# VELOCITIES OBSERVED IN SUPERGRANULES

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**Abstract.** The evolution of the velocity and magnetic fields associated with supergranulation has been investigated using the Sacramento Peak Observatory Diode Array Magnetograph. The observations consist of time sequences of simultaneous velocity, magnetic field, and chromospheric network measurements. From these data it appears that the supergranular velocity cells have lifetimes in excess of 30 h. Magnetic field motions associated with supergranulation were infrequent and seem to be accompanied by changes in the velocity field. More prevalent was the slow dissipation and diffusion of stationary flux points. These observations suggest that surface motions do not exhibit the detailed flux redistribution expected in the random-walk diffusion of magnetic fields. It is suggested that the surface motions are only the reflection of magnetic field-convective motion interactions which occur deeper in the convection zone.

## 1. Introduction

Following Leighton *et al.* (1962) the term 'supergranulation' refers only to a horizontal velocity phenomenon within the solar photosphere. Any study involving descriptive parameters, such as lifetimes and sizes, must consequently deal with the velocities directly. The development of fast photoelectric magnetographs makes it possible to study the supergranular velocity flow, rather than secondary effects such as the location of chromospheric emission regions. Several questions concerning supergranulation can therefore be investigated.

Supergranulation has been interpreted as a convective flow pattern (Simon and Leighton, 1964; Leighton, 1964, 1969; Simon and Weiss, 1968) and consequently used in discussions of convective theory. An important parameter in these discussions is the lifetime of the convective 'supergranular cell', since convective theory can provide estimates of the velocity and temperature structure within a convection cell if the lifetime is known. Several studies of supergranular lifetimes have been undertaken. In the studies of Simon and Leighton (1964) and Rogers (1970) the chromospheric emission network as observed in strong absorption lines was used to define supergranular boundaries. Lifetimes close to 24 h were obtained in this indirect manner. However, detailed studies of magnetic field elements by Smithson (1973) revealed that these elements do not change significantly in their positions over periods of approximately 36 h. If magnetic field elements delineate supergranular boundaries as presumed (Simon and Leighton, 1964) this observation would lead to supergranular lifetime estimates somewhat longer than 24 h. Additional evidence for this hypothesis is provided from Livingston and Orrall's (1964) observation of long-lived magnetic features with supergranular appearance. These 'cells' had lifetimes of 3–5 days and occurred within active regions.

Smithson (1973) suggested that the shorter lifetime derived from emission network studies was misleading due to the manner in which it was derived. Lifetimes in the previous studies were derived from mathematical cross-correlations. However, since the emission network is a 'thin' system defining only cell boundaries, and not the cell itself, small changes in the shape of a cell will cause a large decrease in

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cross-correlation coefficients. This may produce a spuriously short lifetime compared to the real lifetime of the velocity cell. For this reason supergranule lifetimes are more appropriately derived from measurements of the horizontal velocity flow which extend over virtually the entire cell.

Supergranule cell lifetimes are important for another reason. Leighton (1964, 1969) in his theory of the solar activity cycle used supergranular flows to disperse magnetic fields over the solar surface in a random-walk process. However, if the supergranule lifetimes are significantly longer than 24 h as discussed by Smithson (1973), the motions due to supergranular flow are too small to provide for the observed magnetic field dispersal. Moreover, field motions have never been correlated with any material motions, supergranular or any other. Smithson (1973) observed an occasional rapid movement of magnetic flux elements; however, the frequency of these occurrences is insufficient to explain observed changes in the magnetic field pattern. His data appear more consistent with the total disappearance of magnetic field elements. Clearly it is important to determine whether the rapid movement and disappearance of magnetic elements is associated with changes in the velocity flow.

In order to determine mass flow rates within the supergranule, knowledge of the vertical velocity field is needed. Simon and Leighton (1964), Frazier (1970), Deubner (1972), and Musman and Rust (1970) have reported vertical flows associated with supergranulation. However, only the vertical downdrafts associated with magnetic field elements appear well confirmed. A corresponding vertical upflow in cell centers has not yet been shown convincingly. Accurate photoelectric velocity observations are needed to investigate these questions.

This paper reports a time series of observations including simultaneous magnetic, velocity, and emission network information obtained with the Sacramento Peak Observatory Diode Array Magnetograph (Dunn *et al.*, 1974). The results of this study will be discussed in light of the problems mentioned above.

Our use of the strongly magnetically sensitive line Fe I 8468 Å presented difficulties in observing velocities in magnetic regions (this problem has recently been discussed by Frazier (1974)). Recent observations of magnetic field strengths by Harvey and Hall (1974) in the infrared indicate solar magnetic fields may be as strong as 2000 G. At such high field strengths Fe I 8468 Å becomes Zeeman split to such a degree that the components are completely separated and serious errors occur in the velocity measurements. Consequently, a group of magnetically insensitive lines ($g = 0$) were also used to obtain velocity observations. These lines were chosen to represent a range of heights within the solar atmosphere. Data concerning these lines are presented in Table I.

## 2. Analysis and Results

Leighton *et al.* (1962) reported a vertical oscillatory velocity in the photosphere with a period about 300 s and with an amplitude of approximately 0.5 km s$^{-1}$. This phenomenon is of similar velocity amplitude to the supergranular field. As it constitutes an interference to direct observation of the non-oscillatory flow pattern of supergranules it is necessary to remove the 300-sec oscillations from these observations. This was accomplished by averaging together the signals from a sequence of individual scans (each taking 48 seconds of time) over one or more 300-sec periods.

The digital nature of the two-dimensional data made it possible to use two-dimensional Fourier analysis. A two-dimensional Fast Fourier Transform (FFT) computer algorithm was written for this purpose. Since Fourier transforms have the property of separating in frequency space information on differing size scales they are ideal for supergranular studies. The various velocity phenomena, granulation, supergranulation, and 300-sec oscillations have well-defined and different size scales so the information on each of these velocity fields is separated within the frequency space of the Fourier transform. Thus to isolate supergranular effects the data are transformed and all frequencies representing size scales significantly smaller than supergranular flow (30 000 km) are removed; then the transform is inverted producing a filtered picture. However, these filtered pictures suffer from the disadvantage that small scale effects which may be associated with supergranulation, such as the downflows at cell boundaries, may also be removed. In conjunction with conventional means of analysis, such as cinematography of the time sequences obtained, the lifetime of the supergranular velocity flow, the transport of magnetic field, and the vertical velocity structure of the supergranule were studied.

## The Lifetime of Supergranulation

Several sequences of observations covered roughly 10 h each on a single region. While this time was less than the presumed lifetimes (20–40 h) changes in some supergranules within the observed area may be expected. The data from 1974, March 5 covered $9\frac{1}{2}$ h at radius vector $\rho = 0.6$. During that run the seeing remained consistently good, so the March 5 data were chosen for detailed analysis.

A movie was made from the original data. The only processing in addition to magnetic and velocity reductions involved time averaging to remove the 300-sec oscillation effects. Each frame in the movie consisted of one 288-sec average of six 48-sec observations. The movie gives the impression that few changes occurred in the supergranular flow pattern during the 9-hour observation period. However, granular velocities were strong and interfered with the definition of supergranular cells. Additionally, when the seeing became slightly variable, as in the late afternoon, leakage of the 300-sec oscillation was present due to the inconsistent seeing during the 288-sec average. These problems were reduced using the two-dimensional Fourier filtering scheme described earlier to remove granulation and 300-sec leakage. Figure 1 shows the unfiltered data and corresponding filtered data. Each frame consists of an average over four 300-sec oscillations (20 min) or 24 observations. These observations cover nine hours on 1974, March 5. Averages over periods longer than 20 min were impractical due to imperfect guiding in the telescope.

From the time sequence in Figure 1 the impression of minimal change in the supergranular pattern derived from the movies is strengthened. Over the 9 h covered by the data a significant change can be observed in only one of the approximately 9

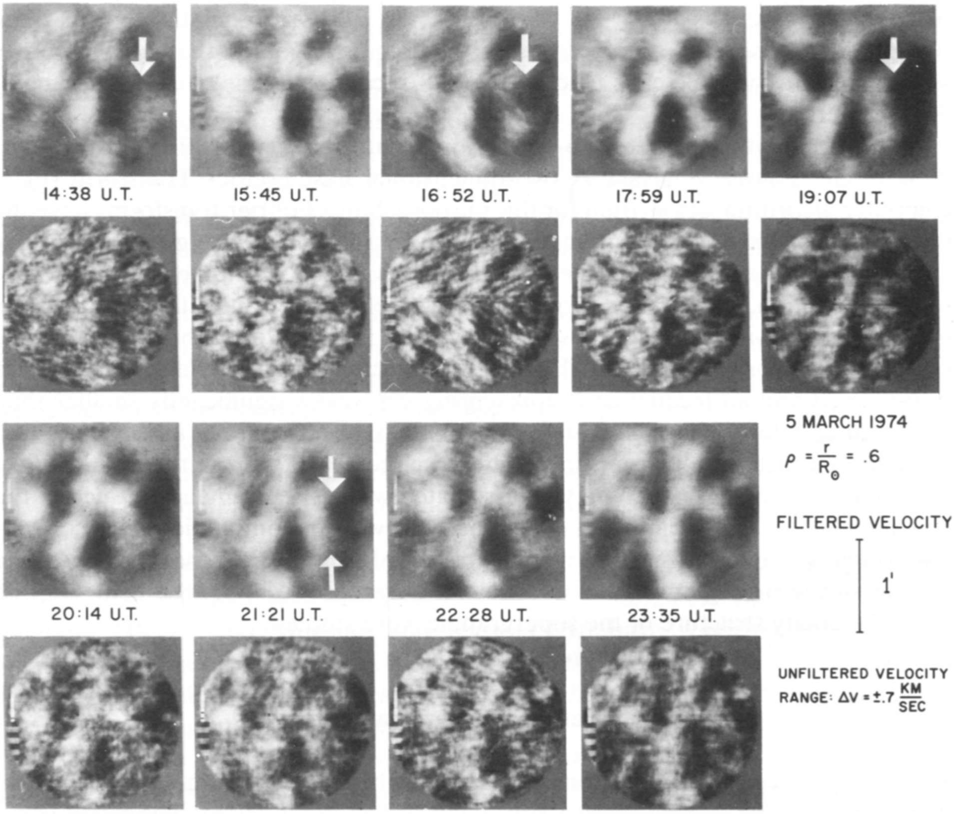


Fig. 1. All day filtered and unfiltered velocity observations for 1974, March 5.

supergranules present. In the early frames the supergranular flow in the right central part of the picture appears weak; however, later in the day the flow has strengthened. Similar behavior was observed in the data of 1974, March 11 and 1974, March 16; however, only 1–2 supergranules in the region under observation appeared to change significantly in the course of the day's observations. The relatively infrequent changes observed are inconsistent with a mean lifetime of approximately 24 h. If the lifetimes were that short, roughly 1/3 or 3–4 supergranules per day, could be expected to change dramatically in an area covering 9–10 supergranules.

The lifetime of the supergranular flow can be derived from the two-dimensional cross-correlation function. This function is given by:

$$XC(\Delta x, \Delta y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y) g(x + \Delta x, y + \Delta y)\, \mathrm{d}x\, \mathrm{d}y$$

$$= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} F(u, v) G^*(u, v)\, e^{i2\pi(u\Delta x + v\Delta y)}\, \mathrm{d}u\, \mathrm{d}v\,. \quad (1)$$

The latter function is the inverse Fourier transform of the cross product of the Fourier transforms of the data fields $f$ and $g$ under study, and $\Delta x$ and $\Delta y$ are the shifts in $x$ and $y$ of the two data arrays, $f$ and $g$, relative to one another. The cross-correlation coefficient at zero shift ($\Delta x = 0$; $\Delta y = 0$) is a measure of differences between two sets of data when they are perfectly matched, as such it can be used to derive lifetimes of structures present in time series of data. The mean lifetime is defined as the time needed for the cross-correlation function to fall to $1/e$ of its original value at zero $\Delta x$ and $\Delta y$ shifts (Simon and Leighton, 1964). The two-dimensional FFT program was used to calculate these functions for the velocity data of 1974, March 5 shown in Figure 1. The results for zero spatial lag ($\Delta x = 0$, $\Delta y = 0$) are independent of signals due to granular velocity structure, since the first data for which cross-correlations were computed are separated by 1 h in time, during which the granular pattern should have completely changed. The correlation fell to 0.7 of its maximum after 9 h. A least squares fit to these points gave a slope of $0.017 \pm 0.009$ yielding a tentative mean lifetime of $36^{+70}_{-12}$ h. To verify this longer lifetime, data covering several days are required. These have been obtained at Sacramento Peak in the last two months and are being analyzed. However, the results discussed in this paper already suggest that velocity cells have lifetimes in excess of the 24-hour value derived from emission network studies.

## 3. Horizontal Transport of Magnetic Field Associated with Supergranulation

Several of the longer data runs showed evidence of magnetic field motions. Just as for the velocity data, casual inspection of the movies leaves the impression of relative inactivity; however, an occasional horizontal motion of magnetic flux points occurred. As with Smithson's (1973) observations these motions were of several forms. The most frequent form of motion appeared to be a slow ($<1$ km s$^{-1}$) motion of existing flux points in which part of the relatively stationary flux point splits off from the magnetic element and moves away. Figure 2 shows an example of this phenomenon. In most cases the moving flux-element moved less than 5000 km and then dissipated. In a few cases of larger velocity (0.5 km s$^{-1} < v < 1$ km s$^{-1}$) the daughter flux point moved 5000–10 000 km and remained visible for the remainder of the day.

A more dramatic form of magnetic field motion was associated with the emergence of new flux. In the few cases of this behavior, new flux emerged and moved rapidly (1-2 km s$^{-1}$) for a distance of 5–10 000 km. In the three single-day observations available no more than one, or in one case, two of these events occurred. Additionally, they always appeared in regions where changes in the velocity flow were underway. One such example is present in the data of 1974, March 5. As mentioned previously a velocity cell was observed to change during the day in the right central portion of Figure 1. During this period a small flux point appeared and rapidly moved to the boundary of the developing supergranule. Figure 3 shows this motion. Associated with this phenomenon changes in the chromospheric emission network occurred. In Figure 3 the $\lambda$ 8542 intensity data for 1974, March 5 are also displayed to show these changes. In the data from early in that day the emission network in the region where the velocity cell changes appears chaotic. Later, when the velocity flow

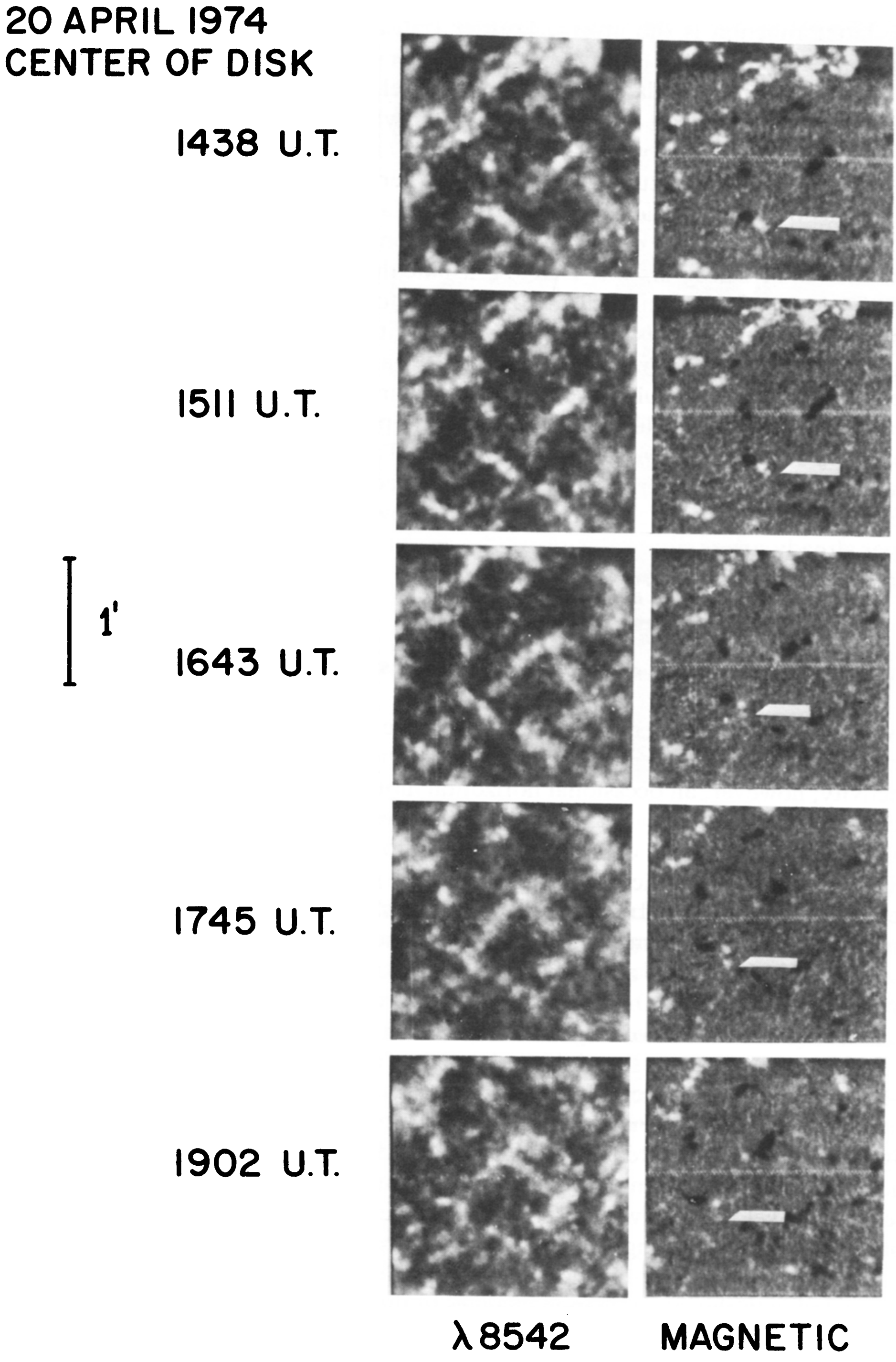


Fig. 2. Example of slow form of flux motion: splitting of existing flux.

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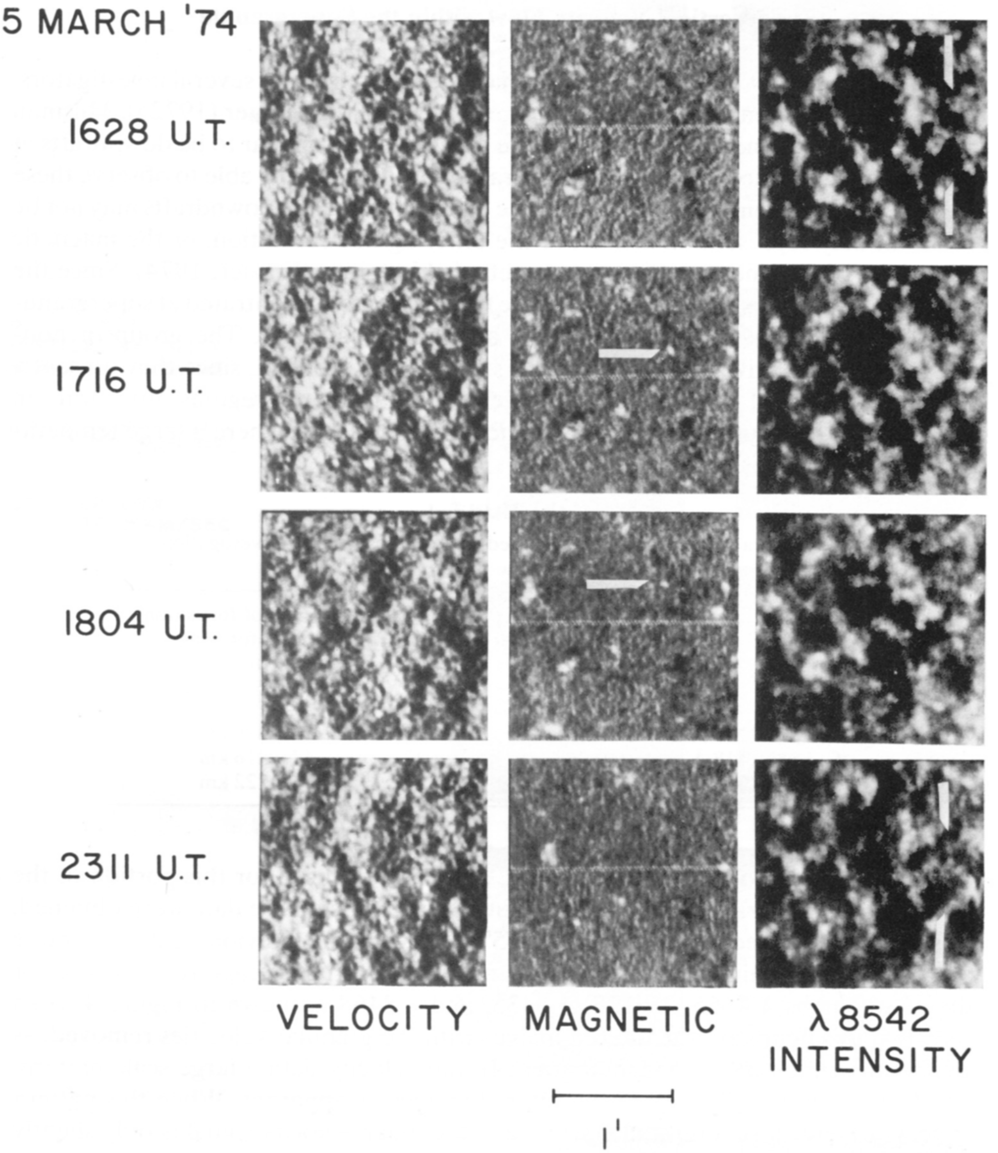


Fig. 3. Example of fast form of flux motion: the appearance of new flux. The frame from 23 11 UT is shifted slightly to the right relative to the other three frames.

has strengthened, the emission network has arranged itself into a well-defined network 'cell'. During this period the emission network showed rapid and frequent disappearances, motions, and reappearances. Similar behavior was observed in other cases of cell development from the data on different days. In all three of these cases the cell strengthening may well represent the formation of a new supergranule cell.

## 4. Vertical Velocity Flow within the Supergranule

Vertical velocities within supergranules have been reported by several investigators. Simon and Leighton (1964), Tannenbaum *et al.* (1969), Deubner (1972a), Musman and Rust (1970), and Frazier (1970) have detected what appear to be downdrafts at supergranular vertices. However since Frazier (1970) was only able to observe these downdrafts in certain lines there exists the possibility that the downdrafts may not be real, but may represent an artifact of the differing line formation, or the magnetic sensitivity of the lines used in the magnetic field regions (Frazier, 1974). Since the observed downflows occur only within the flux elements concentrated at supergranular boundaries this latter suggestion is a distinct possibility. The group of non-magnetically sensitive lines is ideal for a study of this problem, since they present a range of heights of formation, from levels where magnetic regions differ little in temperature structure from non-magnetic regions to levels where a large temperature differential exists.

TABLE I

Data for non-magnetic lines used in the vertical velocity investigation

| Line | Spectrograph dispersion (Å $mm^{-1}$) | Order | Range of formation heights for wings of the line (Altrock *et al.*, 1975) |
|---|---|---|---|
| Fe I 5123.730 Å | 10.507 | 45 | $-51 \rightarrow 286$ km |
| Fe I 5434.418 Å | 9.368 | 42 | $-47 \rightarrow 316$ km |
| Fe I 4065.388 Å | 12.314 | 56 | $-57 \rightarrow 122$ km |

The disk center observations of 1974, July 16 were used for this portion of the study. During several hours of the morning during which these data were obtained, the seeing remained excellent (1 to 1.5″). As with the previous data 24 frame averages over 20 min were computed. A resulting 20-min average velocity map for the wavelengths λ 4065, λ 5123, λ 5435, and λ 8468 is shown in Figure 4. Also shown in this figure are the filtered images with the granular velocities removed, as well as the simultaneous magnetogram. In the velocity data a large scale pattern, which shows especially well in the filtered images, is apparent. While this pattern appears to have a supergranular size scale, the mean velocity signal is only slightly higher than the noise level. Several methods were used to sort out the true nature of this pattern, which does not appear to correlate well with the magnetic field structure.

To determine whether this pattern is related to the long-lived supergranular flow, observations obtained 20 min later during the same run were compared with the earlier data to see if the same velocity structures remained. While a similar large scale velocity pattern was evident, detailed agreement was only partial. Consequently other methods were attempted to study these results.

As mentioned previously, magnetic field elements have been observed to define the vertices of the horizontal supergranule pattern (Simon and Leighton, 1964). A comparison was therefore made between the magnetic field and velocity

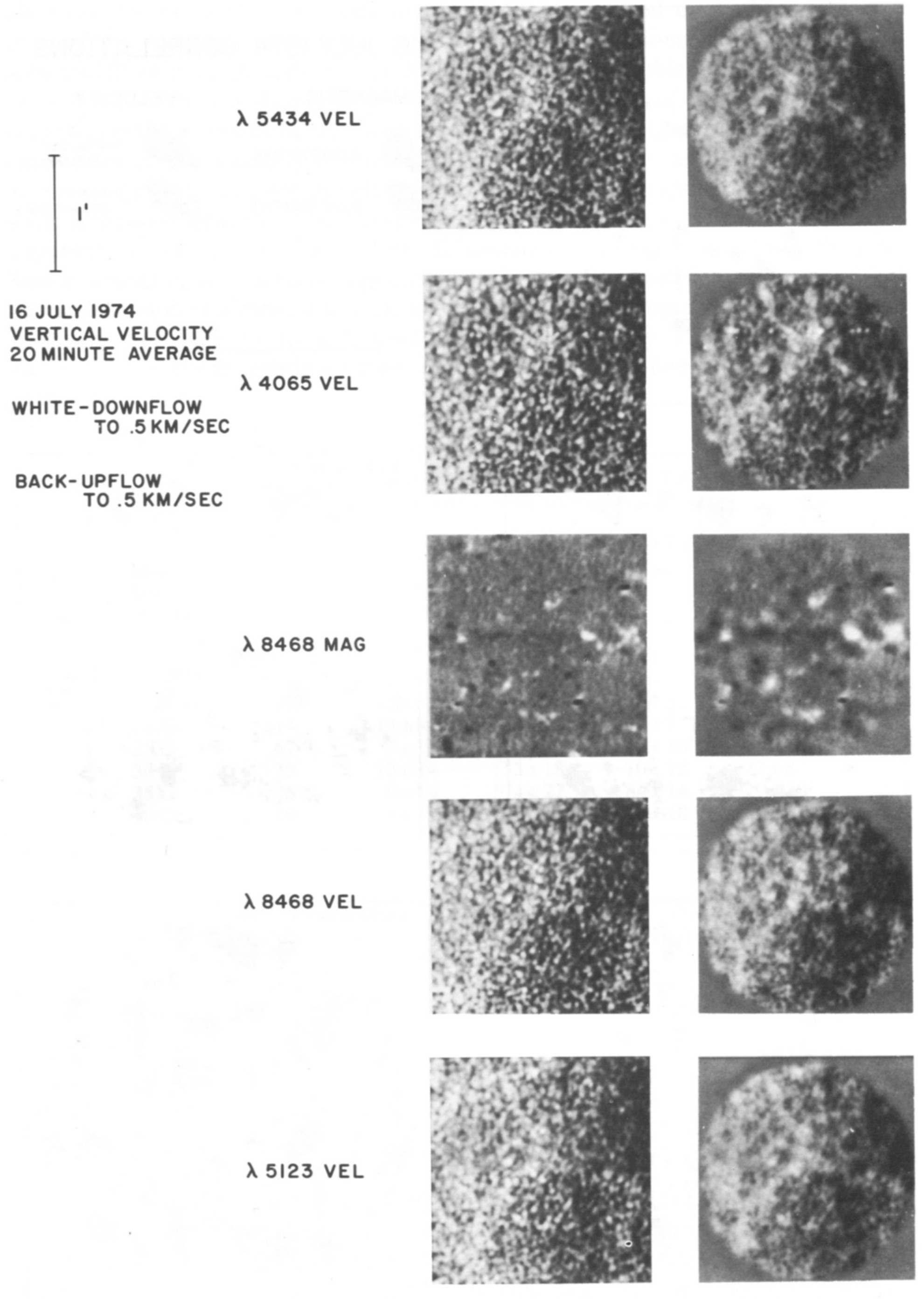


Fig. 4. Filtered and unfiltered velocities in different lines from 1974, July 16.

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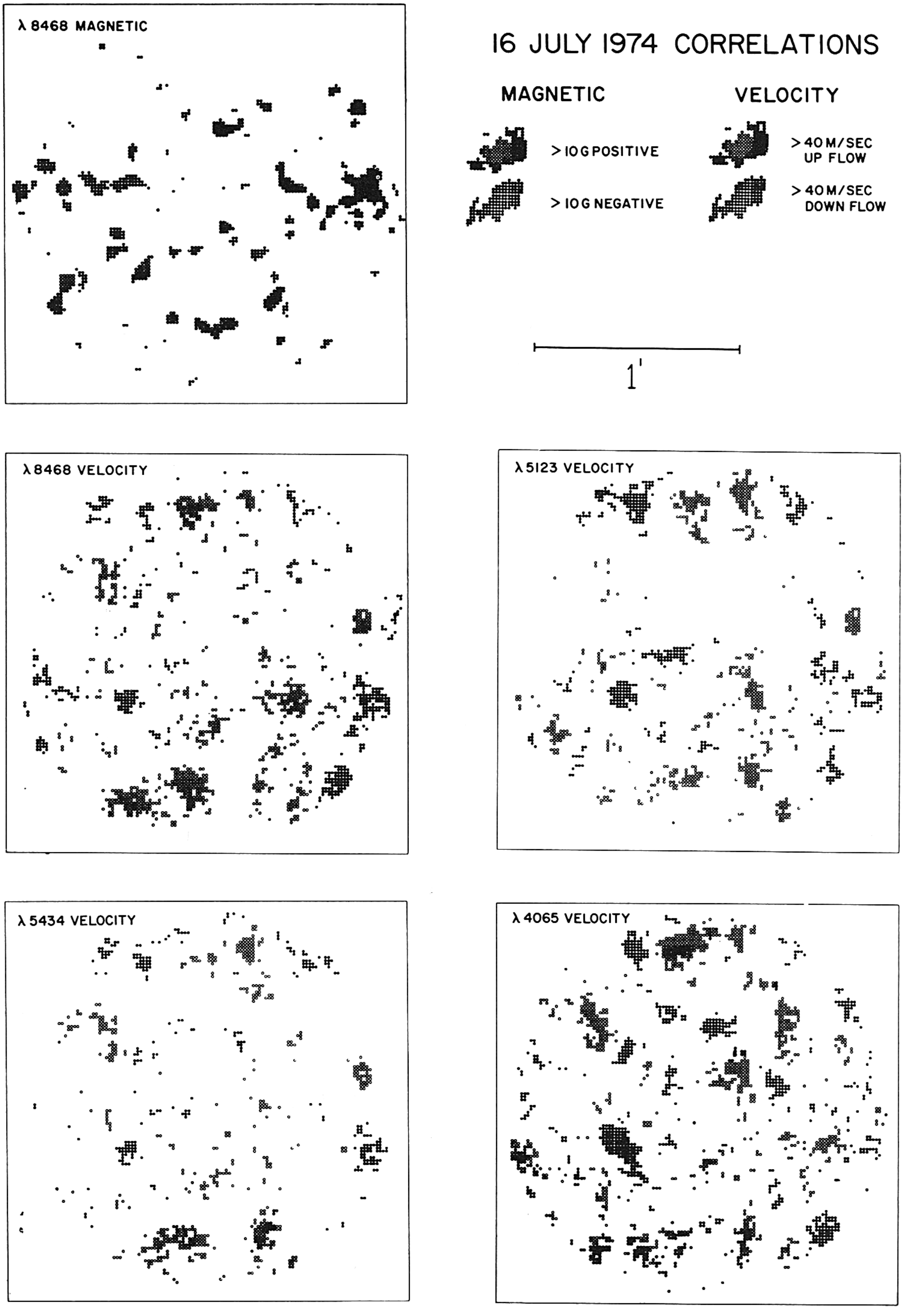


Fig. 5. Velocities and magnetic field above a minimum threshold which correlate over forty minutes in center of the disk data.

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observations. Only those velocity features which appeared on both consecutive 20-min time averages were used, since supergranular motions should persist over substantially longer periods. Figure 5 shows the result of this procedure, with all velocities less than a threshold of 40 m s$^{-1}$ on both sets of data removed. For comparison the magnetic field structure is also displayed in Figure 5; as expected, the emission network is clearly outlined by the magnetic field. An upflow of roughly 50 m s$^{-1}$ relative to the average velocity over the entire frame appears in the center of some emission network cells. However, downflows in magnetic field regions are apparent *only* in the λ 4065 data. Table II lists the velocities observed for each of the lines as a function of observed magnetic field strength. For small field strength λ 8468 seems to show downdrafts; however, as the field becomes progressively stronger this downflow diminishes in strength, until it disappears entirely. This behavior may be attributable to the magnetic splitting and distortion of this line profile as discussed previously.

TABLE II

Mean vertical velocities in magnetic field regions (unfiltered data-downflows positive)

| Magnetic field threshold | Number of 1″ points used | Velocity (m s$^{-1}$) λ 8468 | λ 4065 | λ 5123 | λ 5434 |
|---|---|---|---|---|---|
| 5 G | 3140 | 3 ± 2 | 14 ± 2 | 2 ± 1 | 0 ± 1 |
| 10 G | 594 | 13 ± 4 | 49 ± 4 | −3 ± 3 | −4 ± 3 |
| 15 G | 217 | 15 ± 5 | 85 ± 7 | −16 ± 5 | −7 ± 5 |
| 20 G | 114 | 13 ± 8.2 | 105 ± 10 | −33 ± 7 | −6 ± 6 |
| 25 G | 67 | 3 ± 10 | 116 ± 14 | −45 ± 10 | −15 ± 8 |
| 30 G | 39 | 10 ± 14 | 153 ± 18 | −70 ± 12 | −23 ± 8 |
| 35 G | 28 | 0 ± 14 | 174 ± 22 | −84 ± 14 | −29 ± 10 |
| 40 G | 19 | −9 ± 19 | 193 ± 26 | −92 ± 18 | −38 ± 13 |

Two-dimensional autocorrelation functions were used to verify these ideas. The two-dimensional autocorrelation of a data field $f(x, y)$ is given by:

$$\mathrm{AC}(\Delta x, \Delta y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y) f(x - \Delta x, y - \Delta y)\, \mathrm{d}x\, \mathrm{d}y$$

$$= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |F(u, v)|^2\, e^{i2\pi(u\,\Delta x + v\,\Delta y)}\, \mathrm{d}u\, \mathrm{d}v \qquad (2)$$

which is identical to Equation (1) if $g(x)$ is replaced by $f(x)$. As with the cross-correlation function, this may be calculated by inverse Fourier transforming the amplitude (power spectrum) of the Fourier transform of the data under investigation. This two-dimensional function can be converted to a one-dimensional function by summing the two-dimensional function over radial annuli. The resulting one-dimensional function is a measure of the correlation of the data field with itself for

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radial displacements. The mean size scale in the data is given by the half width of the central autocorrelation peak. Highly periodic data will show secondary maxima at displacements representing the mean size of the periodic structures. The radial autocorrelation function summed over 20 min for each of the wavelengths is shown in Figure 6. The sharp fall-offs of the central maxima with full widths at half maximum (FWHM) of 1500 km are probably attributable to granular signal. However, the more gradual fall-off out to 20 000 km and the possible weak secondary maxima at 30 000 km are indications of velocity structure on a supergranular size scale. The magnetic field autocorrelation function shown in Figure 6 is interesting since its FWHM fall-off of 3500 km is indicative of a mean size of magnetic elements of 4–7″, significantly larger than the seeing size and in line with the visual appearance of the data.

## 5. Summary

The observational results of this study are summarized below:

(1) Supergranule velocity cells may have mean lifetimes considerably longer than the previously accepted value of 24 h, with probable values near 36 h. However, detailed several day observations are still needed to verify this lifetime.

(2) No realignments of magnetic field elements already present at supergranular boundaries in a manner expected from Leighton's 'random walk' mechanism were observed in any of the 10-hour runs which were studied. Since 10 h is only a small fraction of a supergranule lifetime this negative result does not preclude the operation of supergranule random walk processes. However, two forms of magnetic flux motions were observed. Often an existing field element will split and a portion of the flux move away and dissipate. A second form of flux motion occurred when new flux appeared and moved rapidly in regions of changing supergranular flow. The motions are large ($\sim\sim 10\,000$ km) and rapid ($v \sim 2$ km s$^{-1}$) in the latter process.

(3) Magnetic field elements have an apparent size of 5″ ($\sim$3500 km) in data with 1″ resolution. This is larger than the seeing size and is presumably real.

(4) Supergranules may exhibit an upflow of $\sim$50 m$^{-1}$ in the center of each cell; however, this observation needs to be verified with higher accuracy data. A corresponding downflow of $\sim$200 m s$^{-1}$ is observed in magnetic field regions at the boundaries of supergranules. However, this downflow is only observed in the most deeply formed line. The disappearance of this downflow when observed in strongly magnetically sensitive lines is consistent with the hypothesis that strong fields ($B \sim 1000$ G) are present within these regions.

The longer lifetimes of velocity supergranules indicated from this work match Smithson's (1973) values for lifetimes obtained from magnetic field elements. As shown by Smithson this value is too small by a factor of two to explain the observed diffusion of active region magnetic fields as a random walk process due to supergranular motions. The slow breakup of magnetic field elements is difficult to explain in terms of any surface motion. However, this behavior and the sudden emergence of new flux in a supergranule appears more consistent with a model similar to the 'flux-rope' model of Piddington (1975). It may well be true that strong subsurface magnetic fields dominate convective motions to a far deeper level than previously

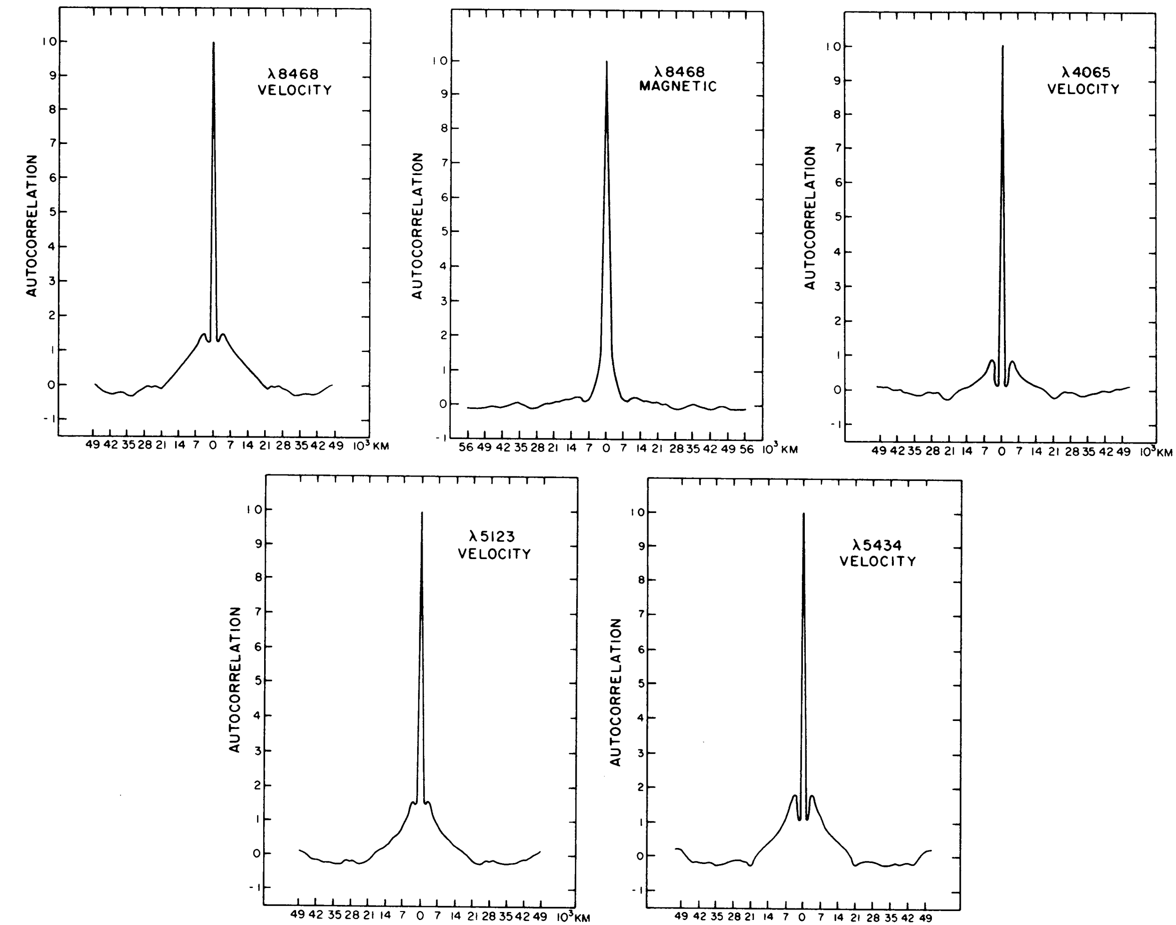


Fig. 6. Radial spatial autocorrelations for the center of the disk data.

thought. If surface magnetic flux strengths are as large as 2000 G, subsurface fields may be concentrated to even larger strengths by convective motions. Thus, if the supergranule is roughly 10 000 km in depth (Mullan, 1971; Simon and Weiss, 1968) as predicted from theoretical considerations, the magnetic field might constrain the convective flow to a considerable degree as suggested by Wilson (1972) for sunspot regions. The observation of infrequent motion of existing flux elements would support the idea that magnetic fields are intimately tied to a single convective cell. Clearly, detailed convective analysis including the effects of strong magnetic fields is necessary.

Chapman (1974) and Frazier (1974) have suggested that the observed downflow at supergranule vertices may be due to line profile changes in the magnetic field regions caused by heating in the low chromosphere. Since the lines used in part of this study were chosen to represent heights where this effect shows a range of importance, this hypothesis was checked. The three non-magnetic lines were studied using an LTE computer program developed by R. W. Milkey for the KPNO CDC 6400 computer and it was found that the absence of vertical velocities in the emission regions is explainable as a line profile effect as suggested by Frazier (1974).

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