intensity and temperature.

The centers of the supergranules located on the Calcium K images landed either in the center of a granule, in an intergranule lane or somewhere in between. Since the intensity variations due to granulation are much larger than those expected for supergranulation, these variations could easily obscure the signal we were searching for. To average out these fluctuations due to granulation and be left with the small underlying supergranule signature, many supergranules has to be sampled and appropriately averaged. 177 supergranules were sampled. After we located the supergranules, we determined the azimuthal average brightness as a function of distance from cell center to boundary using the continuum images. Azimuthal averages were found for equal area annuli. Each annulus had about 50 pixels. Since every supergranule we examined had a different radius, we had to stretch or shrink them to the same size before averaging them all together. We did this by normalizing the radii by the radius found during the identification procedure.

4. Results

Figure 3a. is a plot of the intensity of the supergranules in the Calcium K, Figure 3b. is a plot of the intensity in blue continuum, and Figure 3c. is a plot of the intensity in red continuum. On the y-axis is the fractional intensity as compared to the average value. On the x-axis is the radius from the cell center outwards (center of supergranule being zero and the boundary being one). The scatter is due to each of the 177 supergranules being plotted. The average intensity for each plot is denoted by the line that passes through the points. As one can see, the centers of the supergranules were dimmer on average than the boundaries in the Calcium K. This is also true of the Blue continuum image, the centers of the supergranules were dimmer on average than towards the boundary, thus, indicating that the centers are cooler than the boundaries (Refer to Figure 3b.). This was also evident in the Red continuum plot. The error bars as noted by the dotted line, indicate the standard deviation of the mean. We measured a 0.7% variation in intensity from center to edge in the blue continuum and a 0.45% variation in intensity in the red continuum with the standard deviation of the mean being about 0.1% in the blue and 0.05% in the red. The dimness that we observed in the plots is statistically significant because the error bars are not contributing to it. In plots of only the active network regions (Figure 4), and quiet network regions (Figure 5), the results to be drawn are the same: supergranules are dimmer in the center and brighter towards the network in all three wavelengths. We found the centers of the supergranules to be on average 6.5K
cooler than the network. Figure 6 shows the variation of temperature compared to the mean solar value ($\Delta T$) as a function of distance ($r$) from the supergranule center.

5. Concluding Remarks

We observed that surprisingly, supergranules on average appeared dimmer in the center and brighter towards the cell boundary. This is not a signature of convection. There are two interpretations that one can consider. First, perhaps supergranulation is not convection. One idea about what supergranulation might be, is as an analogy to rip currents in the ocean (Cloutman, 1979). Just as the pounding surf takes and pushes loads and loads of water towards shore, the water does not have enough pressure to overcome the surf and return back to sea. Instead, it gathers more and more fluid and travels horizontally along the shore in currents called rip currents until this pressure is able to be relieved once beyond the surf. In the Sun, granulation lifts material up repeatedly, and maybe gravity is not strong enough to tug the material back down. Instead the material gathers more and more fluid and begins to travel horizontally across the solar surface until the material has acquired enough force to overcome the upward granulation, and then finally plunges downward. The other possibility is that supergranulation is convection, however, something unknown is contributing to the intensity increase seen in the continuum. For example, in the network region we could be looking into deeper layers of the Sun through small magnetic flux tubes (Spruit, 1976) or perhaps magneto-acoustic gravity waves are causing excess heating in those regions.

Glossary

**Calcium K**: spectral line, network shows up extremely well in this wavelength. This spectral line is actually singly-ionized calcium and the K refers to nomenclature given by Fraunhofer

**convection**: form of heat transfer, requires fluid motion, hot fluid rises and cold fluid descends

**network**: small magnetic fields swept into supergranular boundaries by horizontal flows

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References

Figure 1. Image of supergranulation in calcium K from July 6, 1998 taken from the PSPT in Mauna Loa, Hawaii. See text for details.
Figure 2. Close-up of the northern hemisphere region that is outlined in Figure 1. that shows supergranulation in Calcium K. We used the bright network to identify the supergranules, and fit a subset of them with the adjustable circular mask in the lower left corner. Examples of some of our fits are superimposed on the image.
Figure 3. Normalized intensity variations in calcium K (a), blue continuum (b), and red continuum (c) as a function of normalized radial distance from the centers of the supergranules to the boundaries. 177 supergranule intensity variations are individually plotted here with the solid line indicating their average. See text for details.
Figure 4. Same as Figure 3 except that the results are for a subset of the supergranules that were located in the active network regions. 39 supergranule intensity variations are individually plotted here with the solid line indicating their average. See text for details.
Figure 5. Same as Figure 3 except that the results are for a subset of the supergranules that were located in the quiet network regions. 138 supergranule intensity variations are individually plotted here with the solid line indicating their average. See text for details.
Figure 6. Temperature fluctuations, compared to the mean quiet Sun value, as a function of distance from the supergranule center. See text for details.