1962ApJ...136..493E

OBSERVATIONAL STUDY OF MACROSCOPIC INHOMOGENEITIES IN THE SOLAR ATMOSPHERE

III. VERTICAL OSCILLATORY MOTIONS IN THE SOLAR PHOTOSPHERE

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Received Janury 20, 1962; revised March 19, 1962

ABSTRACT

We have studied the Doppler displacements in two time sequences of spectrograms, one showing Fe I 5171.61, Mg I 5172.70 (b_2), and Ti I 5173.75 at the center of the solar disk, the other showing Fe I 5324.19 at the limb.

At the center we find that the velocity field consists mainly of short-lived oscillations of small elements of the solar atmosphere. The r.m.s. velocity amplitudes are 0.42 and 0.81 km/sec at low and high levels, respectively. The periods of the vertical oscillations cover roughly the range 200–300 seconds, with a mean value around 242 sec. The periods seem to decrease with height in the atmosphere. An autocorrelation study shows also that the vertical velocity field is dominated by periodic oscillations, the time-correlation function having a strong positive peak at 300 seconds from the origin. The study of the time lags of oscillations between strong and faint lines suggests that they are of a type intermediate between progressive sonic waves (for the shorter periods) and standing waves (for the longer periods). Gradual transition from the first type to the second seems to occur during the life of a given oscillation. There is an indication that the individual oscillations are associated with individual granules.

Near the limb, the observed horizontal motions consist of slowly changing velocities of the order of 0.5 km/sec in large surface elements, on which are superposed smaller random velocities of short duration. Oscillations rapidly disappear away from the center of the disk. The horizontal and vertical observable motions appear to be physically independent.

I. INTRODUCTION

General theoretical studies over the last ten years have predicted oscillatory motions in the solar photosphere and chromosphere. We note here those of Biermann (1948), Schatzman (1949, 1954), Thomas (1954), Schwarzschild (1948), and Whitney (1958). Leighton (1960) presented the first observational evidence for such motions over a year ago, and (Leighton 1961) reported a large body of further observations by his spectroheliographic technique in 1961. They confirmed the existence of oscillatory vertical motions, the velocity field after a time t showing maximum correlation with the initial one for $t = 296 \pm 3$ seconds. A long-lived "supergranulation" on the sun was also found, composed of cells about 15000 km in diameter, within which material continually flowed horizontally from the center toward the boundaries. At the same time, Evans and Michard (1961) presented preliminary results of measurements of Doppler shifts in a carefully guided series of spectrograms, which showed strong vertical oscillatory motions with periods concentrated around 245 seconds, and relatively long-lived non-periodic horizontal motions. The present paper is an extension of that report.

II. OBSERVATIONAL MATERIAL

The observational equipment and methods of measurement used for the study of sight-line velocities in surface elements on the sun from 1000 to 30000 km in diameter have already been described in the first paper of this series by Evans and Michard (1962*a*).

This present study of the time variation of motions depends entirely on two series of spectrograms with 10- or 15-second exposures, taken at 20-second intervals. The effective length of slit on the 25.6-cm solar image was 5.8 cm. The first series of 60 exposures

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was taken September 30, 1960, with the slit crossing the southern limb of the sun radially, and includes the spectrum around Fe 5324.193 with a linear dispersion of 17 mm/A. The second series of June 19, 1961, consists of 61 exposures at 20-second intervals followed by 43 exposures at 60-second intervals. It shows the spectrum of the center of the disk around Mg 5172.700 (b_2) with a dispersion of 13 mm/A. The guiding, as shown by the persistence of the granular structure in the continuum from one exposure to the next, and the image quality indicated by the detail shown in the continuum and the line "wiggles," approached the best that are attainable at Sacramento Peak. Resolution was about 1″, and the guiding excursions probably did not exceed $\pm 0''.5$. The lines studied, and the microphotometer adjustments used in their measurement are given in Table 1.

Here $\lambda_a - \lambda_b$ is the total separation of the scans on the red and blue sides of the line, and $\delta\lambda$ is the band width.

III. OSCILLATORY MOTIONS AT THE CENTER OF THE DISK

A series of 15 spectrograms of the best image quality covering a period of 500 seconds was selected from the June 19, 1961, observations for the study of vertical velocities at the center of the disk. Intervals between successive exposures in every case were 40 or 20 seconds. Each spectrogram yielded a $v(x)$ curve of velocity as a function of position along the slit (similar to the curves shown in Fig. 2 of the first paper of this series) for each of the three lines Fe 5171.61, b_2, and Ti 5173.75. From these, a $v(t)$ curve of velocity as a function of time could be plotted for any point along the slit.

TABLE 1

MEASURED LINES

λ	Element	Rowland Intensity	$\lambda_a-\lambda_b$ (A)	$\delta\lambda$ (A)
5171 612..........	Fe I	6	0.110	0.058
5172 700(b_2).......	Mg I	20	.132	.058
5173.751.......	Ti I(L)	2	.078	.038
5324.193...........	Fe I	7	0.106	0.045

We have concentrated most of our attention on b_2 and Ti 5173.75 as samples of strong and weak lines, respectively, suitable for showing motions at different heights in the solar atmosphere. In the remainder of this paper we shall call the low-level Ti 5173.75 line the "L line," or simply "L," for brevity. The following analysis depends on $v(t)$ curves in both lines for 160 points along the slit, 120 of which were regularly spaced 1000 km apart. The remaining 40 points were selected at positions where pronounced velocity maxima occurred at some time during the 500 seconds of observation. Corresponding $v(t)$ curves for Fe 5171.61 at a number of the points confirmed our earlier finding that the characteristics of motions in this line are in all respects intermediate between those of b_2 and L.

The most conspicuous feature of the resulting array of $v(t)$ curves is a strong predominance of periodic oscillations, which are characteristic of all the *large* velocities observed. Oscillatory motions in the three lines under study are very strongly correlated. Table 2 is a summary of the characteristics of the oscillations. They display a remarkably small dispersion in periods around 242 seconds, and the oscillations are very nearly identical in both lines. The random turbulent velocity at any instant, ζ, is listed for comparison.

The $v(t)$ curves in Figure 1 demonstrate the unmistakable oscillatory character of the vertical motions. Those of Figure 1, *a*, represent the motions at 1000-km intervals along the line defined by the slit on the sun, showing the extent of large coherent wave fronts.

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The size of the wave fronts is not very definite, since it depends on the stringency with which coherence in phase and shape of $v(t)$ is defined, and different observers arrive at widely varying values from the same set of $v(t)$ curves. If we consider that phases must coincide within 10 seconds and that the velocity ratios in the different $v(t)$ curves must be constant within the observational errors throughout the whole interval of observation, we find that the wave fronts extend between 1000 and 5000 km along the slit image, with a most typical size between 2000 and 3000 km. However, marked similarities in the $v(t)$ curves can often be traced over much larger distances, as in Figure 1, *a*.

The oscillating elements appear to occupy about a third of the solar surface at any one time and a third of the time at any one point. In the areas between oscillating elements the velocities are small and erratic.

The dominance of short-lived periodic motions in the velocity fields of the upper photosphere and lower chromosphere somewhat modifies the significance of the concept of "random turbulent velocity" used in the first paper of this series. Although the distribution of velocities on the solar surface at a given time is probably quite random (apart from some anisotropy in the higher levels), a sizable fraction of the kinetic energy is contained in the distinctly organized non-turbulent motions of many unrelated small elements.

TABLE 2

CHARACTERISTICS OF OSCILLATIONS IN THE SOLAR ATMOSPHERE

	LINE	
	b_2	Ti 5173.75
Amplitude, r.m s.	0 81 km/sec	0 42 km/sec
Standard deviation (single wave)	±0 27	±0 14
Random turbulent velocity, ξ.	0.61	0 31
Mean period	235 sec	249 sec
Standard deviation (single wave)	± 20	± 32
Mean time lag, $t(b_2)-t(5173.75)$	8.4 sec	
Standard deviation (single wave)	±7.8	

a) Characteristics of Individual Oscillations

From the 160 $v(t)$ curves we selected 45 independent "waves" with oscillations lasting more than three-fourths of a cycle and velocity amplitudes greater than ±0.4 km/sec in b_2. While there are certainly oscillations with durations and amplitudes less than these minima, they are difficult to distinguish from the "noise background" of random velocities in the non-oscillating areas of the solar surface and do not give meaningful estimates of periods and amplitudes.

Figure 2 shows the velocity amplitudes, A_b and A_L, for the two lines, defined as half the velocity difference between the maximum and minimum during an oscillation, plotted against each other for individual "waves" on the sun. The amplitude ratio represented by the slope of the straight line is $A_b/A_L = 1.93$, which agrees well with the ratio of random turbulent velocities at a given instant, $\zeta_b/\zeta_L = 1.97$, found in our first paper (Evans and Michard 1962*a*). The histograms of Figure 3 represent the distributions of the observed amplitudes. The r.m.s. amplitudes are $A_b^m = \langle A_b^2 \rangle = 0.81$ and $A_L^m = 0.42$ km/sec. The standard deviations for a single wave are ±0.27 and ±0.14 km/sec in the b_2 and L lines, respectively.

The mean velocity amplitudes are probably lower limits because of the smoothing of the $v(x)$ curves due to imperfect image resolution, in spite of our disregard of amplitudes less than 0.4 km/sec in b_2. The ratios of amplitudes should be reasonably accurate, however.

The "periods" of oscillation, T_b and T_L, were estimated on the $v(t)$ curves, from the separation of successive maxima. Because the whole life of an oscillation is usually between 1 and 2 "periods," the significance of the T_b and T_L parameters is very limited. Their use does not mean that the observed motions are *strictly periodic.* The r.m.s. error of estimation of the period of a single wave, determined from several repetitions, is about 12 seconds. Figures 4 and 5 show, respectively, the distributions of periods and a plot of T_b against T_L for individual waves. Figure 6 is a graph of A_b against T_b for individual waves. The mean periods are $T_b = 235 \pm 4$ seconds and $T_L = 249 \pm 5$ seconds. The

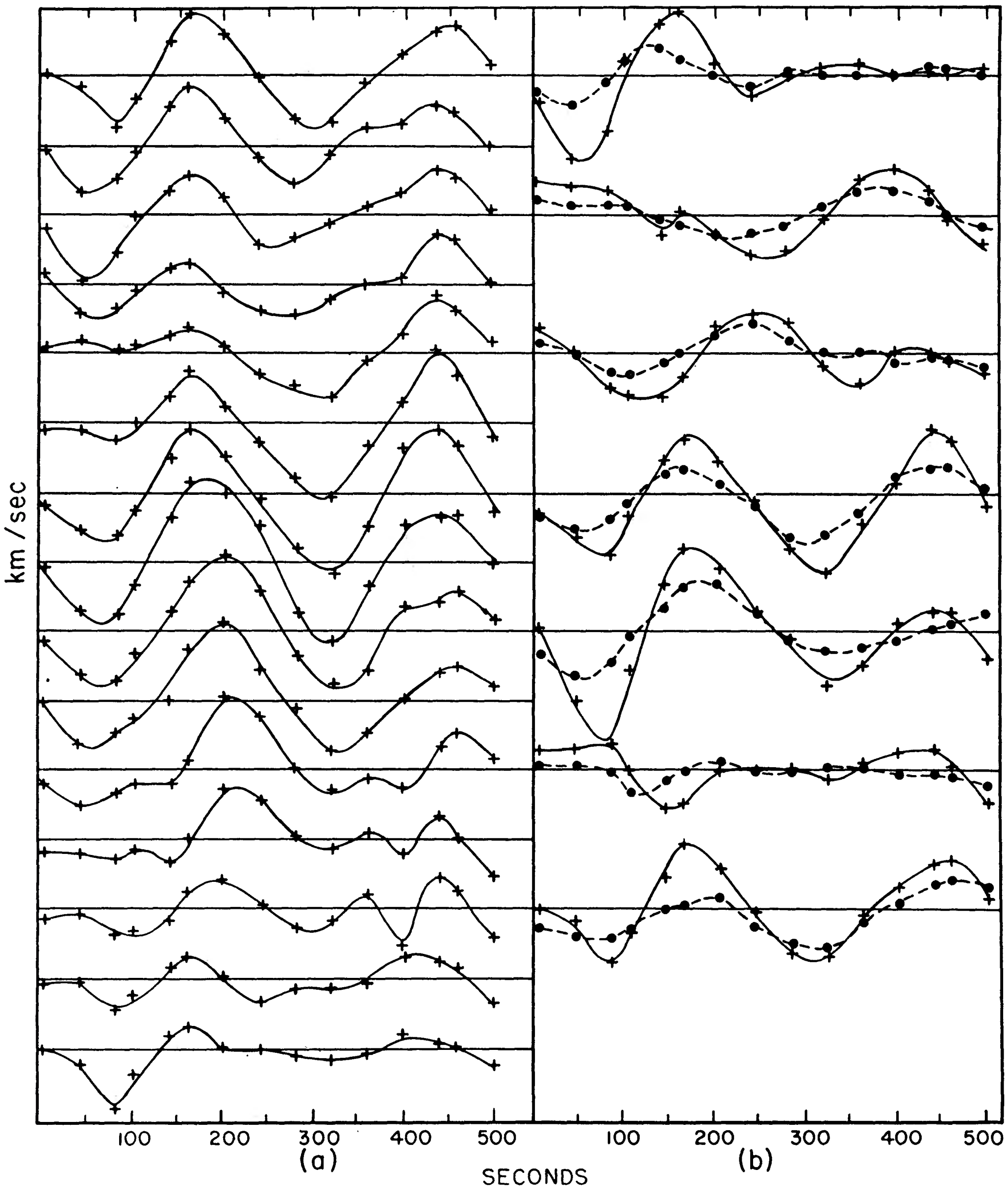

FIG. 1.—Velocity as a function of time for discrete points at the center of the sun for (*a*) fifteen successive points 1000 km apart in b_2 and (*b*) seven independent points in b_2 (*solid curves and crosses*) and Ti 5173.75 (*dashed curves and dots*).

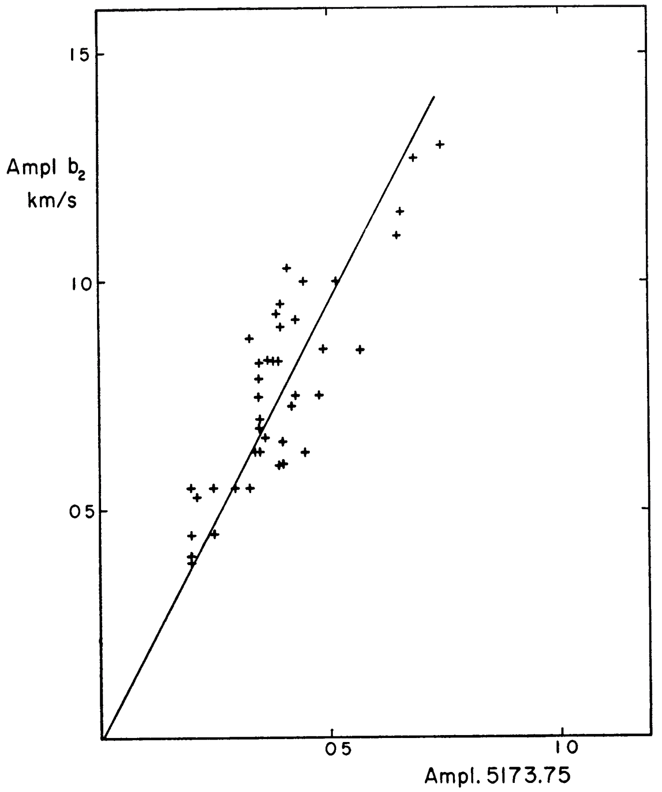

FIG. 2.—The relation between the velocity amplitudes of oscillation at discrete points on the sun observed in b_2 and Ti 5173.75.

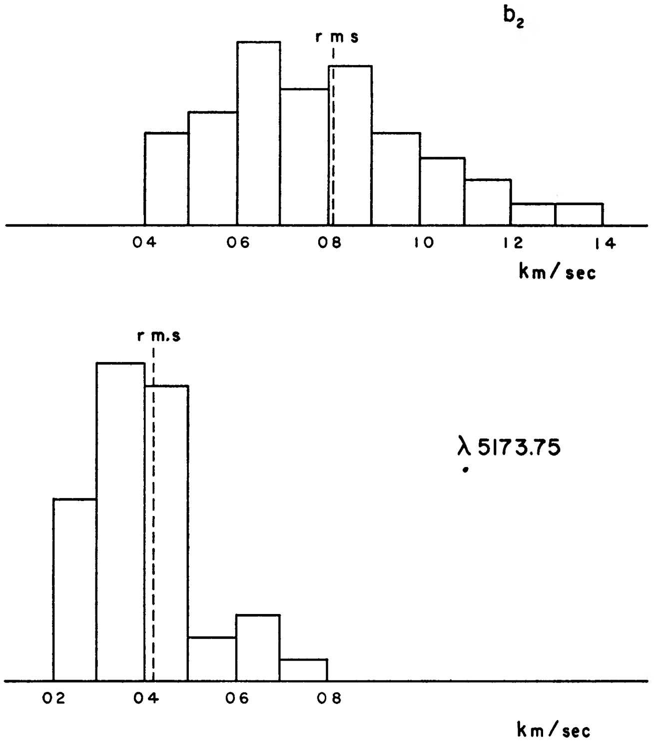

FIG. 3.—The distribution of velocity amplitude in b_2 and Ti 5173.75

r.m.s. deviations in period for single waves, corrected for the errors of estimation, are ±20 and ±32 seconds for b_2 and L. We may draw the following conclusions.

1. The vertical oscillations of the solar atmosphere have a strongly dominant period of about 242 seconds. The dispersion in period of individual waves is surprisingly small. However, periods in the whole range 180–320 seconds were found (Fig. 4).

2. The apparent periods of oscillation at the low level where Ti 5173.75 originates are longer, on the average, than at the high level of b_2. The average difference in period seems to increase progressively with increasing period, from zero for $T_b = 180$ seconds to 25 seconds for $T_b = 280$ seconds (Fig. 5).

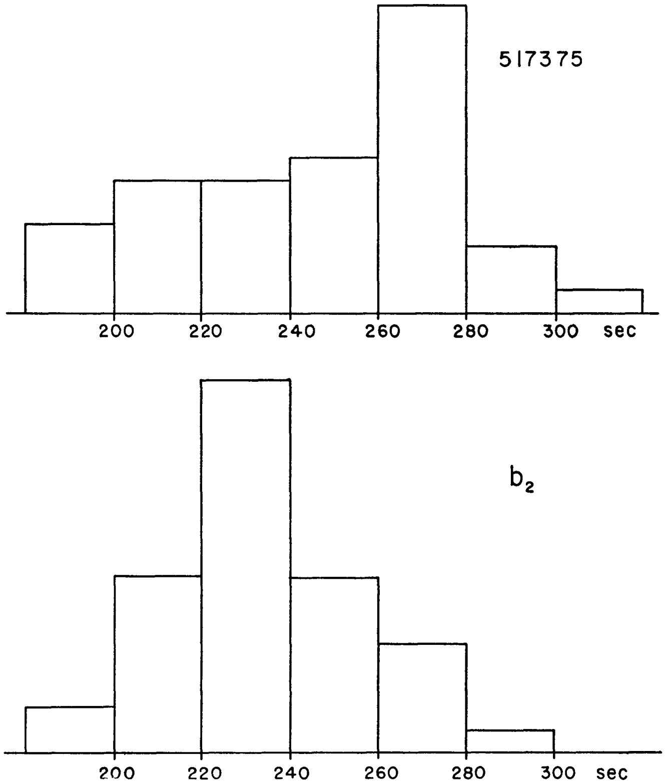

FIG. 4.—The distribution of periods of oscillation in b_2 and Ti 5173.75

3. The periods are independent of amplitudes. (The increased spread in period toward the left in Fig. 6 reflects the greater uncertainty of the period when the amplitudes are small.)

The presence of vertical oscillations in the solar atmosphere immediately raises the interesting question of whether they are progressive waves moving vertically with definite phase lags between the motions at different heights or stationary waves with the same phase at all heights. To answer this question, we estimated the time lag, δt, between the motions in b_2 and L from the $v(t)$ curves for 43 independent oscillations. The difficulty of such estimates will be appreciated from Figure 1, *b*. In all but three of the points the oscillations in b_2 lagged behind those in L by intervals varying from 0 to 27 seconds, suggesting waves with considerable range of upward velocities. Figure 7 is a histogram of the time lags. The mean lag is $\delta t = 8.4 \pm 1.2$ seconds, while the standard deviation for an individual wave is ±7.8 seconds. For three oscillations only, the motion in b_2 is in advance of the motion in L, and δt is negative.

Professor L. Biermann, in a private discussion, has suggested that the observed periods of oscillation, between 200 and 300 seconds, are in the range of transition between progressive pressure waves of short period and stationary gravitational waves of longer periods. We might therefore expect to find a systematic decrease in δt with increasing periods. The periods (mean of T_b and T_L), sorted according to δt, are given in Table 3.

The graph of Figure 8 shows the individual points and the means given in Table 3. In spite of the large dispersion, the mean points suggest that the long-period "waves" are essentially stationary, with small δt's. With decreasing period, the "waves" show decreasing upward velocities, indicated by increasing δt's.

Since we have found that generally $T_b < T_L$, the time lag of b_2 behind L should decrease with time in a given oscillation. Separate estimates of the time lags at the first and second half-periods could be made for 35 oscillations, and at the third half-period for 5 of these; the mean δt are 15, 7, and 0 seconds, respectively, in accord with the expectation. Thus, in most of the oscillations, the phase difference between two given levels continuously changes with time. Obviously, such motions are not strictly periodic. We cannot describe the oscillations by a mixture of typical progressive waves and typical

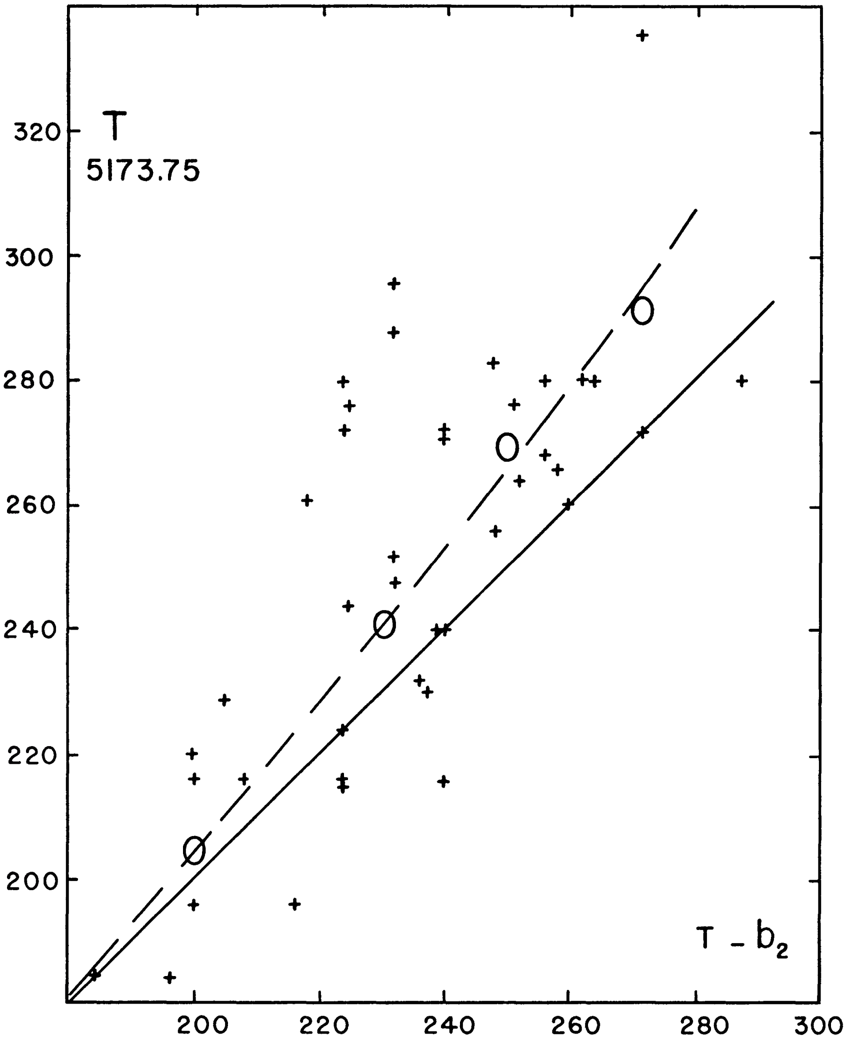

FIG. 5.—The relation between periods of oscillation at discrete points on the sun observed in the lines b_2 and Ti 5173.75. The solid line is the locus of $T_b = T_L$. Open circles represent mean points, suggesting a relation represented by the dashed curve.

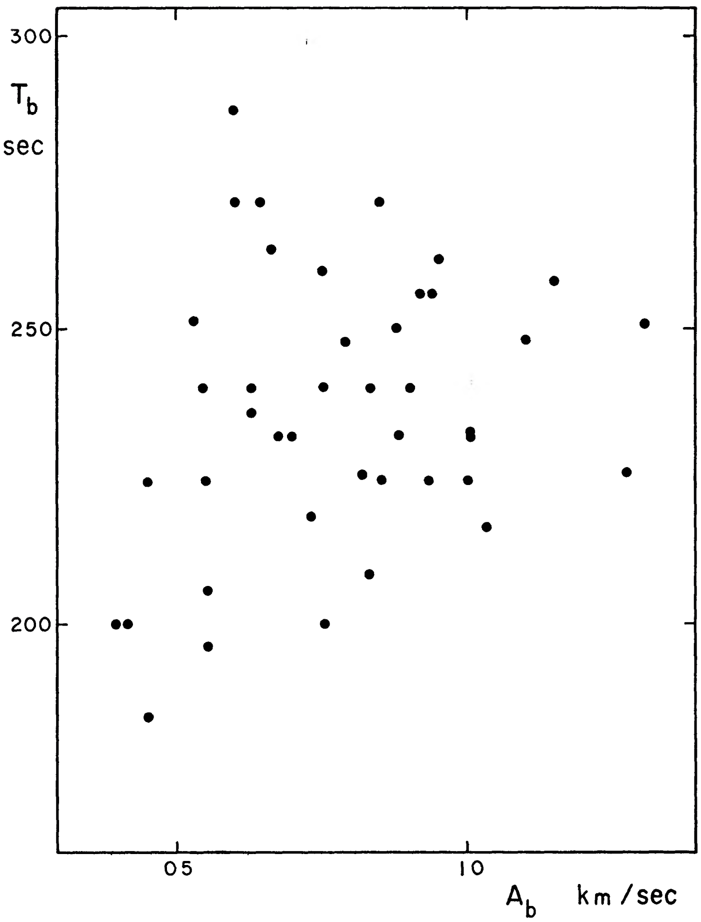

FIG. 6.—Period versus amplitude for oscillations in b_2 at discrete points

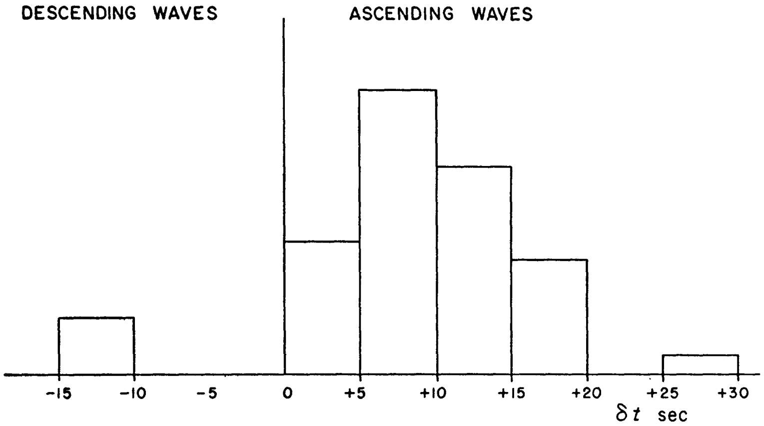

FIG. 7.—The distribution of time lags, $\delta t = t(b_2) - t(5173.75)$

standing waves. We have, instead, a continuous transition from one type to the other during the short life of each oscillation.

The present accuracy of the observations does not permit a full description of the kinematics of the oscillations by detailed analyses of the $v(t)$ curves for the two levels. We have to be content with measuring grossly a few apparently significant parameters of the $v(t)$ curves and trying to interpret the statistical trends in these parameters.

TABLE 3

RELATION BETWEEN PERIOD AND TIME LAG OF OSCILLATIONS IN b_2 AND L

	δt LIMITS			
	0–6	6–10	10–13	13–30
$\langle\delta t\rangle$	3	8	12	19
T	260	248	239	224
No of points	6	14	9	10

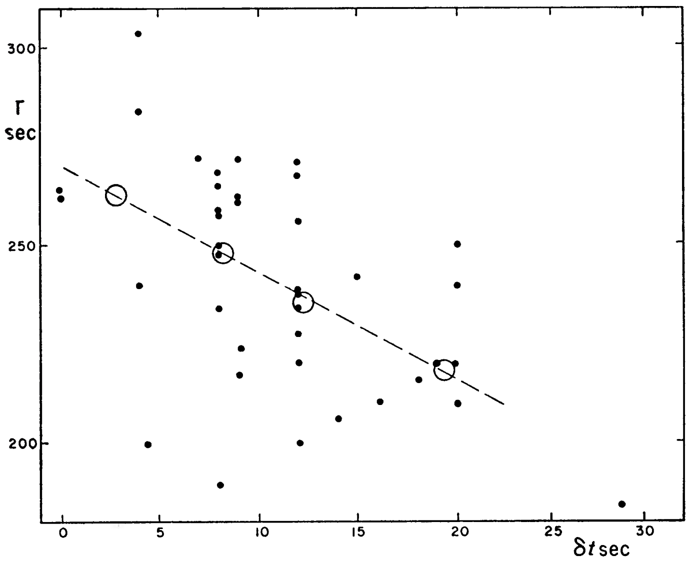

FIG. 8.—The relation between periods and time lags for discrete oscillations. The large circles are means

b) *Preliminary Time-Correlation Curve*

In order to obtain some idea of the relative importance of the oscillatory and non-oscillatory motions in the solar atmosphere, we have determined the variations of the correlation between the velocity fields at different times as a function of the time interval, Δt, for the faint line Ti 5173.75. From the $v(x)$ curves, we calculated the correlation coefficients, $\rho(\Delta t)$, for pairs of spectra, comparing the velocities at 200 points along the slit on each of the spectra numbered 1, 3, and 6 with corresponding points on all later spectra. Figure 9 shows the resulting 35 values of ρ plotted against Δt. To a first approximation, this time-correlation curve has the appearance of a damped sine-curve. The peaks of $|\rho| = 0.5$ indicate that the kinetic energy of the oscillatory motions constitutes a very significant fraction of the total.

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The "period" of $\rho(\Delta t)$ is very near 300 seconds, in excellent agreement with the period of 296 seconds derived by Leighton (1961) from the application of the same autocorrelation procedure to his spectroheliographic photographs of the velocity field. This period differs decisively from the mean period of 250 seconds derived directly for the same line from the study of the strongest individual oscillations. We take this as an indication that in the Fourier spectrum of $v(t)$ there is a long extension of the true distribution of periods toward longer periods; these slower changes cannot be included in our analysis of single "waves" because our total time range is too short and the corresponding amplitudes too small. The presence of these longer periods would shift the maxima and minima of the $\rho(\Delta t)$ curve in the observed direction. The true distribution of periods could be derived from a sufficiently accurate time-correlation curve, the energy of each being given by the Fourier transform of $\rho(\Delta t)$. We expect to perform this analysis when the $\rho(\Delta t)$ curve has been derived in more detail for a larger range of Δt.

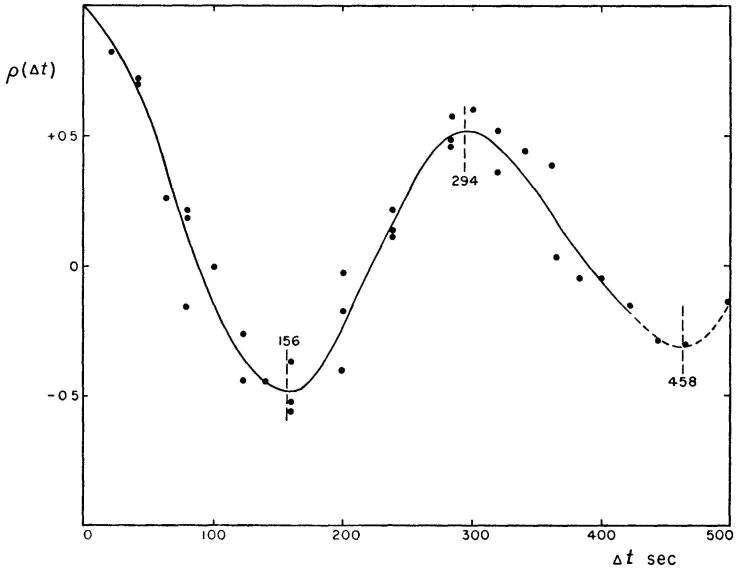

FIG. 9.—The variations of the coefficient of correlation between velocity-curves in Ti 5173.75 as a function of the time interval, Δt, between them.

If the above explanation of the difference between individually observed periods and the "period" of $\rho(\Delta t)$ is correct, the presence of slow changes in the velocity field should produce a residual positive correlation at not too large Δt, which would tend to increase $\rho(\Delta t)$ algebraically. Thus the anticorrelation at $\Delta t = 150$ seconds would be less, and the correlation at 300 seconds would be greater, than the values expected if the slow changes were eliminated. In Figure 9, $\rho(150) = -0.5$ and $\rho(300) = +0.5$, in spite of the fact that the numerical value of ρ generally decays with increasing Δt, as is shown by $\rho(450) = -0.3$. This observed effect is in the expected direction. The Fourier spectrum of the time changes of velocities probably contains not only the dominant periods around 250 seconds but also much longer periods, possibly forming a continuum.

While the correlation procedure gives a more complete representation of the time changes in the velocities, the mean period derived from $v(t)$ curves for the strongest oscillations is probably more directly related to the resonance characteristics of the solar atmosphere. Let us also emphasize that the apparent "period" in the $\rho(\Delta t)$ curve should not be identified with the dominant period in the actual velocities. This identification would be possible only if the changes were strictly periodic with a single frequency.

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c) *Association with Continuum Features*

One other peculiarity of the periodic motions is their relation to the photospheric granulation. In the second paper of this series (Evans and Michard 1962*b*), we confirmed earlier reports of poor correlation between the brightness of the continuum and the Doppler shift in the Fraunhofer lines. In agreement with Servajean (1961), we found, however, that 70 per cent of the strong bright and dark continuum features are associated with violet and red shifts in the lines. A similar qualitative study of our material (and also of a motion picture of the Doppler shifts of medium-strength lines around λ 5330, taken at 6 frames per minute) shows that the appearance of a strong *bright* feature in the continuum is followed by an oscillation in the lines, initiated by a *violet* shift. The first velocity maximum occurs about 40 seconds later than the maximum brightness in the continuum feature, which then appears to fade out in a few minutes without oscillation. The important questions of how prevalent the effect is and whether dark continuum features are associated with Doppler shifts can be settled only by more critical observations. However, it is to be noted that the observed association and time lag qualitatively account for both Servajean's observations and the low but significant correlations found between continuum brightness and Doppler shifts.

IV. VELOCITIES NEAR THE LIMB

The September 30, 1960, series of spectrograms, taken with the slit crossing the southern limb of the sun radially, covered 620 seconds with exposures at 20-second intervals. The spectra extend from $\mu = 0.82$ to the limb. Frames 10, 11, 12, and 20 were unusable because of exposures by static discharges in the camera. The $v(t)$ curves for Fe 5324.18, with Rowland intensity 7, were derived for 62 independent points along the slit, at each of which a pronounced velocity maximum or minimum occurred during the time of observation. A study of the $v(x)$ and $v(t)$ curves showed the following:

a) The sight-line velocity oscillations that are so prominent at the center of the disk degenerate with decreasing μ and are undetectable when μ is less than 0.5.

b) Some sign of oscillation, considerably distorted by random perturbations, was evident in 18 of the $v(t)$ curves. Figure 10 displays the two curves showing the clearest and the two showing the most doubtful oscillations from among these. Of the 18, 11 were in the interval $33° < \theta < 46°$; 7 in the interval $46° < \theta < 59°$; and none at $\theta > 59°$.

c) The r.m.s. amplitude for the 18 oscillating elements was 0.5 km/sec (reduced to the center of the disk, supposing the true motion vertical), and the mean period was 260 seconds. The standard deviations for a single wave were 0.13 km/sec in amplitude and 30 seconds in period. The mean period and amplitude are in reasonable agreement with those found in the oscillations at the center of the disk.

d) The *non-periodic* motions decrease toward the limb beyond $\mu = 0.5$, probably because of the smoothing effect of the diminishing linear resolution on the sun as μ approaches zero. The random sight-line velocities, ξ(r.m.s. multiplied by $\sqrt{2}$), as a function of x along the slit at any one time as shown in the $v(x)$ curves, and as a function of time for a fixed point on the slit as shown in the non-periodic $v(t)$ curves, vary with μ as shown in the accompanying table.

μ	$\xi(x)$	$\xi(t)$	μ	$\xi(x)$	$\xi(t)$
0.2–0.4	0.26	0.14	0.6–0.7	0.37	0.23
0.4–0.6...	0.26	0.19	0.7–0.8.	0.34	0.23

Thus the time variations of sight-line velocity in a non-oscillating surface element are significantly smaller than the variations from point to point on the sun. This result confirms the appearance of the array of $v(x)$ curves, which shows a number of prominent velocity peaks persisting with only small changes throughout the 620 seconds of observation.

V. DISCUSSION

In the preceding we have reported all the information on the oscillations of the upper photosphere that we could, up to now, derive from observation. When the comparison is possible, our observational results agree with those of Leighton. Our most important complement to his work is the possibility of studying individual "waves" with quantitatively measured velocities and phase relationships between motions at two different levels or between velocities and granulation (in the continuum or in lines).

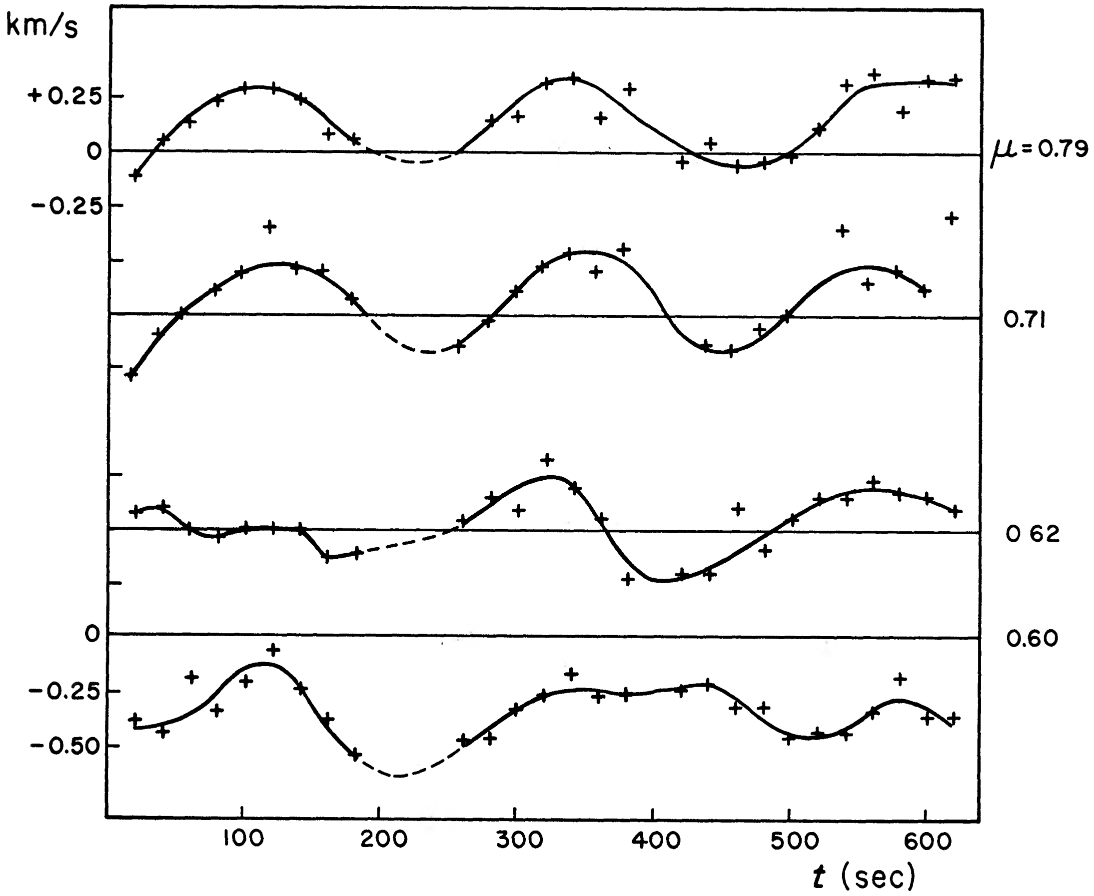

FIG. 10.—The two clearest (μ = 0.79, 0.71) and the two most doubtful (μ = 0.62, 0.60) oscillating $v(t)$ curves away from the center of the solar disk.

The physical nature of the oscillatory motion is by no means obvious from our results. We do not attempt an exhaustive discussion but only a review of some points of interest, with a few remarks pertaining to evident or more subtle observational limitations.

a) The observations at the center of the disk select the vertical component of the motion. They show that a very large fraction of the kinetic energy of this motion is contained in oscillations over a very restricted range of periods, which increase in amplitude with height in the solar atmosphere. The mean amplitudes at the levels of formation of Ti I 5173.75 and the b_2 line are in the same ratio as the random turbulent velocities for these lines at any one time. The dispersion in period of the strong oscillations is less than 15 per cent of the mean, suggesting a kind of resonance effect.

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b) There is a very fast decrease in the visibility of oscillations with increasing distance from the center of the disk. The observable horizontal velocity field near the limb is not oscillatory and appears to consist of large elements of the solar surface (10000–20000 km against a characteristic size of 2000–3000 km for the vertical oscillations) with rather persistent velocities of the order of 0.5 km/sec. These large elements are probably the same as the "supergranulation" described by Leighton, Noyes, and Simon (1962). On the large elements are superimposed small random velocities. It seems, therefore, that the observable parts of the horizontal and vertical motions are independent and have a different physical origin.

c) Two extreme simplified cases of oscillatory vertical motion can be considered: longitudinal pressure waves propagating in a nearly vertical direction with sonic velocity and transverse gravitational waves which may propagate horizontally. For an isothermal atmosphere the transition between the two types occurs for a critical period $T^\circ = 4\pi h/v_s$ (h = scale height, v_s = sonic velocity). For the upper photosphere this quantity is of the order of 300 seconds. The periods of the observed oscillations seem to be on the lower side of this limit. This first argument favors sound waves. However, h changes with height in the solar atmosphere, and there is sufficient uncertainty in its value to limit the significance of this remark.

We may now make a guess at the difference of effective level for our two lines, b_2 and 5173.75 Ti. Calling these levels H and L, we may write, if there is no damping: $\rho_H V_H^2 = \rho_L V_L^2$, where ρ is the density, V the local wave amplitude. From the observed $V_H/V_L \approx 2$, we find $\rho_L/\rho_H \approx 4$. If the local scale height is 150 km, the difference of level is 210 km, and the expected time lag between oscillations at the two levels for sound waves is about 30 seconds. For plane waves propagating at an angle ψ to the vertical, it is easily seen that the phase difference in two points at the levels L and H on a common vertical along the line of sight is reduced (multiplied by $\cos \psi$). Accordingly the time lags of $\backsim$20 seconds found for the *short-period* oscillations ($T_b \approx 200$ seconds) do not differ seriously from the predicted lag for sound waves. However, for the long-period "waves" ($T_b \approx 270$ seconds), the time lag tends toward zero; the vertical component of their phase velocities appears to be in excess of $\approx$100 km/sec, and they are observationally indistinguishable from standing waves.

On the whole, it would seem that the strong oscillations are in the transition range between sound waves and standing gravity waves. But if our results on the progressive decrease of the time lag $\delta t = t_b - t_L$ at successive half-periods are correct, the transition occurs *during the lifetime of a single oscillation*. Then it appears that our choice is not between two simple types of waves (or a mixture of these two types) but that the phenomenon is intrinsically more complicated. The fact that the field of oscillations is observed at a level very close to its probable source (the convection zone) and is in a region of the solar atmosphere intermediate between photosphere and chromosphere does not leave much hope of simplicity!

d) According to our preliminary observations, bright granules are followed by oscillations starting with an upward motion. The difference of level between the "continuum layer" and the L level of formation of our faint line is 200–300 km. The time lag between peak granule brightness and peak violet shift is about 40 seconds. This could be tentatively interpreted in the following way: the formation of the granule is associated with an upward "push" of material; this impulsion propagates upward at the sonic velocity. Both gas pressure and gravity act as restoring forces, thus producing an oscillation. Gas pressure minus gravity will be the force that makes the material bounce upward again. It is likely that gravity is the main driving force when the motion has to propagate downward in the second half-period, and it is then that the initial time lag between layers is progressively reduced. The resulting oscillation is not strictly periodic. The observations suggest further that the oscillation disappears rather through interference with a new one than through damping. It seems that the most useful mathematical approach toward the interpretation of our observations is the paper by Whitney (1958).

e) At higher chromospheric levels, the preliminary results of Leighton *et al.* (1962) show no evidence of oscillatory motion for the "chromospheric" lines Ca II 8542 and Hα. This is confirmed by our preliminary study of Ca II 8542. Motions in this line are complex and poorly correlated with the oscillatory motions in the nearby Fe I 8514 (detailed data on motions in Ca II 8542 will be reported later). It appears, therefore, that the strong oscillations are confined to the layer of formation of lines of neutral metals, that is, to the temperature minimum between photosphere and chromosphere.

f) Because of the thickness of the line-forming layer, we integrate velocities along a length Δz of the line of sight. On the other hand, because of imperfect resolution in the image, we integrate them over a little circle ("tremor disk") of radius Δr. To detect a sizable element of the velocity field at the point under consideration, it is necessary that the motion remains *coherent* along the length Δz and in the area $\pi\langle\Delta r^2\rangle$. This is a serious limitation. Consider, for instance, a vertically progressive sound wave of wavelength Λ. It will be strongly washed out if Δz is of the order of $\Lambda/2$ or larger. We may take $\Delta z \approx 200$ km for a vertical sight line; then vertical sound waves with $\Lambda \leq 400$ km or $T \leq 60$ seconds will not be readily detected by line displacements. Consider also a sound wave with $\Lambda = 1400$ km propagating at 45° to the vertical. It is easily seen that two points 1000 km apart on the solar surface in the vertical plane containing the direction of propagation have opposite velocities. These two points are barely resolved, and the wave under consideration is strongly washed out. Limitations in the observability of different types of motions should be kept in mind when discussing the velocity field.

The authors are grateful to Dr. Biermann for his useful suggestion that there should be a relation between periods and time lags and to Dr. Leighton, who communicated to us the manuscript of his important paper on these problems.

This work was performed while R. Michard was at the Sacramento Peak Observatory as Visiting Astronomer, with the kind permission of the Directeur de l'Observatoire de Paris.

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