SUPERGRANULATION AT THE CENTER OF THE DISK

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Abstract. The Kitt Peak multi-channel magnetograph was used to make raster scans of the supergranulation at the center of the disk. The scan pattern was arranged to largely cancel out the effects of the 5 min oscillations and the granulation and to enhance visible effects of the supergranulation.

The results show vertical supergranular motions. These motions consist of relatively isolated 'patches' of downward flowing material, or 'downdrafts', with an average speed of 0.1 km/s. These downdrafts coincide with patches of magnetic field, and the speed of the downdraft is linearly proportional to the magnetic field strength (50 to 100 G). These downdrafts are also regions of increased brightness in the chromosphere and photosphere.

1. The Observations

The multi-channel magnetograph at the Kitt Peak Solar telescope was used to observe the magnetic, velocity and brightness properties of the supergranulation at the center of the disk. This has been a difficult observation not only because the magnetic, doppler and brightness signals are very weak but also because the doppler and brightness signals are masked by the stronger effects of the granulation and the 5 min oscillations. The limited success of previous attempts to view the supergranulation vertically have left a gap in our observational knowledge of this phenomenon.

Sufficient sensitivity can be achieved by using a Babcock type magnetograph. The unwanted effects of the granulation and the oscillations can be effectively filtered out on the basis of their size and their time behavior by modifying the scanning procedure as follows:

(1) A 2.4 arc s entrance aperture was used, which 'smeared out' much of the granulation.

(2) Every point in the raster was observed twice, with a time interval of 150 s. The two values were later averaged, cancelling out the effects of the 5 min oscillations.

(3) The area was scanned repeatedly for four hours and the results again averaged, further reducing all short-lived effects and enhancing the long lived effects.

Since the data is in digital form, it can be fully processed by a computer and displayed in the form of digital 'photographs'. Figure 1 shows the photospheric magnetic field. The field is clearly broken up into isolated knots and attains surprisingly high field strengths (50 to 100 G). Figure 2 shows the Ca II K chromospheric network. This quiet region shows the same very high correlation between calcium emission and magnetic field that the active regions do. Figure 3 is the photospheric brightness network (as seen in the core of the Fe λ 5250.2 line). The photospheric network is sharper and even more highly correlated with magnetic field. The vertical velocities can be seen on Figure 4. Quite prominent are the downdrafts which coincide with the magnetic regions. With the possible exception of the Calcium emission there is almost no visible indication of a cellular structure.

Howard (ed.), Solar Magnetic Fields, 260–267. *All Rights Reserved.*

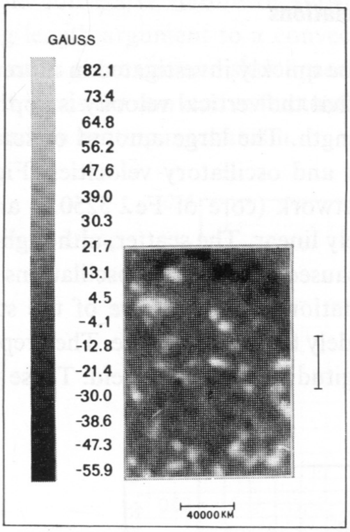

Fig. 1.

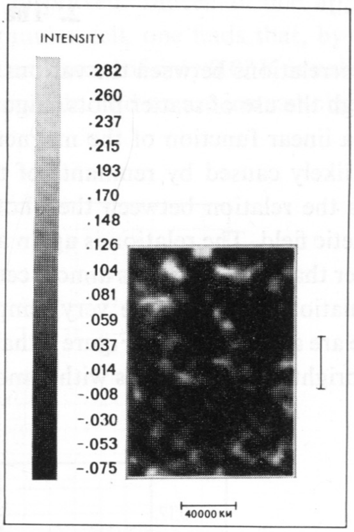

Fig. 2.

Fig. 1. Photographic representation of a magnetogram. North is at the top, west at the right. Magnetic field as measured in the wings of Fe λ 5233.0. Magnetic fields greater than +82.1 G or −55.9 G are present but are displayed as totally white or totally black, respectively, to allow a more effective scaling. This procedure is followed on all such magnetograms.

Fig. 2. The brightness field in the core of the Ca II K line. Intensity is expressed as $(I - \bar{I})/\bar{I}$.

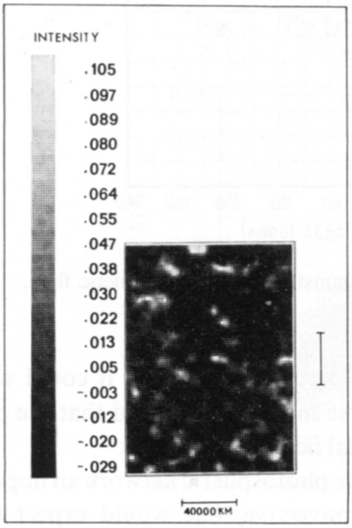

Fig. 3.

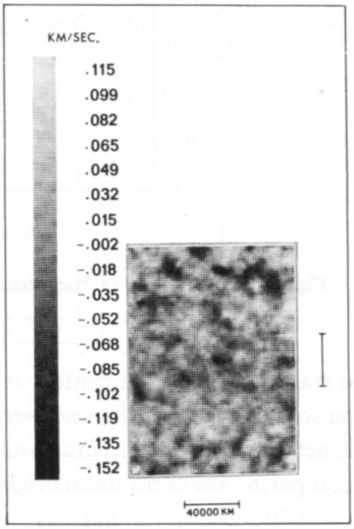

Fig. 4.

Fig. 3. The brightness field in the core of the Fe λ 5250.2 line. The bright patches are slightly sharper than those of Figure 2.

Fig. 4. Vertical velocity measured in the wing of Fe λ 5233.0. Positive velocities are rising.

2. The Cross Correlations

The correlations between the various arrays can be quickly investigated in more detail through the use of scatter plots. Figure 5 shows that the vertical velocity is approximately a linear function of the magnetic field strength. The large amount of scatter is most likely caused by remnants of the granular and oscillatory velocities. Figure 6 shows the relation between the photospheric network (core of Feλ 5250.2) and the magnetic field. The relation is again approximately linear. The scatter, although much smaller than in Figure 5, is almost certainly not caused by either the oscillations or the granulation. There is one very tempting explanation for the source of the scatter: There are a few points in Figure 6 that deviate widely from the average. They represent very bright network points with almost zero longitudinal magnetic field. These points can be traced back to the centers of very small bipolar regions. So it could well be that the scatter is due to the unobserved transverse magnetic field and that the photospheric network is a very accurate indicator of total field strength.

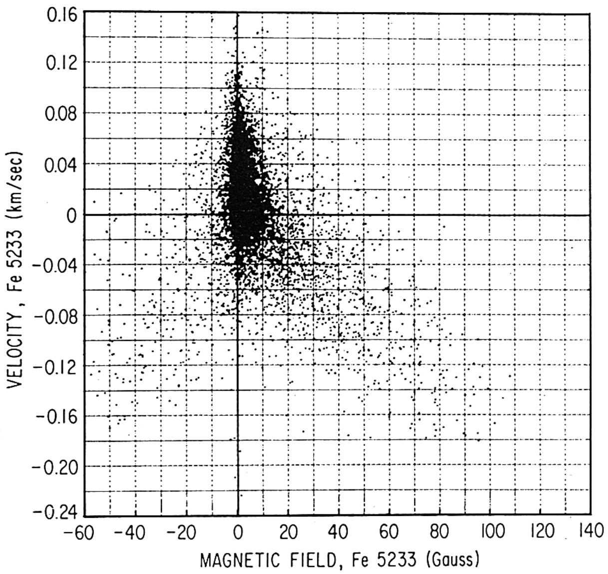

Fig. 5. Scatter plot of the vertical velocity against the vertical magnetic field.

By comparing the continuum brightness with the photospheric network an important result is achieved. If the supergranulation is convective, one would expect to see the continuum show a temperature excess at the center of the cells and a decrease at the edges (i.e. at the network points). Figure 7 shows that the observed effect is exactly the opposite of the expected: The supergranule boundaries are hotter (roughly 10K using $E=\sigma T^4$) than average. This should not however be construed to mean that the convective nature of supergranules is disproved. Indeed if one applies a mixing length argument to a convective supergranular cell, one finds that, by virtue of the cell's great size and slow speed, a temperature excess of only 0.03 K is needed to drive it. Thus the convective fluctuation is unobservable, and we are instead observing a secondary heating mechanism.

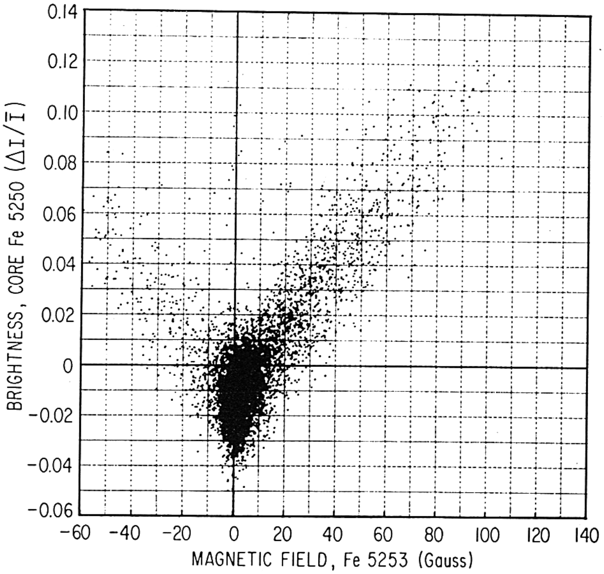

Fig. 6. The brightness-magnetic field relation.

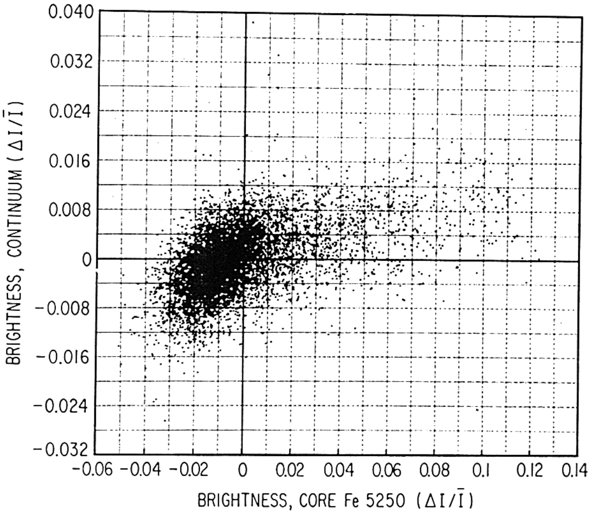

Fig. 7. The continuum brightness compared with the photospheric network. Bright points in the network are also bright in the continuum.

3. Morphology

We now examine the shape and structure of the 'cells', 'patches', 'network', 'knots' and 'downdrafts'. First, let us look quickly at those isolated individual features that may be called patches, clumps, knots, or downdrafts. 39 of them were identified in the field of view. The average profile of them is shown in Figure 8. The full width at half maximum is about 7000 km.

The much discussed supergranular 'cells' are best visible in the Calcium emission

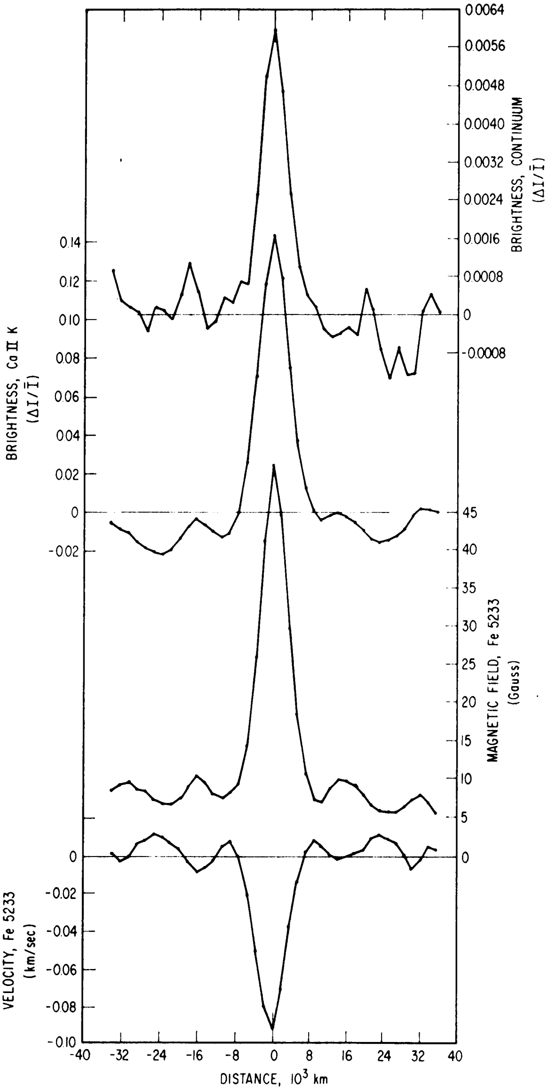

Fig. 8. Average downdraft profiles. Each profile is the average of scans taken in both the X and Y directions across the same 39 points in the raster.

(Figure 2). They are roughly 30000 km in diameter and are partially (sometimes completely) bounded by visible 'walls'. The bright patches are far more visible than the walls and generally lie at the vertices of three or more cells. One can easily identify the more prominent cells; the less prominent ones require much more judgement to define. I have defined 20 cells and computed average 'cell profiles'. This profile extends from one vertex across a cell to the most distant vertex (Figure 9). It is interesting that the velocity profile (the lowest curve) exhibits a strong difference with the classic case of stationary convection, the Bénard cell. In Bénard cells the

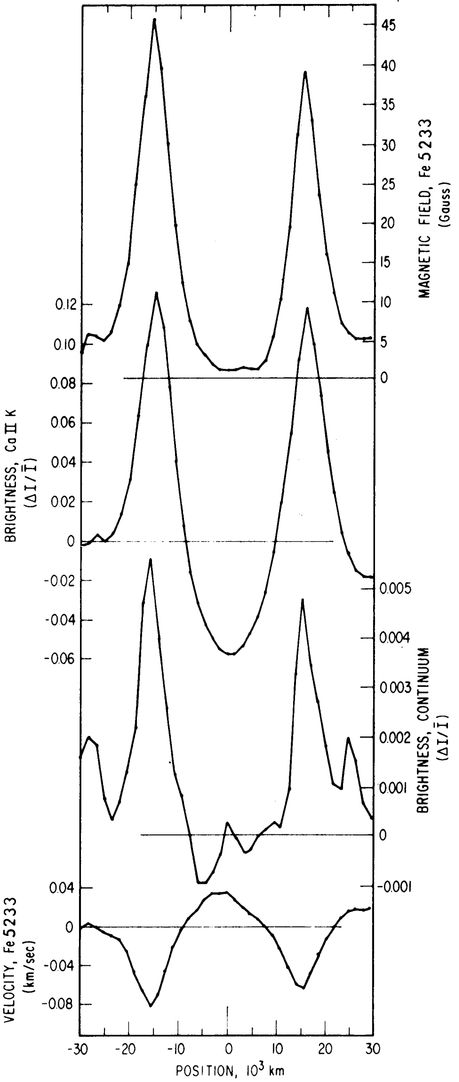

Fig. 9. Average supergranule profiles. Each profile is the average across the same 20 supergranular cells. The diameter of each cell was first normalized to be equal to the average diameter.

upflow at the center attains twice the amplitude as the downflow at the vertices, whereas almost the opposite is observed here. Evidently the magnetic field and/or stratification effects are exerting a strong influence on the flow pattern.

Note also that the magnetic profile has a very low and flat minimum in the center. If magnetic fields are being swept to the boundaries by the supergranular motions, then the process must be very efficient. However, the minimum is not at 0 G. In fact, a very careful inspection of the magnetic field array reveals a background component that is totally uncorrelated with the supergranulation. This background field has a strength of about ±5 G, with opposite polarities being quite common.

4. Conclusion

These results fill in most of the observational gaps in our knowledge of the supergranulation. The flow pattern of supergranulation is now completely known. The brightness network is now observed at all levels of the solar atmosphere, and the presence of magnetic fields and their high correlation with the flow pattern and the network is clearly established. However, some questions remain unanswered and at least one new question has been raised.

Is the supergranulation indeed a convective phenomenon? These observations could not answer this question. They are consistent with a convective hypothesis, but they indicate that the behavior is much more complicated than a simple stationary flow pattern.

What is the source of the secondary heating effect indicated by the presence of the bright network? Is it even a heating effect, or perhaps a density condensation? Heating could be caused by the dissipation of Alfvén waves via collisions between ions and neutral atoms. The downflowing material will also have an effect.

Perhaps the most important of all the results is the surprisingly high magnetic field strength at the vertices. Previously the magnetic field strength was thought to be only a few gauss. This implies that $\beta \gg 1$ and that the gas flow dominates the magnetic field. Now, with field strengths of 100 G common, $\beta \ll 1$ and the role of the magnetic field becomes very important. This makes magnetohydrodynamic models of supergranulation extremely difficult, but I believe that if we are to fully understand this phenomenon, such models will be necessary.

Discussion

Kuperus: Did you find both polarities concentrated in small areas along the boundary of the supergranulation network?

Frazier: There was a reversal of polarity (more accurately a small bipolar region) at only 3 out of 39 supergranular vertices. I suspect that this low frequency is just a result of the fact that I happened to observe a region that was primarily unipolar. There could well be large quiet regions where the polarities are much more mixed.

Kuperus: Could you give a typical dimension of these areas over which you find the magnetic field reversal?

Frazier: About 8000 to 10000 km.

Simon, G. W.: Two comments: First, it is not surprising to find field strengths of 50 G at supergranule boundaries; in fact, since supergranules are formed in the convection zone where equipartition energies are much higher than in the photosphere where the observations are made, I would expect to find fields of several hundred gauss at the boundaries. Second, theoretical incompressible fluid convection models show down drafts at boundary vertices with larger velocities than the central up drafts, so your observations of the velocity distributions are in good agreement with what one would expect, if the results of the incompressible fluid theory can be applied to the case of the solar atmosphere.

Frazier: Answer to comment #1. If one makes the assumption that has usually been made, that is that the magnetic volume force is negligible, and that $B^2/8\pi = \frac{1}{2}\varrho v^2$, then one must apply this equality at all levels. This means that although the magnetic field might be very strong in the convection zone, it would still decrease rapidly with height and be very small at the photospheric levels. One must still investigate the magnetic volume force to see if it can maintain a field strength greater than equipartition of energy would imply.

Answer to comment #2. I was using a very crude model of convection, namely Bénard cells. as my reference. If a more sophisticated model exists which reproduces the observed assymmetry, then I would be very happy to see it.

Deubner: Do you have a feeling for a time scale of the weak background fields, whether these could possibly be as long as e.g. the supergranules, or only for intermediate periods between the granular and supergranular lifetimes?

Frazier: I observed one raster scan per hour for four hours, so neither my time resolution nor my time span was adequate to answer this question well. Most of the background fields did not change at all throughout the four hours. A few showed detectable changes within a few hours and in two cases, very weak bipolar regions evolved abruptly in less than one hour (one appeared and the other disappeared). This question certainly deserves further observations.

Weiss: I would like to comment on Dr. Frazier's remark that fields concentrated by subphotospheric convection should decrease rapidly with height. If the field is concentrated at about 2000 km depth into regions with a similar scale, then the photospheric field intensity need not be too drastically reduced and surface fields of several hundred gauss might be expected.

Frazier: Again, I would say that this cannot be done without the magnetic volume force. If it indeed can be done with the use of this term, then I would feel very gratified.