Long-lived Giant Cells Detected at the Solar Surface

J.G. Beck[‡], T.L. Duvall Jr.[†] & P. H. Scherrer[‡]

‡ W. W. Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA 94305-4085 USA

† Laboratory for Astronomy and Solar Physics, NASA/Goddard Space Flight Center, Greenbelt, MD 20771 USA

30 years ago it was first predicted[1] that giant convection cells should exist in the sun. These cells would span the entire zone unstable to convective motions, now known to cover the outer 29% of the radius.[2] The traditional mixing length model of this zone,[3] has convection cells extending over a pressure scale height, which is much thinner than the entire zone. The exciting prospect of detecting directly flow from deep within the sun stimulated a number of observational studies which, however, have failed to detect such cells,[4–6] although some studies[7–10] hint they exist. In the present work, we detect at the solar surface, at the rather small velocity of 3.6 m/s, cells living for several months with size 40-50 degrees of longitude and <10 degrees of latitude. This rather large aspect ratio, >4, is unexpected from most theories (although not all[11]). 505 days of continuous, very stable dopplergrams from the SOI/MDI instrument on the SOHO satellite made possible this significant observational advance.

Only smaller scales of convection have been definitely seen at the surface: the 2 Mm (Megameter) granulation with velocities of 1 km/sec and lifetime 10 minutes,[12] the 5 Mm mesogranulation[13] and the 30 Mm supergranulation[14] with velocities of 0.5 km/s and lifetime of 1 day, all much smaller than the 210 Mm depth of the convective zone. The size of granulation is related to the scale height of the atmosphere just below the surface.[12] This is the only scale of convection that would appear at the surface according to the mixing length theory.

Previous observations show that any giant cell signal must have less than 10 m/s velocity.[15] To see such a small signal amidst the cacophony of smaller scale, higher velocity signals requires careful observations and analysis. Continuous coverage and a very stable observing platform are crucial. To this end, we decided to study the giant cell question using dopplergrams from the SOI/MDI instrument.[16] The raw dopplergrams have 1024x1024 pixels covering the projected disk of the sun and are observed every minute with the primary objective being helioseismic studies. For the present study, we used dopplergrams to measure directly the flow of material at the surface. Unfortunately, the telemetry used to transmit the full resolution dopplergrams to the ground is only available part of the time. However, low resolution averages of the dopplergrams are computed each minute on board and later transmitted to earth. For the present study, dopplergrams averaged into 140 bins covering most of the solar disk have been analysed for the period May 1996 to December 1997. One of these bins near the disk center covers 10 degrees of longitude and 10 degrees of latitude, increasing to 14 degrees of longitude near the edge. We have been able to use data covering 97% of the time interval.

A more detailed description of the data reduction will be published elsewhere, so just a brief discussion is presented here. The per-minute bin means are averaged over the 1440 minutes in a day, leaving one set of 140 bins for each of 505 days to be analysed. To enable further analysis, some removal of extraneous signals is done: 1) the relative velocity of the spacecraft and each bin is subtracted, 2) 4 discontinuities in the velocity signal caused by adjustments to the instrument setup are corrected by addition of a constant after the adjustment, 3) some spurious spikes are removed, 4) a large slow drift of the velocity signal is removed by fitting a 7-th order polynomial in time to the result of the previous steps. Most of the variance of the resultant signals is from horizontal motion, probably supergranulation. This can be seen from the root-mean-square (rms) signal varying from 2.5 m/s near the center of the solar image to 10.2 m/s near the edge, where we are more sensitive to horizontal motions.

To separate out the short-lived signals we calculated the temporal autocorrelation function (Fig. 1) for three bins at 5 ± 5 deg latitude and 46 ± 7 deg, 60 ± 7 deg, and 74 ± 7 deg longitude away from the disk center. The peaks in this function at multiples of the solar rotation period of 27 days clearly demonstrate the existence of long-lived features. The decay in the height of this peak suggests a lifetime of four months for the causative signals. The height of the first peak at 27 days shows that 0.2 of the variance repeats after this interval, or an rms signal of 3.6 m/s. The full width at half maximum of the peak near 27 days of 3.3 days suggests that the size of the features is (3.3 days) x (13.3 deg/day), or 44 deg in longitude, where 13.3 deg/day is the solar rotation frequency at this latitude. Clear signatures of long-lived features have been detected in this way in the latitude range ± 30 deg.

In a previous giant cell search,[17] spurious Doppler shifts from sunspot regions masqueraded as a long-lived signal. A characteristic of such a signal is that it would appear symmetric on the east and west sides of the solar disk. A true giant cell signal would likely have a component that is antisymmetric across the center of the disk. That is, a horizontal motion towards the west would show blue shift when seen on the east side of the image and later when it rotated to the west side it would show a red shift. To look for this component, we calculated the cross correlations of the signal from bins of the previous paragraph with counterparts on the west side of the central meridian (Fig. 2). It takes approximately 7 days for a feature to rotate from one bin to the other. So if there is a long-lived east-west horizontal motion, it will reveal itself in Fig. 2 by a negative correlation near 7 days, and then also at 7+27, 7+54, etc. This is just what we see in Fig. 2, confirming that what we have are long-lived, giant features. Such distinctive signatures have been seen in the latitude range ± 30 deg.

To remove the effect of short-lived noise we derived weighted averages of the data from all longitudes with the same central latitude to isolate the signal antisymmetric across the central meridian. The weight used is the sine of the longitude with respect to the central meridian and the data from the different longitudes is shifted in time before averaging to account for the solar rotation. By averaging the signals for a full disk passage, short lifetime signals should be reduced in amplitude considerably. The resultant map is shown in Fig. 3. Features repeating at the time interval of one solar rotation are evident. An autocorrelation of the same latitude band (5 ± 5 deg) as Fig. 2 is shown in Fig. 4. The amplitude of the long-lived component is clearly larger, the effect of averaging over several lifetimes of the shorter-lived supergranular signal.

A two-dimensional autocorrelation of the region between ± 30 deg of latitude shows a significant feature at 27 days. This feature has a full width at half maximum in the latitudinal direction of 10 deg. But 10 deg is about the size of our samples in latitude so we conclude that we have not resolved the latitude extent of the features and that they have an aspect ratio > 4. This is perhaps the most surprising result of this analysis. Some theories predict exactly the opposite,[18] that cells would be elongated in latitude and look like "bananas".

In the future, we need to resolve the latitude size of the cells, which hopefully can be done using higher resolution averages of the raw dopplergrams (0.6deg bin size) that are transmitted to earth each minute. Do these cells extend to the bottom of the convective zone, as originally predicted[1]? This question may be addressed using the technique of time-distance helioseismology, which has recently uncovered subsurface flows.[19–21]

Correspondence and requests for materials to J. Beck at jbeck@solar.stanford.edu.

References

1. Simon, G. W. & Weiss, N. O., Supergranules and the Hydrogen Convection Zone, *Zeitschrift für Astrophysik* **69**, 435-450 (1968).

2. Christensen-Dalsgaard, J., Gough, D. O. & Thompson, M. J., The Depth of the Solar Convection Zone, *Astrophys. J.* **378**, 413-437 (1991).

3. Chan, K. L., Nordlund, Å, Steffen, M., & Stein, R. F., Recent Development in Solar Convection Theory, *Solar Interior and Atmosphere*, ed. A. N. Cox, W. C. Livingston, & M. S. Matthews, Univ. of Arizona Press, 223-274 (1991).

4. LaBonte, B. J., Howard, R., & Gilman, P. A., An Improved Search for Large-scale Convection Cells in the Solar Atmosphere, *Astrophys. J.* **250**, 796-798 (1981).

5. Snodgrass, H. B. & Howard, R., Limits on Photospheric Doppler Signatures for Solar Giant Cells, *Astrophys. J.* **284**, 848-855 (1984).

6. Chiang, W.-H., Petro, L. D., & Foukal, P. V., A Photometric Search for Solar Giant Convection Cells, *Solar Physics* **110**, 129-138 (1987).

7. Cram, L. E., Durney, B. R., & Guenther, D. B., Preliminary Observations of Velocity Fields at the Solar Poles, *Astrophys. J.* **267**, 442-454 (1983).

8. Hathaway, D. H. *et al.*, GONG Observations of Solar Surface Flows, *Science* **272**, 1306-1309 (1996).

9. Simon, G. W. & Strous, L. H., Supergranular Evolution, Solar Rotation, and a Search for Giant Cells, *Bulletin AAS* **29**, 1402 (1997).

10. Ulrich, R. K., Large Scale Convection and the Solar Radius, *in Proc. of IAU Symp. 185: New Eyes to See Inside the Sun and Stars*, ed. F.–L. Deubner, J. Christensen-Dalsgaard, & D. W. Kurtz, Kluwer, 1998 (in press).

11. Snodgrass, H. B. & Wilson, P. R., Solar Torsional Oscillations as a Signature of Giant Cells, *Nature* **328**, 696-699 (1987).

12. Bray, R.J., Loughhead, R. E., & Durrant, C. J., *The Solar Granulation*, 2nd edition, Cambridge Univ. Press (1984).

13. November, L. J., Toomre, J., Gebbie, K. B., & Simon, G. W., The Detection of Mesogranulation on the Sun, *Astrophys. J.* **245**, L123-L126 (1981).

14. Leighton, R., Simon, G., & Noyes, R., Velocity Fields in the Solar Atmosphere: Preliminary Report, *Astrophys. J.* **135**, 474-499 (1962).

15. Brown, T. M. & Gilman, P. A., Techniques for Detecting Giant Cells Using Spatially Resolved Solar Velocity Data, *Astrophys. J.* **286**, 804-809 (1984).

16. Scherrer, P. H. *et al.*, The Solar Oscillations Investigation – Michelson Doppler Imager, *Solar Physics* **162**, 129-188 (1995).

17. Scherrer, P. H., Bogart, R., J. T. Hoeksema, & Yoshimura, H., The Detection of Global Convective Wave Flows on the Sun, *in Seismology of the Sun and Distant Stars*, ed. D. O. Gough, Reidel, 93-102 (1986).

18. Gilman, P. A., Nonlinear Boussinesq Convective Model for Large Scale Solar Circulations, *Solar Physics* **27**, 3-26 (1972).

19. Duvall, T. L. Jr., D'Silva, S., Jefferies, S. M., & Harvey, J. W., Downflow Under Sunspots Detected by Helioseismic Tomography, *Nature* **379**, 235-237 (1996).

20. Kosovichev, A. G., Tomographic Imaging of the Sun's Interior, *Astrophys. J.* **461**, L55-L57 (1996).

21. Giles, P. M. *et al.*, A Subsurface Flow of Material from the Sun's Equator to its Poles, *Nature* **390**, 52-54 (1997).

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Figure 1: The autocorrelation of the time series for three bins at latitude 5 ± 5 deg. The slowly-decaying features near the solar rotation period of 27 days, 54 days, 81 days and 108 days demonstrate the presence of long-lived structures rotating with the sun. The correlation coefficient of ≈ 0.2 near 27 days indicates that 20% of the variance is correlated after this period and 80% is not. The uncorrelated 80% is thought to arise from short-lived smaller convection cells.

Figure 2: The cross correlation of the time series for bins on the east side of the solar disk with bins on the west side at the same latitude of 5 ± 5 deg. The bin pairs for each correlation are separated by 100 deg of longitude and so a feature at one bin on the east side of the disk will rotate to the bin on the west side in 7 days. A flow feature with a positive sense of doppler shift on the east side will be seen as a negative feature 7 days later on the west side. So we conclude that the negative features in the correlation at 7 days, 7+27 days, 7+54 days, 7+81 days, 7+108 days are clear indications of long-lived horizontal flow features.

Figure 3: Maps of the east-west component of flow speed obtained by averaging over a disk passage. A white signal corresponds to flow in the direction of solar rotation. Solar latitude is shown on the left scale. Time is on the horizontal axis with the first half of the 505 days covered in the top image and the second half in the image below. The range of dates covered is shown in the lower corners of the images. The small black boxes along the bottom of the images are separated by the rotation period defined by Carrington of 27.2753 days. About half the variance in these images is due to the long-lived structures and the other half of the variance is caused by shorter-lived smaller-scale supergranules.

Figure 4: The autocorrelation computed for the map of Fig. 3 for the latitude $5 \pm 5\,\mathrm{deg}$. The signals at multiples of the solar rotation period have higher amplitudes, as more of the short-lived noise has been averaged out. Also shown is an exponential fit to the peak amplitude. The fit falls to e^{-1} of its original value in 126 days.