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THE DETECTION OF MESOGRANULATION ON THE SUN

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ABSTRACT

Time averages of velocity measurements at disk center on the quiet Sun reveal the presence of a fairly stationary pattern of cellular flow with a spatial scale of 5–10 Mm. Such mesogranulation has a spatial rms vertical velocity amplitude of about 60 ms^{-1} superposed on the larger scale supergranular flows. The lifetimes of mesogranules appear to be at least 2 hr.
Subject headings: Sun atmospheric motions — Sun: granulation

I. INTRODUCTION

One of the striking properties of the observed convective motions on the Sun is the discrete spectrum of their horizontal scales. Granules have scales of order 1 Mm (10^3 km), supergranules of order 30 Mm, and giant cells may be of order 150 Mm or greater. Although the cellular patterns of both granulation and supergranulation show a range of sizes, their characteristic scales differ by a factor of 30. The existence of giant cells is much less certain, being inferred mainly from magnetic field patterns and possible variations in differential rotation.

We report here recent observations of steady vertical velocity that show strong evidence for yet another scale of convective motion, intermediate between granulation and supergranulation. Time-averaged Doppler measurements made at disk center with the Sacramento Peak Observatory (SPO) diode array instrument reveal a fairly uniform pattern of motion that alternates in sign on a spatial scale of 5–10 Mm and persists for at least 2 hr. These structures, which we have called mesogranules, correlate well between velocity images in a photospheric Fe I line and a chromospheric Mg I line formed just above the temperature minimum.

The results presented here for mesogranulation were obtained in the course of a program of coordinated ground-based and *OSO 8* satellite observations aimed at determining the height dependence of the large-scale steady flows associated with supergranulation (November 1979; November *et al.* 1979). The traditional view of supergranulation in the photosphere is that it is a cellular motion dominated by horizontal velocities with amplitudes of about 1000 ms^{-1}. Extensive searches for systematic cellular flow at disk center have been largely inconclusive: Distinct sites of downflow of order 50–100 ms^{-1} have been identified, many of which correlate strongly with regions of enhanced magnetic fields; upflow is generally more elusive or below the limit of detection (Simon and Leighton 1964; Tanenbaum *et al.* 1969; Frazier 1970; Musman and Rust 1970; Deubner 1971; Worden and Simon 1976). The difficulty in measuring the large-scale, low-amplitude vertical flows associated with supergranulation is that they overlap in both time and space with the granulation and 5 minute oscillations, which have amplitudes about an order of magnitude larger. Our observations of vertical velocity, time averaged over 60 minute periods, show clear evidence of flows on a supergranular scale as well as revealing for the first time the presence of mesogranulation.

II. OBSERVATIONS

The SPO diode array operates at the exit slit of the echelle spectrograph attached to the vacuum tower telescope (Dunn, Rust, and Spence 1974; Rust and Bridges 1975). For our observations at disk center, the array is divided into seven strings of 64 diodes with 1″ spacing arranged parallel to the slit. Pairs of diode strings are located in the magnetically insensitive Fe I λ5434 and Mg I λ5173 spectral lines: for the Fe I line, the strings are centered at $\lambda_0 \pm 0.095$ Å with 0.075 Å masks; for Mg I, they are at ± 0.066 Å with 0.090 Å masks. The Fe I line allows us to measure Doppler velocities in the lower photosphere (Altrock *et al.* 1975), while the Mg I line is representative of the temperature minimum region (Altrock and Canfield 1974). Sites of enhanced magnetic field in the photosphere are identified from a third pair of diode strings located on the magnetically sensitive Fe I λ8468 line. The remaining string of diodes is used to map the chromospheric emission network in the center of Ca II λ8542.

Two-dimensional intensity, velocity, and magnetic

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images are obtained in these lines by spatially scanning the solar image across the spectrograph slit. One complete raster covers a nominal area at disk center of 200″ × 270″ with 1″ spatial resolution. Such rasters are repeated every 85 s. Our data base comprises about 18 hr of observations over 5 days. The determination of the instantaneous velocities at each spatial position, together with the instrumental errors in our measurements, is discussed in November *et al.* (1979). We believe the present observations represent an improvement over earlier SPO diode array measurements in two respects: First, we have improved the stability of the spectrograph using newly developed algorithms to correct for drifts in sensitivity of individual diodes (November and Simon 1981). Second, we have stabilized the telescope guiding and corrected for residual image displacements by making suitable spatial shifts. The persistent motions are then determined by time averaging the velocity data. In the absence of any absolute spectral standard, we take the zero of our velocity scale to be the spatial average of the steady velocities over the entire image.

Our observing raster has been chosen to sample an area including about 30 supergranule cells and to do so with a repeat time rapid enough to resolve any oscillatory or nonsteady motions that possess substantial power. Thus in addition to the persistent flows obtained by time-averaging the data, we are able to determine the power in the time-varying motions by taking Fourier transforms. This permits us to estimate the residual oscillatory velocities present in averages formed over finite intervals in time.

III. RESULTS

Figure 1*a* (Plate L3) shows a Ca II λ8542 intensity picture and Figure 1*b* the corresponding Mg I λ5173 velocity average. The region shown is a 60″ × 160″ section of the larger raster located at disk center on the quiet Sun. Each picture represents a 60 minute time average of 42 rasters with 1″ × 1″ spatial resolution. The same velocity data are again shown in Figure 1*c*, smoothed here by a 3″ × 3″ running mean in order to suppress the residual noise. These observations on 1978 June 12 yield structures and flow amplitudes typical of those obtained on the other 4 days.

In the Ca II intensity picture (Fig. 1*a*) light areas delineate regions of enhanced network emission; for the velocity averages, we use the convention that light areas indicate downflow, dark areas upflow. Here one can see that isolated sites of large-amplitude downflow coincide with specific Ca II bright features, in agreement with previous observations. Such features are known to be associated with high magnetic field strengths. In addition, these images show that broad regions of general downflow tend to correlate with the Ca II network as a whole, while those of upflow occur more often in the cell interiors (non-network regions). In order to emphasize this correlation, we increase the spatial averaging width to 9″ × 9″ and show the resulting image in Figure 1*d*. Such an average serves to isolate the larger scale supergranular patterns, which may then be readily compared with the Ca II emission network. This is probably the first clear evidence of a vertical flow structure in accord with the view of supergranulation as convective cellular motion.

Superposed on the supergranular velocities in Figures 1*b* and 1*c* is a smaller scale pattern of steady flow that appears to be quite uniform over network regions and cell interiors alike, with no apparent counterpart in the Ca II intensity features. In order to distinguish these motions from the larger scale flows, we subtract the supergranular image shown in Figure 1*d* from the original velocity image in Figure 1*b*. The resulting mesogranular patterns are displayed with 1″ × 1″ spatial resolution in Figure 1*e* and smoothed to 3″ × 3″ in Figure 1*f*. These flows are space filling and apparently cellular in structure, the regions of up- and downflow being about equal in area. While the mesogranular velocity pattern is strikingly apparent in Figure 1*f*, detailed comparison of the images in Figures 1*e* and 1*f* shows that the 3″ × 3″ averaging does not change the inherent character of the flow pattern. We recognize that the sense of the velocities is somewhat uncertain, for we have defined the zero of the velocity scale to be the spatial average of our velocity image. However, the dynamic range in the amplitudes of the mesogranular motions is about $\pm 150\ \mathrm{m\,s^{-1}}$, the spatial rms amplitude being about $60\ \mathrm{m\,s^{-1}}$ compared with $40\ \mathrm{m\,s^{-1}}$ for the larger scale supergranular flows.

In order to determine the lifetimes of the mesogranular features, we have taken various means of the data obtained in several 6 hr observing runs. These suggest that the same pattern of cellular motion can be clearly identified for periods of about 2 hr, after which the evolution becomes increasingly evident. Spatial autocorrelation analysis of the supergranular image in Figure 1*d* yields a correlation scale of about 30 Mm based on the location of the secondary peak. Similar analysis of Figure 1*e* shows a representative scale for mesogranulation of about 7 Mm. Two-dimensional spatial Fourier transforms of the mesogranular velocity field indicate that the primary power lies in the 5–10 Mm range of horizontal scales. A Mg I intensity picture, corresponding to the velocity image in Figure 1*f*, shows a low-contrast pattern of light and dark features with the same range of scales.

We believe this to be the first report of a persistent two-dimensional velocity field intermediate in scale between granulation and supergranulation. Some motions of similar scale have been reported previously and may in retrospect be found to be related to mesogranulation. Power spectra of one-dimensional velocity measurements in C I were presented by Deubner (1977), who attributed a peak at 4 Mm to a possible clustering of granules. Cannon and Wilson (1970) had earlier found velocity variations on a scale of 6 Mm in Mg I spectrograms, though they made no attempt to separate out what should be significant contributions from 5 minute oscillations.

The results presented here depend strongly on how well we have canceled out the effects of oscillations and granulation in determining the persistent velocities.

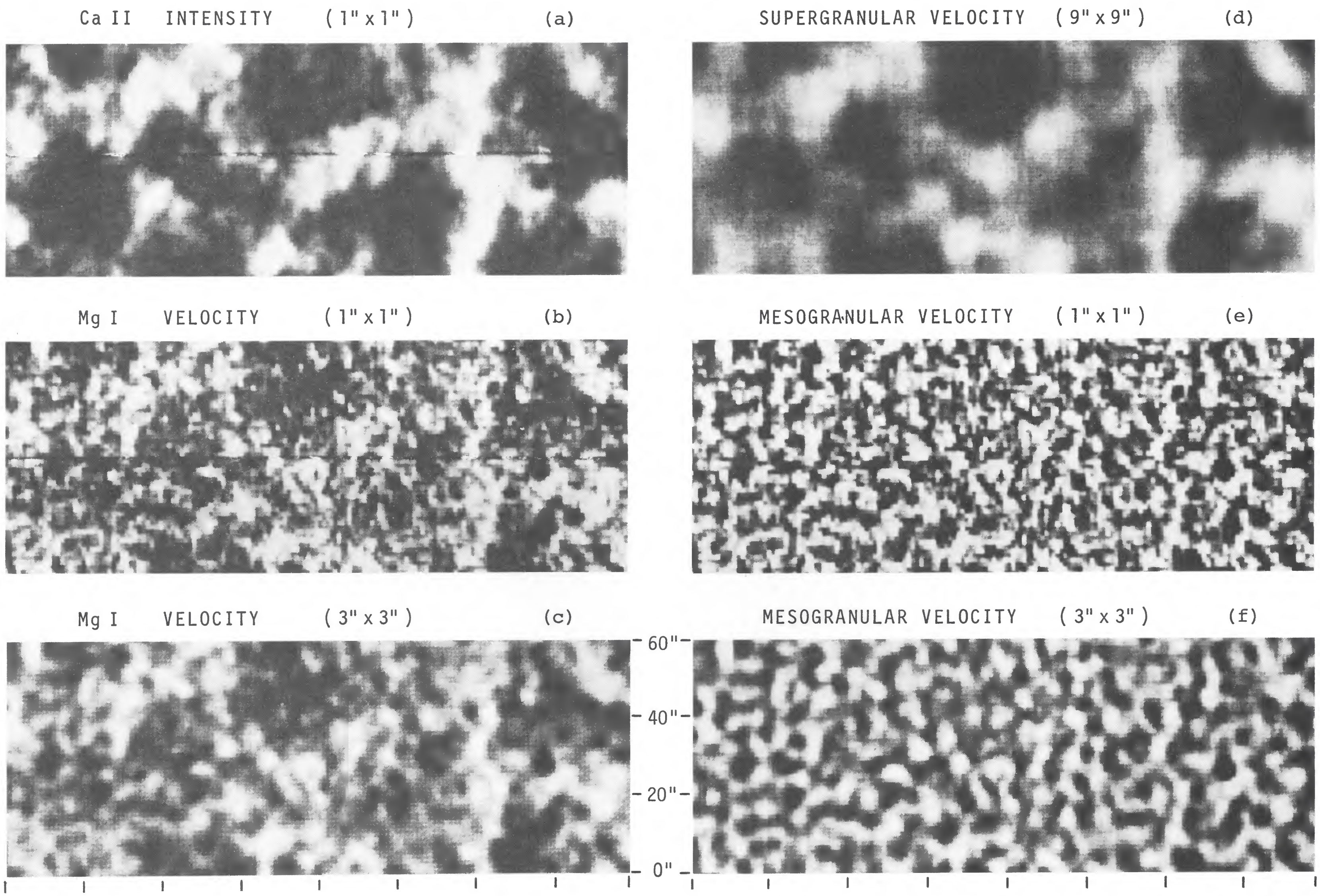

FIG. 1.—Supergranulation and mesogranulation as determined from observations time averaged over a 60 minute period on 1978 June 12. The images show a 60″ × 160″ section of the larger raster at disk center on the quiet Sun. The network of enhanced Ca II emission appears as bright regions in (*a*). The corresponding Mg I velocity image is shown with 1″ × 1″ spatial resolution in (*b*) and with 3″ × 3″ resolution in (*c*). Here light areas indicate relative downflow, dark areas upflow. The same velocity data, spatially averaged by a 9″ × 9″ running mean, are shown in (*d*) so that the larger supergranular patterns of steady flow may be compared with the Ca II emission in (*a*). The supergranular image in (*d*) is then subtracted from the original velocity map in (*b*) to reveal the cellular patterns of mesogranulation shown in (*d*) with 1″ × 1″ resolution. The mesogranular flow is more readily apparent with the 3″ × 3″ resolution in (*f*).

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The 5 minute oscillations have typical rms vertical velocities of about 400 ms^{-1} in Fe I and about 600 ms^{-1} in Mg I (e.g., Keil and Canfield 1978), and they show substantial power at frequencies between 2.5 mHz (400 s) and 5 mHz (200 s) (Deubner, Ulrich, and Rhodes 1979). Given this broad band of frequencies, a Doppler sum (the average of two velocity measurements made 150 s apart) does not necessarily cancel the oscillatory signal but may instead reduce it by only a factor of 2. Since the oscillations are spatially resolved by our 1″ sampling, their residual velocity signals can be determined from power spectra in time or by ascertaining how the spatial rms velocities decrease with the number of rasters averaged. We find that the residual oscillatory signal in our 60 minute time averages is typically 12 ms^{-1} in Fe I and 8 ms^{-1} in Mg I. Such a signal is comparable to our estimated detector errors.

The effects of granulation on the velocity signal are more difficult to estimate, as our 1″ sampling element does not spatially resolve the granular motions. Since the bright portions of the granular cells are ascending, the average position of the line is blueshifted (cf. Beckers and Nelson 1978). The amplitude of this shift varies from one raster element to another owing to differences both in the vigor of the individual granules and in their packing geometry. We estimate that the fluctuations about the mean blueshift have rms amplitudes of about 10 ms^{-1} in our 60 minute time-averaged Fe I velocity maps. Since the granular motions appear to decay rapidly with height (e.g., Keil 1976), their effect on our time-averaged Mg I observations should be negligible. It is for this reason that we emphasize the Mg I results here.

Why have mesogranular scale motions not been detected in previous studies of supergranulation? We believe that our two-dimensional observations at disk center are the first to be made with sufficiently frequent time sampling and sufficiently long time averaging to reveal these intermediate scale flows. By taking care to estimate the granular and oscillatory components in our time-averaged velocity maps, we are able to extend such averages until these residuals fall substantially below the signal from the more persistent, steady motions. This procedure enables us to measure the large-scale, low-amplitude vertical flows associated with supergranulation. The simple ploy of subtracting out these larger scale motions then serves to reveal the underlying pattern of mesogranular flow, which persists for several hours.

IV. DISCUSSION

What might be the origin of the mesogranulation? The preliminary evidence suggests to us that mesogranulation may be the result of convective overshooting into the stable atmosphere: the mesogranules have a cellular appearance, and their fairly uniform distribution over the supergranular cells implies that they are not magnetically controlled. Such convective overshooting could be driven in either of two ways: (*a*) These 5–10 Mm motions may be the "missing" scale of solar convection. It is reasonable to suppose that the discrete scales of granulation and supergranulation arise in some fashion from the discrete depths at which H and He are ionized (Simon and Leighton 1964). The ionization of H occurs at a depth of about 2 Mm and may produce the 1 Mm horizontal scale of granulation. Similarly, the second ionization of He at a depth of 20 Mm may contribute to the 30 Mm scale of supergranulation. Finally, the giant cells of global scale would reflect the overall 150 Mm or so depth of the convection zone. What has always been missing from such a scenario is a scale of cellular motion arising from the first ionization of He at a depth of 7 Mm. Thus it is tempting to conjecture that He^{+} serves to drive these intermediate scales of convective motion. (*b*) Alternatively, the mesogranules may just be higher spatial harmonics of the primary supergranule cell. The presence of some harmonic structures may be expected on the basis of simplified numerical experiments with convection (Spiegel, Toomre, and Gough 1981). However, such overtones could well exhibit time variations shorter than those of the primary cell: thus a determination of mesogranular lifetimes alone will not necessarily serve to discriminate between these two possible explanations. Nor do theoretical models presently exist to help in making such a discrimination.

Further observations are required to clarify the general properties of mesogranulation. So far we know that these flows as seen at disk center persist for at least 2 hr. In order to establish statistics for their actual lifetimes and evolution, we are presently analyzing four sets of disk-center data recently obtained with the SPO diode array, each spanning at least six continuous hours. Additional observations were carried out near the limb in an attempt to identify the horizontal component of mesogranulation. The topology of the mesogranules must still be sorted out. We appear to see distinct sites of both ascending and descending velocities superposed on the larger-scale supergranular flows; whether these are plumes surrounded by torus-shaped regions of return flow remains to be determined. If mesogranulation is indeed related to convection, then knowing the manner in which the motions close in the atmosphere may help us to deduce its driving mechanism.

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