SOME PROPERTIES OF VELOCITY FIELDS IN THE SOLAR PHOTOSPHERE*

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Abstract. Photoelectric records of the Doppler effect (DE) and longitudinal Zeeman effect (LZE) were obtained with the Capri magnetograph of the Fraunhofer Institut photoelectric, using the Fe I line λ 5250.22. Each record consists of 65 scans repeated along the same line on the sun. The analysis of 16 records covering a total of 485 oscillating regions (period 300 sec) leads to the following results:

(1) The mean lifetime of the DE-oscillations outside active regions is 20 min and 32 min in the neighborhood of spotgroups. Discarding the weakest sporadic oscillations, one obtains 27 min and 43 min respectively. The most frequent lifetime in both cases is 15 min.

(2) The mean linear distance of two oscillating regions is about 6″ and is slightly less in active regions (10–20%). Neglecting the weakest oscillations, a distance of 9″ is obtained.

(3) The oscillations begin and end with small amplitudes, and a maximum is reached only after some periods. In no case was an 'onset' of an oscillation with maximum amplitude observed. It is suggested that the photospheric oscillations are not so much based on the excitation by single overshooting granules, as on mutual disturbance or interference of standing waves, propagating horizontally with about 6 km/sec.

(4) The mean peak-to-peak amplitude of single oscillations decreases from about 600 m/sec in flux-free regions to < 400 m/sec in regions with 100 gauss and more.

(5) Structures with stronger fields and preferentially downward motions coincide with the borders of supergranular cells.

1. Introduction

Oscillations of certain parts of the solar atmosphere have, hitherto, been investigated by means of three different observational techniques. Each of them yielded a great deal of information, but some of the conclusions drawn from the observations were contradictory. This is not too surprising when one considers in detail the pecularities of the different methods.

Spectra: A spectrum reveals the maximum content of information obtainable simultaneously for all structures covered by the spectrograph slit. Comparing lines of different strengths or different parts of a given line profile, the height dependence of the observed phenomena can be studied. The evaluation of absolute wavelengths allows one to fix an absolute zero level for velocity fluctuations. Time series of spectra show the variability of the phenomena and phase relations (Evans and Michard, 1962; Frazier, 1966). Corresponding to the large amount of data obtainable from one single spectrum, evaluation is a rather complex process. With regard to Doppler shifts, where equidensitography or automatic positioning machines are involved, the sensitivity is comparatively low.

Doppler spectroheliograms: The ingenious method of Leighton (1962), which has so clearly shown the oscillations and horizontal motions discussed here, is never-

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theless restricted to the same sensitivity as the direct spectrographic method and moreover to the statistical treatment of a large number of unidentified elements. This may lead to an inadequate representation of the properties of individual elements.

Photoelectric measurements: One possible procedure is to keep the scanning spot on a certain interesting detail of the sun's image and to record the time variation of the measured quantity directly (compare e.g. HOWARD, 1967). With respect to the Doppler oscillations this method has two disadvantages. The zero velocity level is a priori unknown, because the special magnetograph technique makes the determination of absolute wavelengths difficult. Slow drifting of the involved DC amplifiers may cause, in addition, false DE signals. Moreover, the high time resolution obtained with conventional DE recorders is not at all necessary for an investigation of changes which develop in the order of minutes.

Therefore, another method seems to be specially suited, which combines some properties of the spectrographic method with the high photoelectric sensitivity. The sun is scanned along a section of a single straight line with a scanning rate chosen according to time constant, size of scanning spot, length of scan, and desired time resolution. The scan is then repeated on the same line, as often as necessary. If the section runs parallel to the sun's axis and its extension is sufficient to cover at least one supergranulum ($>1'$), then it is possible to derive for the DE a local zero level by averaging over the total length of the scanned region. This holds independently of the heliographic position (solar rotation) and of possible slow DC drifts. The deviation from true zero level will be certainly below 100 m/sec, probably below 50 m/sec. The following observations are obtained by this method.

2. Observations

Using the longitudinal part of the vector magnetograph of the Capri observatory (Fraunhofer Institute, Freiburg), during summer and autumn 1966, some records of this type were obtained. The telescope (for description of the instrument see KIEPENHEUER, 1964) has a combined photoelectric guiding and scanning system acting on a diagonal mirror by means of two servomotors. An accuracy of $1''$ for guiding and scanning is achieved. The time constant is 0.1 sec. Scanning is possible in any direction relative to the solar axis; the maximum scanning length possible is $5'$, the scanning rate can be chosen in steps from 12 to 600 sec per scan. The size of the scanning spot was in most cases $3'' \times 3''$, corresponding to $(0.52\ \text{mm})^2$ at the spectrograph slit. Occasionally it was reduced to $2'' \times 2''$.

The Doppler (DE) part of the vectormagnetograph (a detailed description of the instrument is in preparation) offers the possibility of averaging the DE signal by means of a RC-filter up to a time constant of 100 sec, and to record the difference between the momentary value and this gliding mean. The sensitivity of the DE measurement is certainly better than 20 m/sec. It is determined by the residual inner turbulence of the spectrograph (20 m focal length, Bausch and Lomb grating, 600 grooves/mm, $158 \times 212\ \text{mm}^2$, blaze angle $48°35'$).

TABLE I
Observations

No.	Date	Position	$\sin\theta$	$\cos\theta$	Length of scanning strip	Scanning period	Scanning aperture	Remarks
43	3.10.66	center of the disk	0	1	1′	52 sec	3″ × 3″	undisturbed region
44						32		
45						32		
46	4.10.66	center of the disk	0	1	1′	52	3″ × 3″	undisturbed region
47						52		
48						32		
49	5.10.66	21 N 50 E	0.80	0.60	1′	52	3″ × 3″	facular region at the common border of two CA
50						52		
51	7.10.66	21 N 24 E	0.515	0.855	1′	32	3″ × 3″	same region as number 50
52	10.10.66	18 N 17 W	0.415	0.91	1′	52	3″ × 3″	vertical structures near CA
53						52		
54						32		
55	10.10.66	18 N 17 W	0.415	0.91	1′	32	3″ × 3″	horizontal structures near CA
56	10.10.66	22 N 13 W	0.42	0.905	2′	52	3″ × 3″	section of CA
58	12.10.66	6 N 56 E	0.83	0.56	2′	52	3″ × 3″	inner section of the penumbra of a single spot
60	19.10.66	22 N 20 W	0.485	0.87	2′	52	2″ × 2″	section of CA

The sensitivity of the LZE measurement is about 3 gauss using a 3″ × 3″ scanning spot with a time constant of 1 sec. The photospheric Fe I line λ 5250.22 was used throughout this investigation.

Table I gives a survey of all records on which this analysis is based. It contains the heliographic position, length of the scanning line, scanning rate, size of scanning spot, and a short description of the character of the scanned region. Each record consists of 65 repetitive scans. The scanning direction was always parallel to the sun's axis. The drifting of the region perpendicular to the scanning line due to solar rotation has been suppressed by shifting the guiding photocells properly in the opposite direction.

During the records, control-filtergrams have been obtained in the red wing of Hα by reflection from a silvered diaphragm in the secondary focus of the telescope (image diameter 15 cm). A 0.5 Å-Hα-Filter (Halle) was used. The exposure time was 1/30–1/15 sec on Kodak 4 E.

The DE and LZE, together with time marks for each control-filtergram, were recorded on photographic plates by means of the recording unit of the vector magnetograph (DEUBNER, 1966). For evaluation, the original records were projected and redrawn in form of iso-maps. Figures 1 to 4 give samples of the DE-LZE-records.

3. Results

A. LIFETIME OF THE 300-SEC OSCILLATION

All records exhibit clearly the oscillations of the DE discovered by LEIGHTON (1962), which have a period of roughly 300 sec. Whereas previous measurements indicated a lifetime of oscillating regions in general not exceeding 3–4 periods, in all our records regions can easily be found with oscillations lasting up to 10 periods (see e.g. Figures 1 and 4). A slight lateral drift, which can be observed in some cases, may cause, when using a fixed scanning spot, the period to be 'lost' sometimes. This simulates a shorter lifetime.

In order to evaluate the lifetime of single oscillations, all clearly recognizable amplitudes of coherent DE structures were joined in series by a straight line reaching as far as the 300-sec oscillations could be followed in time backward and forward, namely, until the amplitude (peak-to-peak) is lost in between two of the isocontours. That means, that it has become less than 200 m/sec (<100 m/sec in some cases). A slight lateral drift of some seconds of arc has been neglected in some cases, where an isolated oscillation series can be traced without any doubt. In general the series run strictly parallel (i.e. without shift). If larger displacements occur, the following amplitudes are regarded as belonging to a separate series. Since the total duration of one record covers a time of 54 min or 34 min, a relatively large number of oscillations are recorded only incompletely. Statistically, the lifetime of an incomplete oscillation is just bisected by the interruption of the record. Accordingly, these oscillations are treated as the uninterrupted ones, after the measured lifetime has been redoubled.

Figure 5 shows the distribution of lifetimes separately for active and inactive regions of the sun. The greater frequency of long-living oscillations in active regions

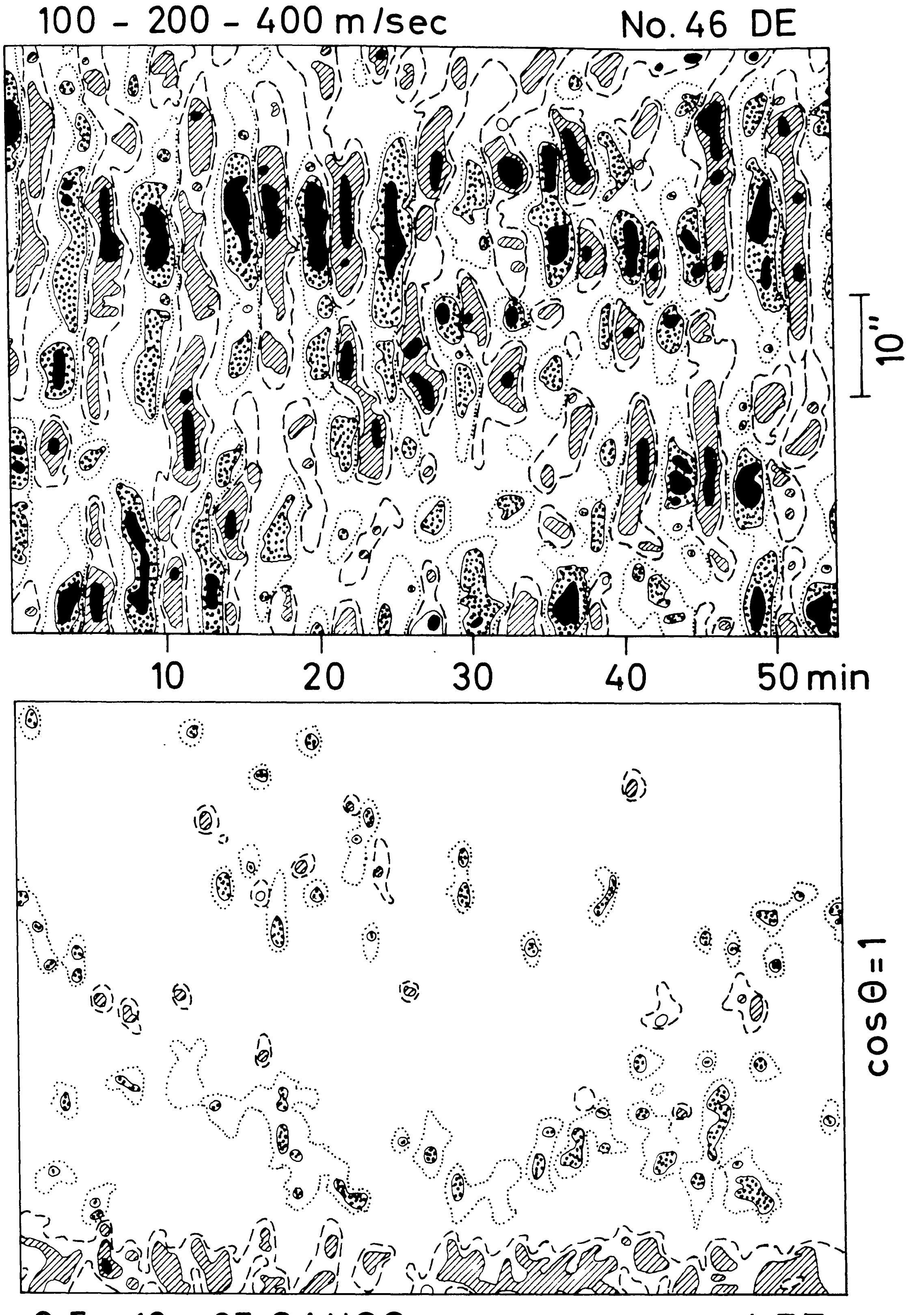

Fig. 1. DE-LZE-record No. 46. This record was made near the center of the sun's disc in a region removed from plages. *Top*: Velocity fields. The dotted regions have negative (upward), the hatched regions have positive (downward) velocities. *Bottom*: Magnetic fields. The dotted regions have S-polarity, the hatched regions N-polarity. The velocities and field strengths corresponding to the isocontours are indicated in the figures.

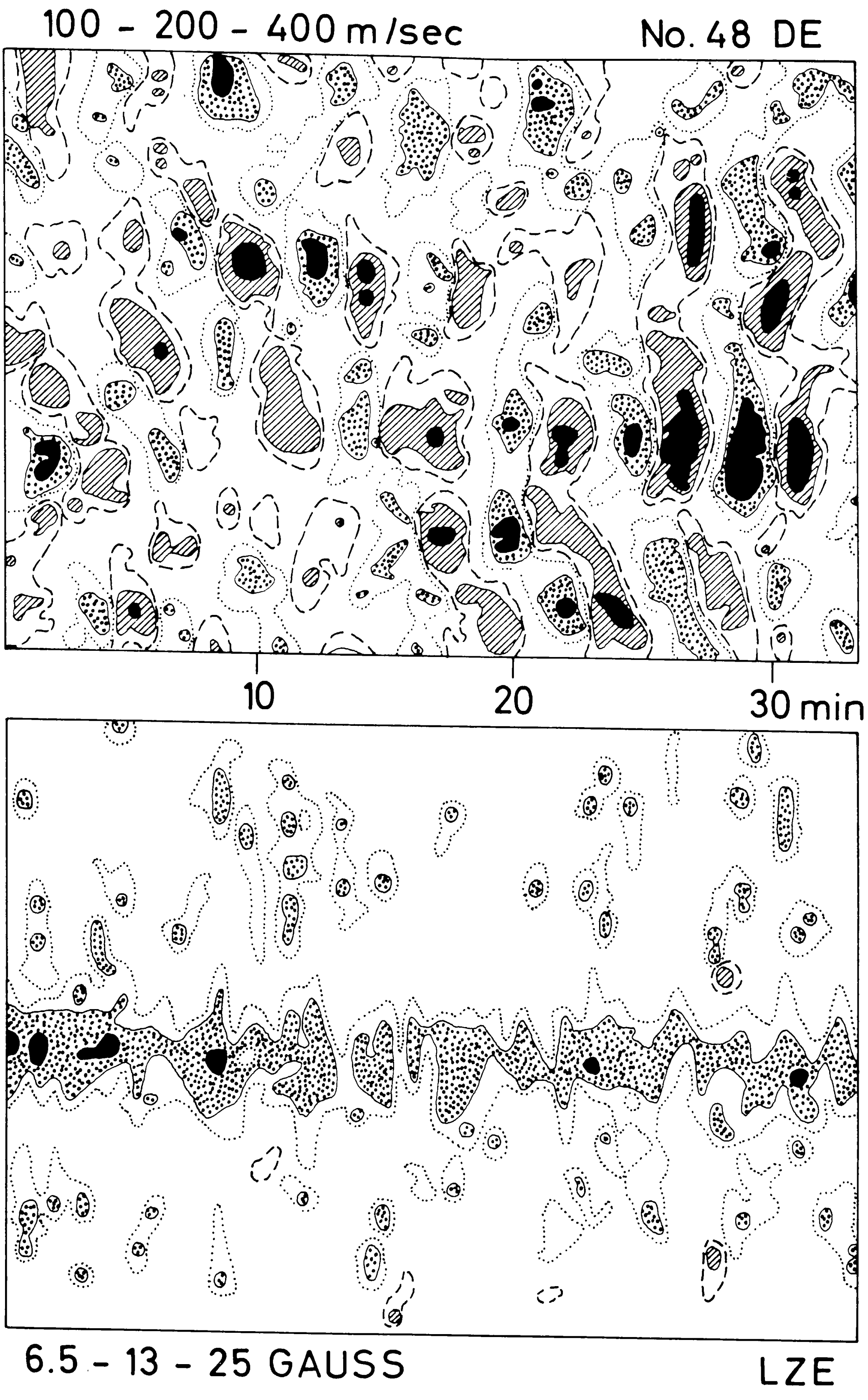

Fig. 2. DE-LZE-record No. 48. Region removed from plages near the center of the disc. Higher time resolution (shorter scanning period) than in Figure 1. Note long chain of increasing amplitudes at the lower right.

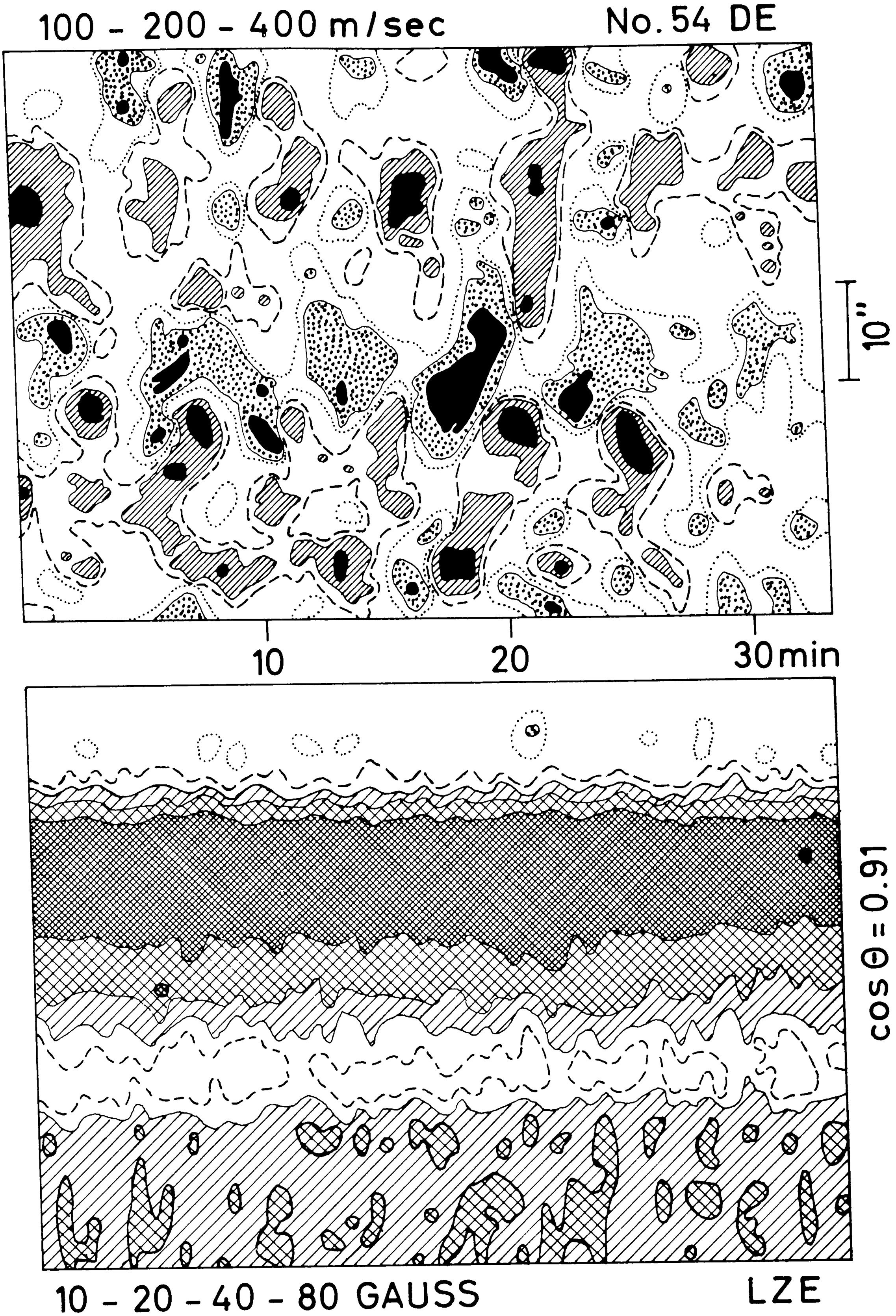

Fig. 3. DE-LZE-record Nr. 54. Region with preferentially vertical structures near center of activity, about half way from center to limb.

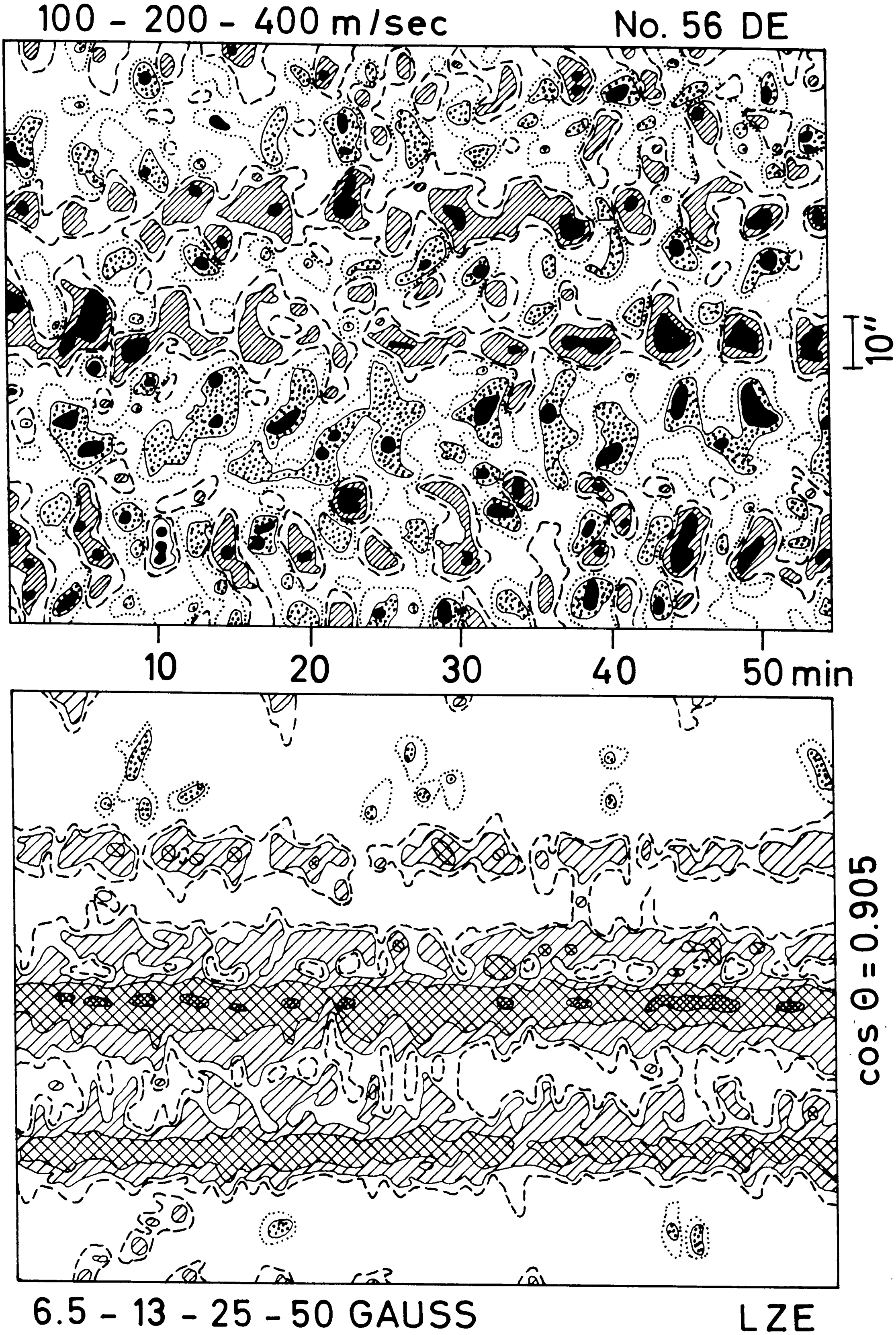

Fig. 4. DE-LZE-record Nr. 56. Section of a center of activity, about half way from center to limb. Reduced scale. Note the spatial coincidence of constant downward velocities (hatched regions) and stronger magnetic fields.

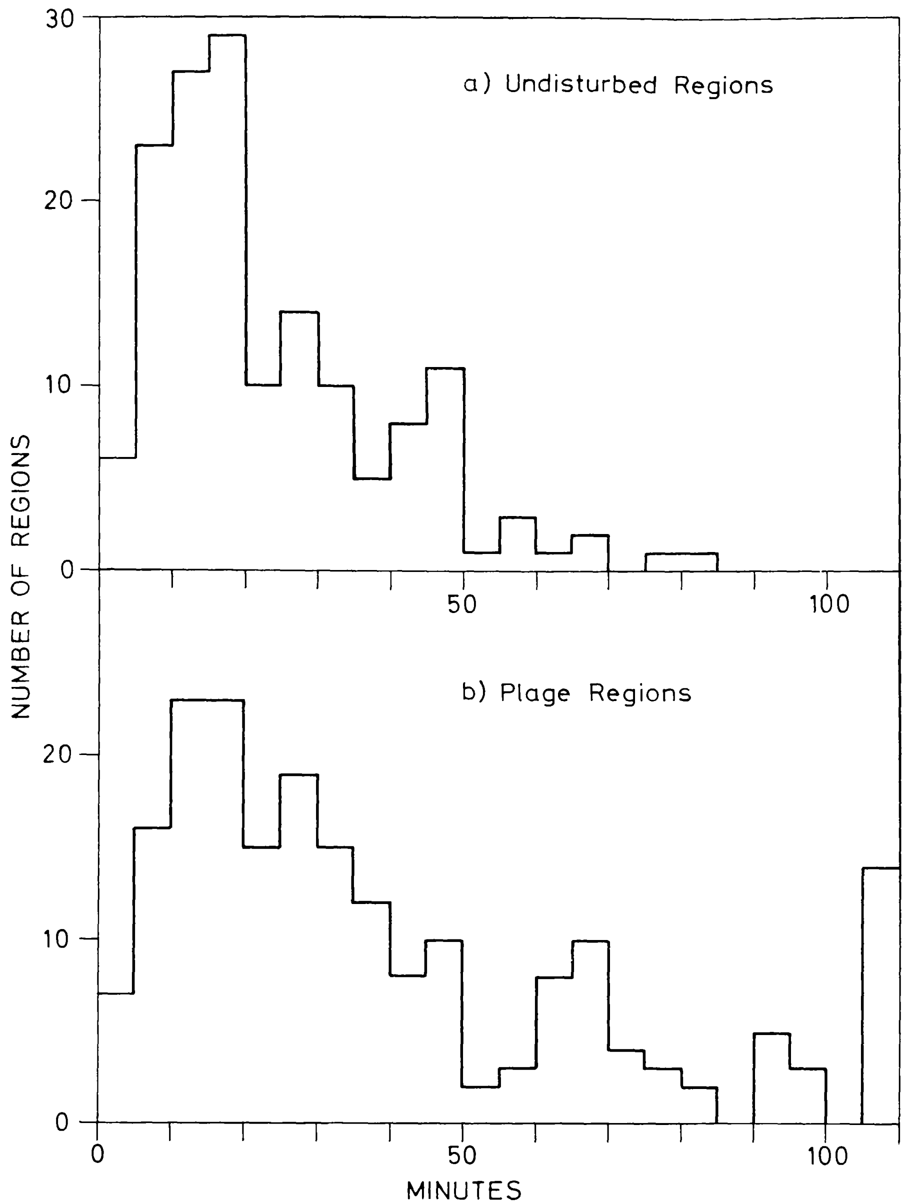

Fig. 5. Histograms showing the distribution of lifetimes of single oscillations for active and inactive regions of the sun separately. Sporadic oscillations with maximum peak to peak amplitudes < 400 m/sec are excluded. Peaks at 65–70 and 105–110 min reflect the finite recording time only.

can be clearly recognized, whereas in both distributions a lifetime of about 15 min seems to be the most frequent.

The mean lifetime from a total of 485 single values is 20 min for the undisturbed sun and 32 min in active regions. If only oscillations reaching a peak-to-peak amplitude of at least 400 m/sec are considered, lifetimes of 27 min and 43 min are obtained respectively. These unmistakable oscillations only are plotted in Figure 5.

B. THE DISTANCE OF OSCILLATING REGIONS

A mere view on any one of the DE-records shows, that the photosphere at any time is filled up with oscillating regions and that, after a series of oscillations fade away, a new series starts immediately at the same point or nearby (see Figure 1). Only 50% of the solar surface at most has a momentary vertical velocity component less than 100 m/sec (compared with the local zero level defined above).

From 13 recordings with a scanning length $L = 1'$ the mean distance λ of oscillating elements has been calculated, using the ratio of the measured lifetime T_i and the recording time t for the entire record in the simple formula:

$$\lambda = \frac{t}{\sum_i T_i} \cdot L$$

TABLE II

Mean Linear Distances for Single Records including All Oscillations

	non active regions	active regions
	5″.7	6″.2
	7″.6	5″.9
	7″.3	5″.6
	6″.5	6″.0
	6″.0	4″.8
	6″.6	5″.5
		5″.3
mean	6″.6	5″.6
r.m.s.	± 0.7	± 0.5

Table II contains the single values for each record and the means for undisturbed and active regions separately. The linear distance of roughly 6″, derived by means of the above equation, is in reasonable agreement with the value that can be estimated directly from the records. In Table III the same values discarding the 'weak' oscilla-

TABLE III

Mean Linear Distances for Single Records excluding Oscillations with peak-to-peak Amplitudes < 400 m/sec

	non active regions	active regions
	9″.9	12″.3
	9″.9	11″.8
	11″.0	6″.9
	8″.0	11″.0
	8″.1	6″.4
	10″.2	7″.7
		6″.2
mean	9″.5	8″.9
r.m.s.	± 1.1	± 2.5

tions are given. There is a considerable scattering of the single values. Nevertheless a slightly higher density of oscillating elements in active regions seems to be indicated.

C. THE VARIATION OF AMPLITUDES

With regard to this special behaviour, earlier observations (NOYES and LEIGHTON, 1963; EVANS and MICHARD, 1962; JENSEN and ORRALL, 1963; HOWARD, 1967) differ considerably or at least are ambiguous. Due to the fact that one series of oscillations gives way to another almost without interruption, and due to the close neighborhood of adjacent elements, it is rather difficult to isolate the 'beginning' or the 'end' of a certain series. But the following is quite evident from inspection of the records: Strong oscillations occur neither at the beginning, as it should be expected from the theory (MEYER and SCHMIDT, 1967) nor at the end of a series, as stated by MICHARD (1964). Any series taken apart exhibits, on the contrary, a more or less symmetrical character with maximum amplitudes near the middle of the series. Not many long-living oscillations have been recorded completely. But the number of series which show a slow decrease of a strong amplitude equals, approximately, the number of cases where an increase of amplitude can be followed over several periods (see an example e.g. in Figure 2).

D. THE ZERO VELOCITY LEVEL AND THE INFLUENCE OF SUPERGRANULATION

Comparing DE records from the center of the solar disk (Figures 1 and 2) with others from a greater distance (Figures 3 and 4; $\sin\theta=0.42$), it can be seen that, in the first case, the amplitudes of the oscillations lie symmetrically with respect to mean zero-velocity level. A constant vertical component changing across the solar surface cannot be detected (the lowest level shown by the isocontours is 100 m/sec). On the contrary, the oscillations at some distance from the center of the disk show generally strong red- or blue shifts of their zero levels. This effect should be expected, because the horizontal flow of the supergranulation (SIMON and LEIGHTON, 1964) has already a significant DE component (≈ 0.2 km/sec) at a distance half way from center to limb.

In Figure 6 the distributions of the means for any two subsequent amplitudes (single oscillations) are plotted separately for the center of the disk and the other regions ($\sin\theta=0.4$ ... 0.8). Distribution 6b clearly shows two maxima at about ± 150 m/sec corresponding to the components of the horizontal flow. Both distributions are slightly asymmetrical in favour of positive DE. This might be interpreted as another indication of downward vertical motions at the border of the supergranulation cells.

E. CORRELATION OF CONSTANT VELOCITY COMPONENTS AND MAGNETIC FIELDS

It can be seen from DE records of disturbed regions and simultaneous LZE maps (see Figures 3 and 4) that structures which are superimposed by a strong (constant) downward-velocity component often coincide with stronger magnetic fields.

Taking the means of subsequent amplitudes (momentary constant-velocity component) used in the previous section, the mean DE level for different field strengths

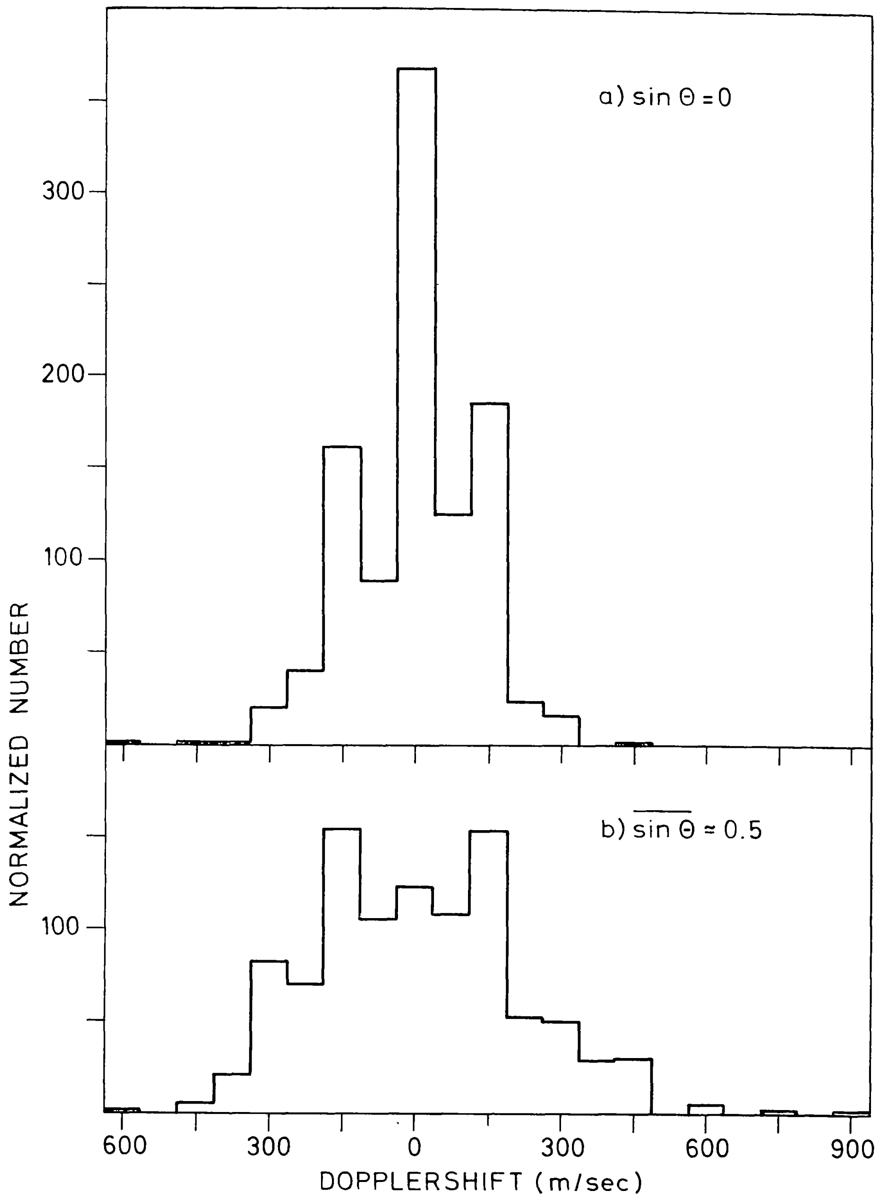

Fig. 6. Histograms showing the distribution of constant velocities measured in oscillating regions for the center of the disc and other regions separately.

has been calculated and is plotted in Figure 7. There is an unambiguous transition from upward velocities to downward velocities with increasing field strength. Each curve is derived from a group of records with equal magnetic sensitivity. Since the zero-velocity level is only a relative one – deduced, as described, by averaging over more than one scanning period – each curve contains positive and negative velocities.

The correlation between Doppler shift and magnetic field cannot be due to the downward motion at the borders of the supergranular cells because of its low velocity. It therefore must be ascribed to the geometric effect (see Figure 8) which, by oblique projection, produces coincidence of regions of the maximum Doppler component of

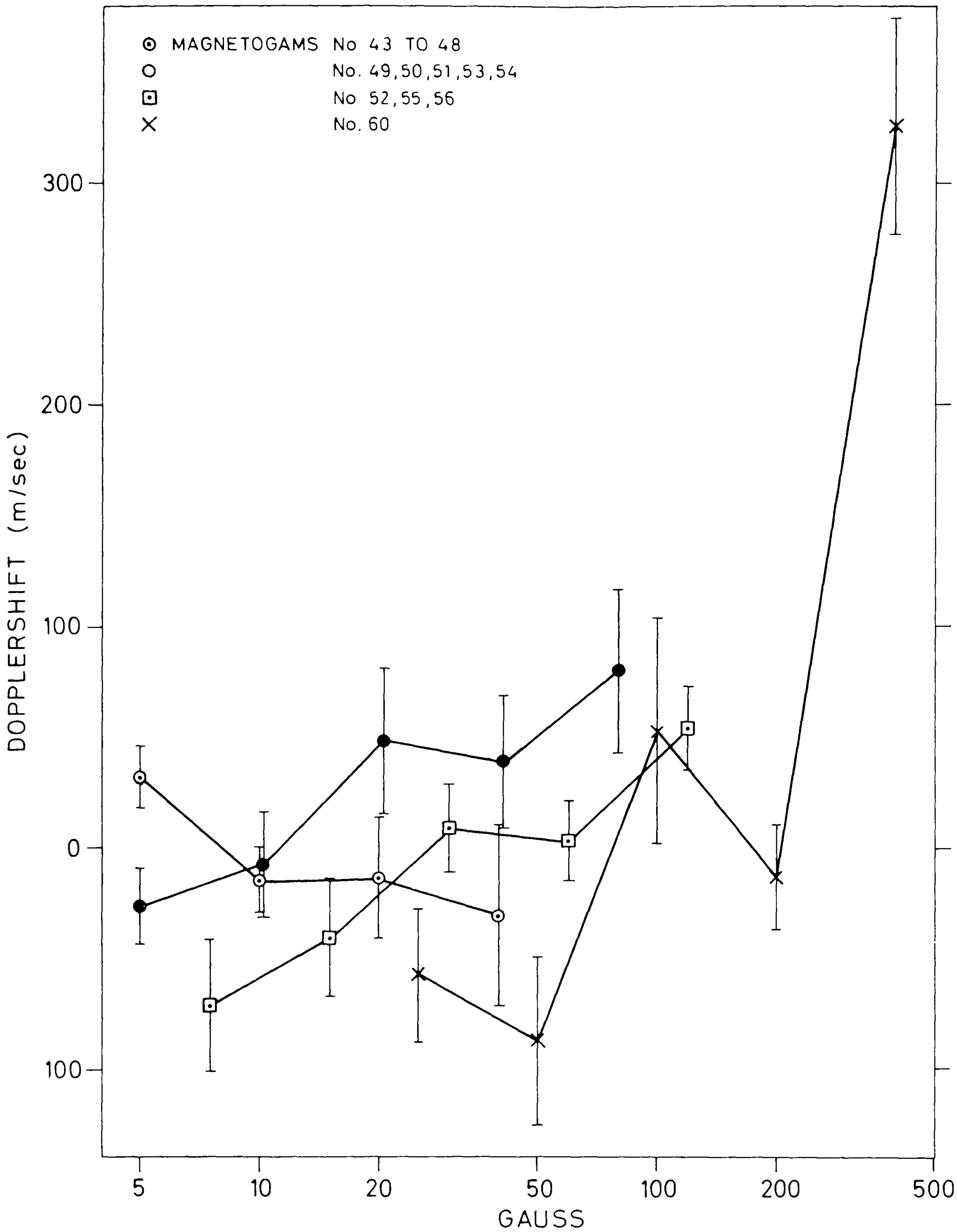

Fig. 7. A plot of the mean constant velocities measured in oscillating regions against the longitudinal magnetic-field component measured simultaneously in these regions.

the horizontal motion directed away from the observer with regions of maximum of the longitudinal magnetic field component.

This rough analysis is in good agreement with the idea that the magnetic flux is preferentially concentrated at the borders of supergranular cells by horizontal motion. This is specially true also for stronger field intensities ≧ 200 gauss in facular regions.

The inversion of the observed correlation in regions free of activity near the center of the disk (see open circles in Figure 8) cannot be understood from the material presented here. To check this observation still more detailed measurements are needed.

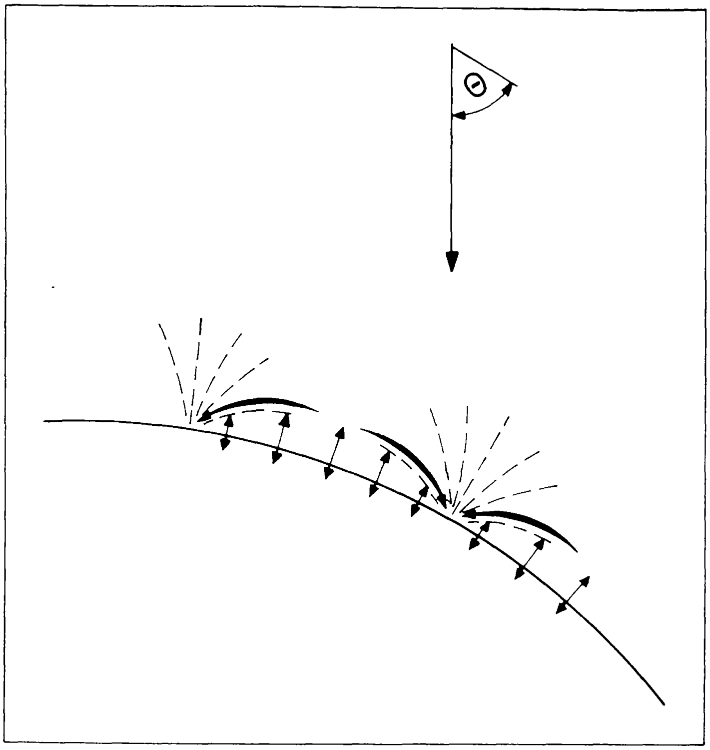

Fig. 8. Coincidence of constant downward motions and stronger magnetic fields is produced at the border of a supergranulum by oblique inspection.

F. THE INFLUENCE OF MAGNETIC FIELDS ON THE MEAN AMPLITUDE OF THE OSCILLATIONS

Raster-scan recordings of the DE in form of maps will display a hardly discernible mixture of constant velocities, oscillations, and seeing effects, depending strongly on the scanning rate. An attempt to deduce a correlation between velocity fields and magnetic fields from such records and simultaneous magnetograms may therefore lead to contradictory results (LIVINGSTON, 1966). HOWARD (1967) has compared some 'fixed point' records of DE in quiet and active regions, and states that in active regions the amplitudes are 25% lower than in regions with field strengths below 5 gauss.

The mean peak-to-peak amplitude has been calculated from our records for different field strengths. The results are plotted in Figure 9. From 10 gauss to 100 gauss, the mean amplitudes decrease distinctly from about 600 m/sec to 400 m/sec. Whether the mean amplitudes still change beyond these limits cannot be firmly decided. The difference in amplitudes between the center of the disk and the curves of other regions ($\cos\theta = 0.8$) is probably due to the unisotropy of the oscillatory motion. Assuming a purely vertical motion, the line of sight component should be reduced by an amount of 20%. This is in good agreement with our observations. The result of Howard is therefore quantitatively confirmed.

As can be seen from the Figures 1 to 4, the longitudinal magnetic field signal is sometimes also apparently subject to considerable quasi-oscillatory changes in the range of periods of 2 to 6 min. This cannot be due to instrumental noise, since the

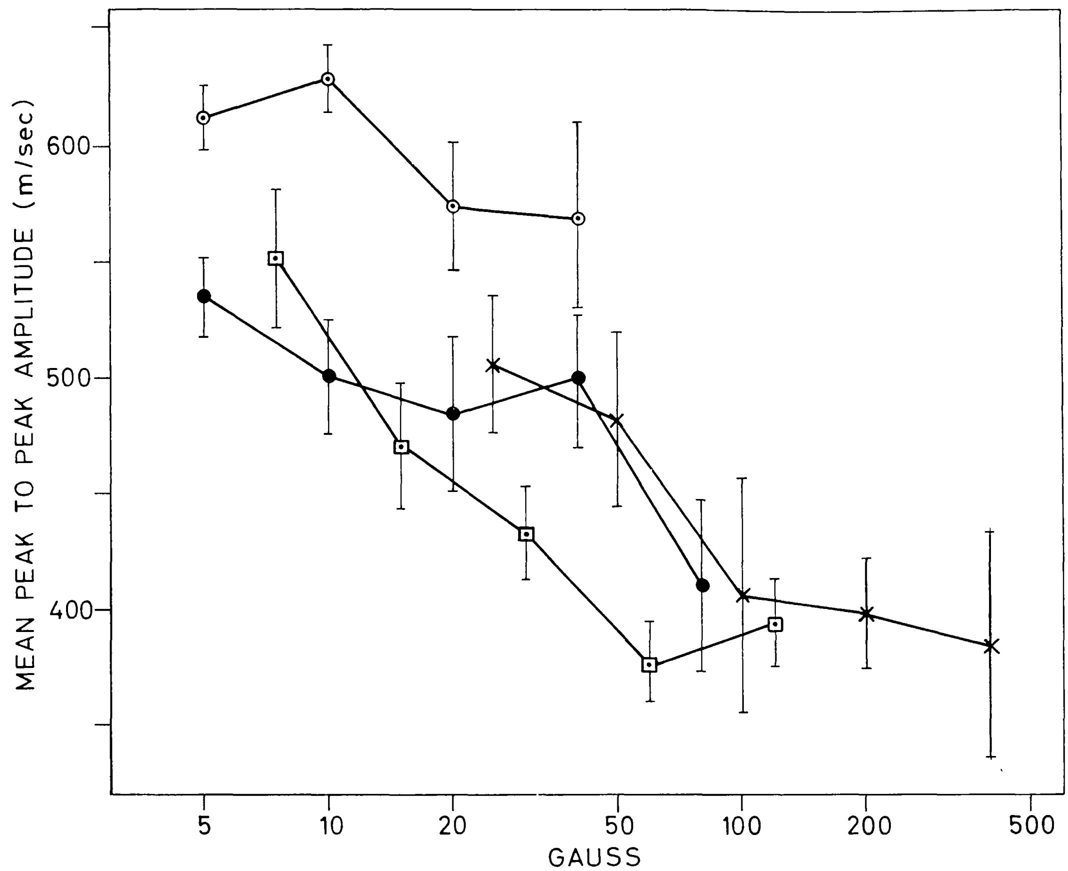

Fig. 9. A plot of the mean peak-to-peak amplitudes of single oscillating regions against the longitudinal magnetic-field component.

changes occur also in regions of strong magnetic fields. Before investigating this effect, the influence of atmospheric seeing on LZE measurements with small scanning apertures has to be studied carefully.

4. Discussion

Whereas the geometric dimensions of oscillating structures derived here are in good agreement with the results of Evans and Michard (1962) and Howard (1967), there are some differences with regard to the development of single oscillations.

As described in Section 3, in no case could an oscillation be observed to start with the highest amplitudes. Amplitudes of 400 m/sec and higher are always introduced by weaker ones. After the first observable onset of an oscillation, the amplitudes sometimes continue to rise some 10 to 20 min before a maximum is reached. This observation is in direct conflict with the idea, that an overshooting granulum is the only cause that sets the oscillation going. The contradiction remains also, if one considers that, in general, the scanning track will miss the centers of pulsating regions. The absolute amplitudes at greater distances, where a rise of amplitudes during some periods can be expected, are too low to be detected among strong local oscillations. In other words, the observed oscillations are essentially local ones.

There is another inconsistency between different measurements of the lifetime. Even the most frequent lifetime of about 15 min derived from Figure 5 exceeds the mean value of 8 min estimated by NOYES and LEIGHTON (1963). The drift of solar surface structures by the solar rotation relative to the spectrograph slit is $\leqslant 10''$, if one assumes that the solar limb is guided. Thus, only in the case of long-living oscillations could the measurement possibly be affected. This is verified by one of our own records, which was recorded without compensation for solar rotation. Maybe the higher photoelectric sensitivity of our records and the individual treatment of *single* oscillating regions applied in this analysis explain the different results. The superposition of oscillations with different periods – corresponding to different physical conditions of the solar atmosphere in different regions – leads, of course, to a relatively short lifetime. It is defined by the width of the common power spectrum, and may differ considerably from the lifetimes of single oscillations. HOWARD (1967) states that even in a given region the power spectra vary from observation to observation. In addition, he shows examples of oscillations lasting some 30 min, which he obtained during a fixed-point record with the Mt. Wilson magnetograph.

Occasionally, a drift of oscillating structures parallel to the scanning direction is observed in our records. The maximum lateral velocity component observed corresponds to that of a disturbance propagating horizontally with 6 km/sec. This equals roughly the velocity of sound in the photospheric layer. The increase of coherence length of a region oscillating in phase, which can be also found occasionally in our records, happens with the same propagation velocity.

Apart from propagation parallel to the surface, which can be recognized only rarely because of disturbances by adjacent structures, the records discussed here suggest a picture of the velocity field on top of the photosphere consisting not so much of singly incited and independent oscillations, as of interweaved standing waves with a characteristic wavelength of $10''$–$15''$. The observed variation of amplitudes is apparently not the outcome of dissipative processes, but is most probably due to a mutual disturbance or interference of neighboring elements. In the time of 15 min (the most frequent lifetime) the observed horizontal disturbances move (6 km/sec) just about by the mean distance of $6''$–$9''$. This favours the idea of mutual influence by interference.

Acknowledgements

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