

VELOCITY FIELDS IN THE SOLAR ATMOSPHERE

I. PRELIMINARY REPORT*

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ABSTRACT

Velocity fields in the solar atmosphere have been detected and measured by an adaptation of a technique previously used for measuring magnetic fields. Data obtained during the summers of 1960 and 1961 have been partially analyzed and yield the following principal results:

1. Large "cells" of horizontally moving material are distributed roughly uniformly over the entire solar surface. The motions within each cell suggest a (horizontal) outward flow from a source inside the cell. Typical diameters are 1.6×10^4 km; spacings between centers, 3×10^4 km ($\sim 5 \times 10^8$ cells over the solar surface); r.m.s. velocities of outflow, 0.5 km sec^{-1} ; lifetimes, 10^4 – 10^6 sec. There is a similarity in appearance to the Ca^+ network. The appearance and properties of these cells suggest that they are a surface manifestation of a "supergranulation" pattern of convective currents which come from relatively great depths inside the sun.

2. A distinct correlation is observed between local brightness fluctuations and vertical velocities: bright elements tend to move upward, at the levels at which the lines $\text{Fe } \lambda 6102$ and $\text{Ca } \lambda 6103$ are formed. In the line $\text{Ca } \lambda 6103$, the correlation coefficient is ~ 0.5 . This correlation appears to reverse in sign in the height range spanned by the Doppler wings of the $\text{Na } D_1$ line and remains reversed at levels up to that of $\text{Ca}^+ \lambda 8542$. At the level of $\text{Ca } \lambda 6103$, an estimate of the mechanical energy transport yields the rather large value 2 W cm^{-2} .

3. The characteristic "cell size" of the vertical velocities appears to increase with height from ~ 1700 km at the level of $\text{Fe } \lambda 6102$ to ~ 3500 km at that of $\text{Na } \lambda 5896$. The r.m.s. vertical velocity of $\sim 0.4 \text{ km sec}^{-1}$ appears nearly constant over this height range.

4. The vertical velocities exhibit a striking repetitive time correlation, with a period $T = 296 \pm 3$ sec. This quasi-sinusoidal motion has been followed for three full periods in the line $\text{Ca } \lambda 6103$, and is also clearly present in $\text{Fe } \lambda 6102$, $\text{Na } \lambda 5896$, and other lines. The energy contained in this oscillatory motion is about 160 J cm^{-2} ; the "losses" can apparently be compensated for by the energy transport (2).

5. A similar repetitive time correlation, with nearly the same period, seems to be present in the *brightness fluctuations* observed on ordinary spectroheliograms taken at the center of the $\text{Na } D_1$ line. We believe that we are observing the transformation of potential energy into wave energy through the brightness-velocity correlation in the photosphere, the upward propagation of this energy by waves of rather well-defined frequency, and its dissipation into heat in the lower chromosphere.

6. Doppler velocities have been observed at various heights in the upper chromosphere by means of the $\text{H}\alpha$ line. At great heights one finds a granular structure with a mean size of about 3600 km , but at lower levels one finds predominantly *downward* motions, which are concentrated in "tunnels" which presumably follow magnetic lines of force and are geometrically related to the Ca^+ network. The Doppler field changes its appearance *very rapidly* at higher levels, typical lifetimes being about *30 seconds*.

In an earlier paper, Leighton (1959) described a method for obtaining "spectroheliograms" whose density variation indicated the presence of Zeeman splitting due to longitudinal magnetic fields on the sun rather than actual light-intensity variations. This method is readily applicable to measurements of Doppler shifts as well as Zeeman splitting, giving a "spectroheliogram" of the line-of-sight velocity field in the region of line formation. The present paper describes some of the velocity observations made in this way during the summers of 1960 and 1961. Some of the results have been reported by Leighton (1960, 1961).

I. OBSERVATIONAL TECHNIQUES

The specific details of the method were described in the above-mentioned paper, so we shall give here only a brief description of how it has been adapted to the measurement of Doppler shifts.

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To observe velocity fields, one omits the quarter-wave plate and polaroids which are used in observing magnetic fields and utilizes instead a "line-shifter," comprising two glass blocks situated just below the exit slit, one for each of the two images formed by the beam splitter (Fig. 1, *a*). These blocks may be tilted equal amounts in opposite directions about an axis parallel to the slit, thus shifting the spectrum at the exit slit equal amounts in opposite directions. With the blocks initially having no tilt, the slit is precisely centered on a spectral line having a symmetrical profile. The blocks are then tilted a prescribed amount, so that the wavelength of light passed by the slit corresponds to a position on the red wing of the line for one image and an equidistant position on the violet wing for the other image (Fig. 1, *b*). A Doppler shift of the line then moves the line core *toward* the slit for one image and *away* from the slit for the other, thereby producing opposite changes in the amount of light passed by the slit to the photographic plate.

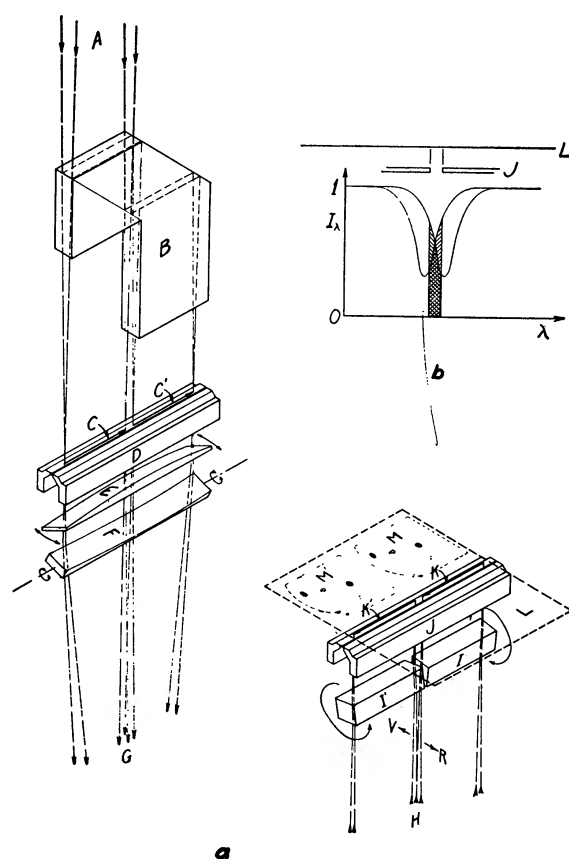


FIG. 1 —(a) Schematic diagram of the optical system *A*: vertical light-beam of the 65-foot tower telescope. *B*: optical glass beam splitter (moves with spectroheliograph). *C, C'*: duplicate images. *D*: entrance slit (19 $\frac{3}{4}$ cm long). *E*: double-convex lens used to adjust the "tilt" of the spectral lines *F*: double-concave lens used to adjust the "curvature" of the spectral lines. (*E* and *F* also act as a field lens for the spectrograph.) *G*: "split" light-beam proceeding toward the collimator lens *H*: dispersed light-beam proceeding from the camera lens (*V* and *R* designate the violet and red directions along the spectrum). *I, I'*: plane-parallel glass blocks, whose equal and opposite tilt serves to "shift" the spectra of the two images *C, C'* equally in opposite directions *J*: exit slit. *K, K'*: monochromatic image "strips" passed by exit slit. *L*: photographic plate. *M, M'*: latent images on photographic plate, built up of successive "strips" by the motion of the spectroheliograph. (b) Diagram of the action of the line shifter, showing the displaced line profiles. The crosshatched sections represent the portion of the line profiles admitted to the photographic plate *L* by the exit slit *J*.

The resulting two images are "canceled" with each other photographically by the same method as was previously used: a unity-gamma contact transparency is made of one of the images such that, when placed on its own negative, a uniform gray field results. When placed on the other negative, however, the Doppler shift contribution to the image is enhanced, while density variations due to variations of intrinsic brightness on the sun "cancel" to a uniform gray. Thus a "spectroheliogram" is produced in which darker-than-average areas represent velocities of approach, and lighter-than-average areas, velocities of recession or vice versa. The variations of transmission of this "Doppler plate" are, over a significant range, proportional to the velocities on the sun; the proportionality constant is determined by the calibration method described in the previous paper or, preferably, by introducing an accurately known wavelength shift by moving the exit slit by a small, precisely defined amount at some time during the exposure (Fig. 4).

In practice, several pairs of images are usually taken in succession. By photographically subtracting, in the same way as above, two *singly canceled* plates (each representing the Doppler field from a single pair of images), a "double cancellation," or *Doppler difference* plate, is obtained. If the two original image pairs were exposed under identical conditions and *if the velocity field on the sun were the same for both pairs*, the two singly canceled Doppler plates would be identical, and their Doppler difference would be an uninteresting uniform gray. However, a time interval of a few minutes elapses between exposures, due to the finite scanning speed of the spectroheliograph, during which appreciable changes in the velocity field occur. A second cancellation results in signals which sufficiently exceed the "noise" due to imperfect registration, guiding errors, and seeing fluctuations to provide a measure of *accelerations* in the solar atmosphere. Some of the most interesting results so far obtained involve changes in the photospheric velocity field which occur during the traversal time of the spectroheliograph.

If, between taking two successive pairs of images, the glass blocks are reversed in their tilt, the sign of the Doppler contribution is reversed on each image, and the "polarity" of the Doppler signal is reversed on the singly canceled plate. Then, when a second subtraction is made between two such Doppler plates of opposite polarity, the Doppler signals *add*. This *Doppler sum* would produce a fourfold enhancement of the Doppler contribution to each original image, while other signals would cancel to zero, if the velocity field did not change during the time interval between exposures.

A typical observational procedure might be as follows: the glass blocks of the line shifter are initially tilted so that the two halves of the plate receive light from opposite wings of a spectral line. At $t = 0$, the spectroheliograph is started moving south across the 17-cm solar image. (The scan direction of the instrument is roughly parallel to the axis of rotation of the sun.) It finishes an 11-cm scan 3 or 4 minutes later. Immediately the spectroheliograph is stopped, the plate changed, the line shifter either reversed or left unchanged, depending on the purpose of the observation, and the spectroheliograph again started, moving north. Several seconds are required to make these changes. The spectroheliograph finishes its traverse 3 or 4 minutes later, 6 or 8 minutes after beginning the sequence.

Each of the two pairs of images is canceled to form a Doppler plate, and the two resulting plates are again canceled to form either a Doppler difference or a Doppler sum plate, depending, respectively, on whether the shifter was untouched or reversed between exposures.

Such a Doppler difference (or sum) plate has the characteristic that the time elapsed between recording the two velocities which are subtracted (or added) varies linearly from nearly zero at one end to 6 or 8 minutes at the other end. The effects of still longer time delays may be observed by waiting a certain time between taking the two exposures. Doppler difference or sum plates with *constant* time differences over the entire image may be obtained by subtracting two pairs of images scanned in the *same direction*

at the same traverse speed. The application of all these techniques will be described later with the presentation of data obtained by them.

Many sequences of such observations were obtained at the 65-foot solar tower telescope of the Mount Wilson Observatory during the summers of 1960 and 1961. For most of these observations a 17-cm diameter image, formed by the 30-cm objective, was used. In a few instances, however, the entire solar disk was recorded, using a 5-cm image. The field of view covered by a single image is about 9 by 11 cm (16' by 20' on the 17-cm image). The spectral lines used were Fe 6102.4, Ca 6102.8, Na 5896, Ba⁺ 4554, Mg 5173, Ca⁺ 8542, Mg 5528, H α , and sometimes others. Both slits were ordinarily set at 0.05 or 0.07 mm width, corresponding to angular resolution of about 0".6–0".8 on the 17-cm image,¹ and a wavelength window of 0.07–0.10 Å. The line shifter was usually set so that this window was centered about 0.10 Å either side of the line center, except that, for H α , considerably greater offsets were used. Precise setting of the second slit on the unshifted line is required to insure that the two images are taken at wavelengths equidistant from the line center and thus represent the same physical height in the atmosphere. The spectral line is rendered straight and parallel to the slit by means of certain optical elements which serve to introduce adjustable curvature and tilt into the lines (Fig. 1) and is photometrically centered on the slit to within 0.01 Å along the entire slit length.

II. MEASUREMENT PROCEDURE

In order to extract reliable statistical information from a Doppler plate without undue amounts of calculation, a device (Fig. 2) was built which carries out the operations involved in evaluating auto-correlation (A-C) and cross-correlation (C-C) functions over a two-dimensional field. The two-dimensional A-C function $C(s, t)$ is defined by

$$C(s, t) \equiv \frac{K}{A} \iint T(x, y) T(x + s, y + t) dA \equiv K \langle T(x, y) T(x + s, y + t) \rangle,$$

where A is the area, $T(x, y)$ is the transmission of the plate at the point (x, y) , K is a normalization constant, and the integration area is made sufficiently great that fluctuations due to the boundaries are negligible. To obtain the A-C function over a given area A , two copies of the plate are made, in a right- and left-handed pair, so that they may be placed in register with their emulsions in contact. On one plate, the entire area except for the area of interest is masked off. The plates are fixed to separate frames, which are placed in a holder in such a way that their emulsions are in contact and in register. A motor drive slides one plate slowly past the other. Collimated light is passed through the two plates and is brought to a focus on the photocathode of a photomultiplier tube. When the plates are displaced an amount s in the x -direction and t in the y -direction, relative to each other, the photomultiplier records $C(s, t)$. In practice, t is usually zero. The signal $C(s, 0)$ from the photomultiplier is amplified and fed into a 0–10-mv chart recorder. Since the fluctuation of $C(s, 0)$ seldom exceeds 10 per cent, a 10 $\times$ multiplier resistor is inserted in the circuit, along with a 90-mv bucking voltage. Thus the chart recorder's range is between 90 and 100 mv, and the full scale of the chart represents a 10 per cent change in the signal. Multiplication by other factors with appropriate bucking voltage is also sometimes used.

Two easily measured parameters of an A-C function yield relatively direct information about the field $T(x, y)$ from which the function was obtained. The full width at half-maximum (FWHM), when converted into units of km on the sun, provides a measure of the *linear size* of the elements in the field; the normalized height of the central

¹ Because of smearing effects due to the atmosphere and the spectrograph, the actual resolution attained on the 17-cm image was about 2'' under good conditions in 1960 and about 1'' in 1961. Only plates taken under very good seeing conditions were utilized for the measurements reported here.

peak, $H \equiv [C(0, 0) - C(\infty, 0)]/C(\infty, 0)$, is equal to the *mean-square variation of transmission* on the plate. Of course, an A-C function contains much more information than that given by its height and width; in fact, one can obtain from it the spectral distribution of the statistical field represented by $T(x, y)$, since the Fourier transform of the A-C function is the absolute square of the Fourier transform of $T(x, y)$ (Blackman and Tukey 1959). In the present preliminary report, only the height and FWHM are used. Many of the A-C functions possess interesting characteristic shapes which we plan to analyze in detail later.

III. SENSITIVITY AND ERRORS

An indication of the *sensitivity* of the method is provided by Figures 3 and 4. Figure 3 shows a doubly canceled Doppler sum plate of the entire solar disk, taken on the wing of the Ca 6103 line with the 5-cm solar image. The line "tilt" was adjusted to zero, using unimaged sunlight, so that the velocity field due to the solar rotation appears as a rather uniform density gradient from east to west. Figure 4 shows a doubly canceled Doppler sum plate of a part of the solar disk, taken on the wing of the Ca 6103 line with the 17-cm solar image. On this plate the line "tilt" was adjusted so as to suppress the uni-

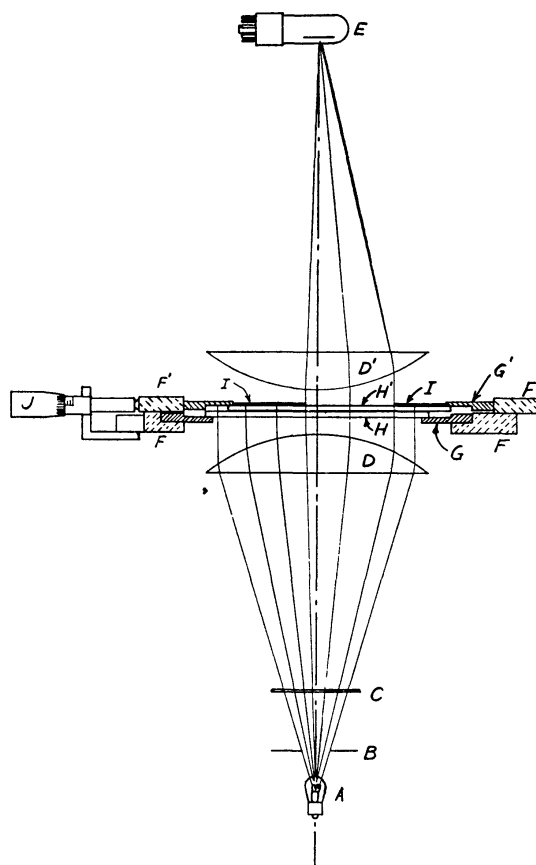


FIG. 2—Schematic diagram of the autocorrelation device. *A*: 6-v, 4.5 A coiled-filament lamp, air-cooled to reduce convection currents. *B*: beam defining stop. *C*: gradient-compensating filter. This filter has a linear density gradient from edge to edge; by adjusting its azimuth, an over-all "tilt" of the A-C curve may be avoided. *D, D'*: plano-convex condensing lenses. *D* renders the light parallel, and *D'* concentrates it upon the photomultiplier cathode, *E*. *F*: fixed mounting frame. *F'*: movable frame. *G, G'*: circular plate carriers. These carriers may be rotated 0°–360° in azimuth and locked in position. *H, H'*: matched right- and left-hand plates, emulsion sides in contact. The plates are fixed to the carrier *G, G'* so as to be in register when the carriers are concentric and co-azimuthal. *I*: aperture stop which defines the area of integration. *J*: motor-driven micrometer, which slides frame *F'* slowly past *F*. (Motor not shown.)

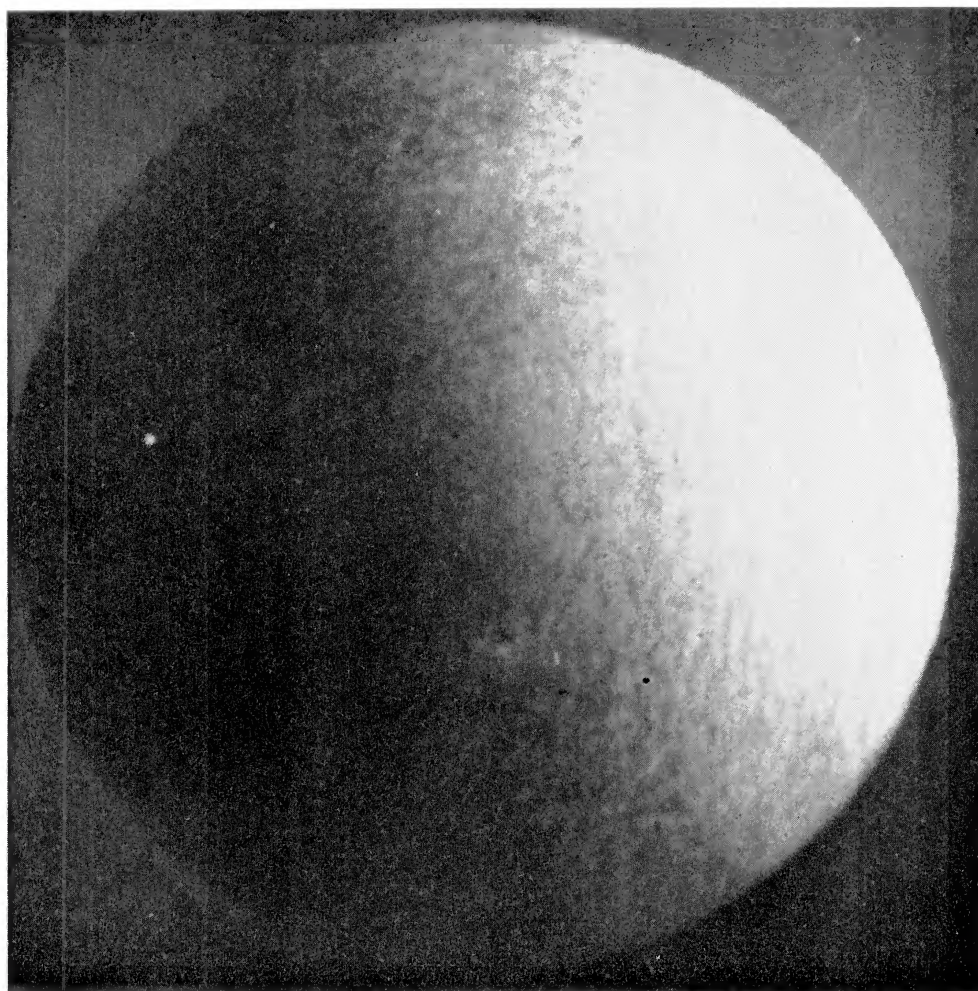


FIG. 3.—Doppler sum plate of 5-cm solar image, showing the effects of rotation. June 25, 1960, 14^h30^m U.T.

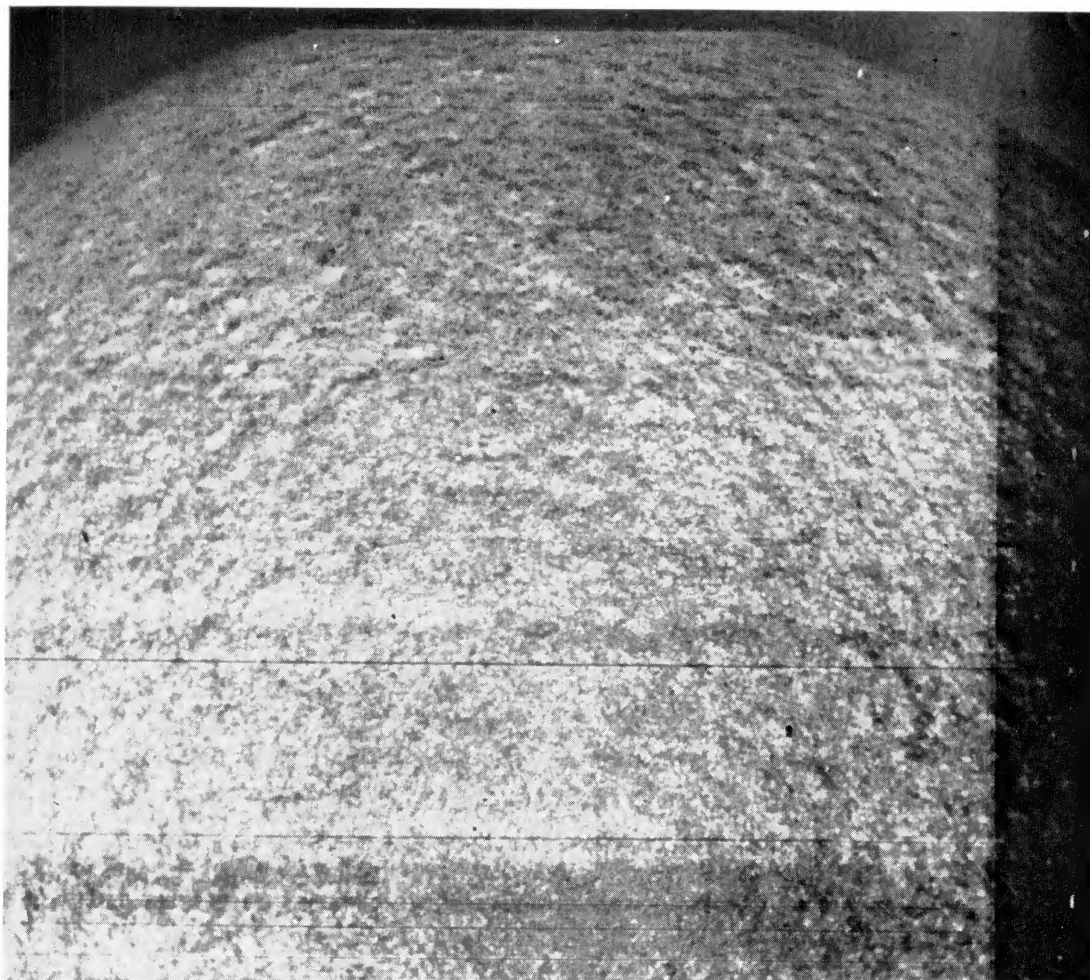


FIG. 4.—Doppler sum plate of 17-cm solar image in the line Ca 6103, showing large- and small-scale velocity fields. The dark strip at the right corresponds to a line-of-sight velocity of 0.75 km sec^{-1} . Dark areas are receding. June 11, 1961, $14^{\text{h}}10^{\text{m}}$ U.T.

form gradient due to solar rotation, but at a certain point during the exposure the exit slit was shifted in position by 0.010 mm, which is equivalent to the Doppler shift due to a velocity of 0.75 km sec^{-1} . It is apparent from these plates that a velocity component of but a small fraction of a kilometer per second is detectable.

It is not possible to state a general number which describes the *precision* of a velocity measurement, because of the presence of both random and systematic errors which vary with the particular type of plate, the seeing, the number of cancellations involved, and a number of other factors. We are obliged to calibrate the velocity sensitivity of each plate by means of the calibration procedure described in the earlier paper or by introducing a standard "Doppler shift" by moving the exit slit by a precisely defined amount, as illustrated in Figure 4. The latter method, which has been used on the 1961 plates, is preferred because it appears directly as a density change on the plate itself at every stage of cancellation and is therefore less susceptible to systematic errors in the subsidiary photographic steps. We estimate the error due to systematic effects to be 10–20 per cent for each step involving a print, so that the calibration error inherent in the earlier procedure may be 50–100 per cent on doubly canceled plates but is smaller at all stages by the slit-offset method.

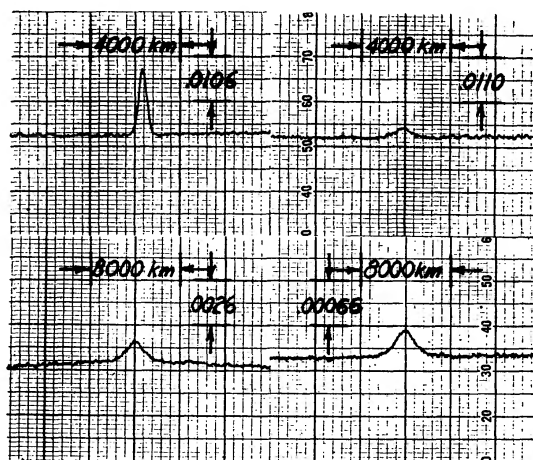


FIG. 5—Autocorrelation-curves of plate grain and Doppler "noise." *Top, left:* plate grain of fogged II-F plate, in focus. *Top, right:* the same, slightly out of focus (as used). *Bottom, left:* Doppler "noise" for Na 5896 noise plate, single cancellation. *Bottom, right:* the same, double cancellation. (The vertical scale is referred to the original plate in each case.)

In order to estimate the magnitude of the "noise" error due to imperfect adjustment of the correction lenses and line shifter, imperfect registration of the two images, non-unity gamma in the cancellation process, and plate grain, we expose a plate so that both images record the same wing of the spectral line rather than opposite wings. All that should remain from a single subtraction of two such images is "noise" from the above-mentioned sources, and the mean-square fluctuation of transmission on such a singly canceled "noise" plate should approximate the mean-square noise signal on a singly canceled normal Doppler plate. Figure 5 shows A-C curves for singly and doubly canceled noise plates exposed 0.10 Å to the red of the center of the line Na 5896. Such measurements indicate mean-square noise on single cancellation of 0.0012 and 0.0025, or $(0.13 \text{ km sec}^{-1})^2$ and $(0.16 \text{ km sec}^{-1})^2$ on the two respective lines Ca 6103 and Na 5896. Also shown in Figure 5 are A-C curves of the plate grain of a uniformly fogged II-F plate, with the grain both in sharp focus and *slightly* defocused.²

² The singly canceled plates are duplicated as $1\times$, unity-gamma projection transparencies. At this stage, the images are purposely thrown *slightly* out of focus, to avoid compounding the "noise" due to photographic grain (Fig. 5).

IV. RESULTS

a) *Long-lived, Large-Scale Motions in the Photosphere*

Figure 6 shows a Doppler sum plate similar to that shown in Figure 3, except that the line "tilt" due to solar rotation has been removed by adjustment of the tilt-correcting lens (Fig. 1). Immediately apparent on this plate and in Figure 4 are numerous velocity "cells" many thousand kilometers in diameter, superimposed upon the gray background which represents zero velocity. Toward the limb, the cells appear elongated parallel to the limb, as if seen in projection, and near the center of the disk they are scarcely visible at all. There is no apparent difference between equatorial and polar regions, although latitudes greater than about $\pm 60^\circ$ are difficult to study. Closer inspection of the more prominent cells reveals that the side nearer the center of the disk is generally lighter (darker), while that nearer the limb is darker (lighter), i.e., this "polarity" is the same for all and always corresponds to a velocity of approach for the near side and of recession for the far side. The same individual cells are easily seen on plates taken an hour or so apart.

These qualitative observations may be synthesized into the following picture: *There exists on the sun a system of horizontally moving currents, which are distributed rather uniformly over the solar surface in many more or less individual "cells," each many thousand kilometers in diameter. Within each cell, the motion is from the center toward the outer boundary. The lifetime of a cell is on the order of several hours.*

Some of the properties of the large cells were measured through the use of A-C and C-C functions as outlined in Section II. The rather typical A-C functions shown in Figure 7 possess several interesting and important features. First, the FWHM of the function for an offset direction parallel to the limb may be used as a measure of the average size of the cells; we find $1.4\text{--}1.8 \times 10^4$ km from measurements made on Na 5896 plates.³

A second feature is the "undershoot" exhibited by A-C curves for radial offsets (i.e., perpendicular to the limb). This comes from the "antisymmetry" of $T(x, y)$ about the center of each cell in this direction, as may be seen by evaluating the A-C function of a function which shows symmetry along one axis and antisymmetry along the other. For example, let a typical cell correspond to a velocity $V_\rho(\rho) = F(\rho)$ where ρ is the radius vector of a system of plane-polar co-ordinates in the solar surface with origin at the center of the cell. The line-of-sight velocity component observed at an angle θ from the vertical direction thus would be

$$V_l(x, y) = \frac{1 - \mu^2}{\mu} \frac{y}{\rho} F(\rho),$$

where $\mu = \cos \theta$ and (x, y) are rectangular co-ordinates on the photographic plate, with y measured in the radial direction on the solar image. (Note that $x^2 + y^2/\mu^2 = \rho^2$.) The function V_l is seen to be even in x , but odd in y . One-dimensional A-C curves for various mathematically simple even and odd functions are shown in Figure 8. (The test functions and A-C curves have all been suitably normalized so as to agree in their vertical and horizontal scales.) The similarity between these curves and those of Figure 7 would appear to support the conclusion that the horizontal velocity field is far from random in nature and that, in fact, a high degree of local correlation, of the general type described above, is present.

A third feature of the A-C curve (Fig. 7, *b*) causing it to differ somewhat from the curves of Figure 8 is the secondary maximum at about 3.5×10^4 km. We believe that this indicates a certain regularity in the spacing of the individual cells which make up

³ The effects of the smaller-scale granulation velocities, which have sizable horizontal as well as vertical components, may be eliminated by using the 5-cm image, on which the granulation is *unresolved*, and by using C-C curves for images taken several minutes apart, on which the granulation is *uncorrelated*.

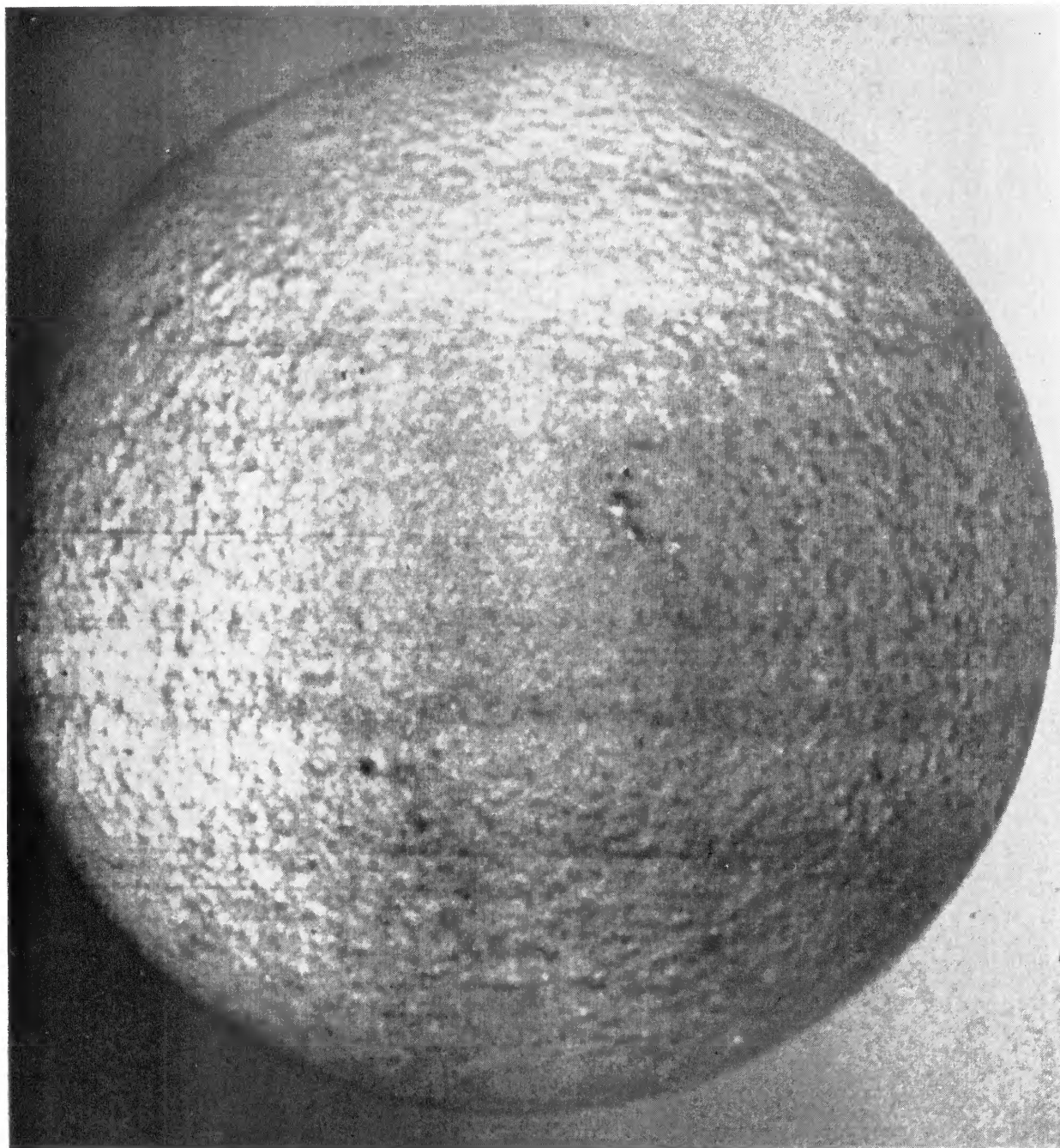


FIG. 6.—Doppler sum plate of 5-cm solar image, showing the large-scale velocity field. Dark areas are receding. June 15, 1960, 14^h11^m U.T.

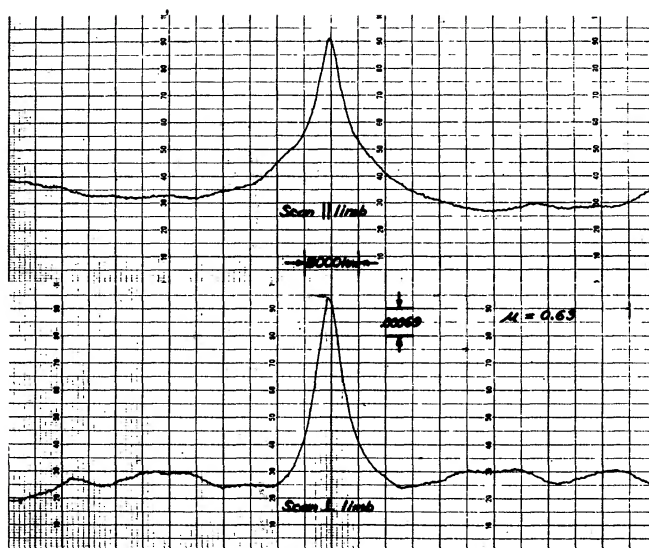


FIG. 7.—Autocorrelation functions of velocity field near $\cos \theta = 0.63$, showing anisotropic effects discussed in text. The small-scale field has not been suppressed in this case, so that a considerable part of the total peak height is contributed by the short-lived motions. Plate taken June 22, 1960.

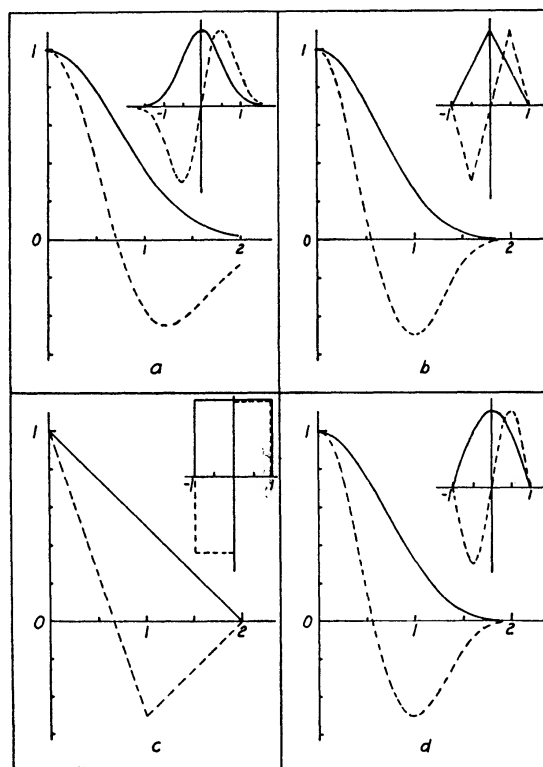


FIG. 8.—“Theoretical” autocorrelation-curves for the various one-dimensional symmetric and anti-symmetric functions shown. The horizontal and vertical scales have been chosen arbitrarily for convenient intercomparison. *a*, Gaussian; *b*, triangular; *c*, rectangular; *d*, sinusoid.

the field. This supposition is strengthened by comparing the total number of cells that should be present on the solar surface, on the basis of an average spacing $d = 3.5 \times 10^4$ km, with the number found by actual count. Thus we find $N = 4\pi R_{\odot}^2/d^2 = 5 \times 10^3$, which agrees almost exactly with the counted number $N' = 5.0\text{--}5.5 \times 10^3$.

We have attempted to estimate the lifetime of the cellular pattern by evaluating C-C functions for plates taken at different times. We find that a distinct correlation persists for at least an hour. It is difficult to utilize much longer time intervals because of difficulties introduced by the solar rotation and deterioration of the seeing. Our tentative conclusion is that the lifetime of a single cell may well be many hours.

Finally, it may be remarked that one sees, superficially, a distinct similarity between the velocity-cell pattern and the "chromospheric network" pattern seen on $\text{Ca}^+ \text{K}_2$ spectroheliograms. We have not yet, however, formulated and applied a suitable quantitative test for such a correlation. A broader study of this and other features of the large velocity cells is now under way.

b) Brightness-Velocity Correlation

If one examines a pair of Doppler images (using the 17-cm image and the line Ca 6103), a qualitative difference between them is apparent even before any photographic cancellation: the image corresponding to the red side of the line has more "contrast" in its small-scale features than does that taken on the violet side (Fig. 9A). We interpret this as being due to a local correlation between brightness and vertical velocity, such that brighter-than-average areas tend to be associated with upward velocities and darker areas with downward velocities: On the red side of the line, the variations in the light transmitted by the slit resulting from the local Doppler shifts and variations due to intrinsic brightness fluctuations tend to reinforce, while on the violet side of the line they tend to cancel. The effect is so marked that even a previously uninformed observer can easily identify to which side of the line each image corresponds.

The line Fe 6102 shows a brightness-velocity correlation of the same sign, although not so large. This line is somewhat weaker than Ca 6103 and has a higher excitation potential and hence is formed at a lower level in the atmosphere.

A correlation of the same sign is also found in the Na D₁ (λ 5896) line wing for offsets greater than about 0.15 Å from the line core. However, plates taken less than about 0.12 Å from the line core shows a *reversed* correlation: at these heights brighter-than-average areas are associated with *downward* velocities. Observations in Mg 5172 and $\text{Ca}^+ 8542$ show that the correlation remains reversed for still higher levels in the atmosphere.

The basis for these conclusions is indicated in Figure 9B, which shows A-C and C-C curves of images taken near the center of the solar disk on the red and violet sides of the lines Fe 6102, Ca 6103, $\text{Ba}^+ 4554$, Na 5896, and $\text{Ca}^+ 8542$. The height of the peak of each A-C curve gives the mean-square transmission variation on the plate, which is a quantitative measure of the "contrast."

To analyze the correlation quantitatively, let us express the light-intensity passing through the slit when set on the red and violet sides of the lines, respectively, as

$$\begin{aligned} a) \quad I_r &= I_0 [1 + \delta(x, y) + \beta(x, y)] \\ \text{and} \quad b) \quad I_v &= I_0 [1 - \delta(x, y) + \beta(x, y)], \end{aligned} \tag{1}$$

where δ is a (small) variation in intensity due to a Doppler displacement of the line relative to the slit and β is a (small) variation in intensity due to a variation in intrinsic brightness on the sun. We take β to be positive for an increase in local brightness and δ to be positive for a violet local Doppler shift. Further, let I_0 be the average local brightness on the sun, so that $\langle \beta \rangle = 0$. (The area used to calculate I_0 is assumed small compared with the total solar disk but large enough to contain a great number of brightness elements.)

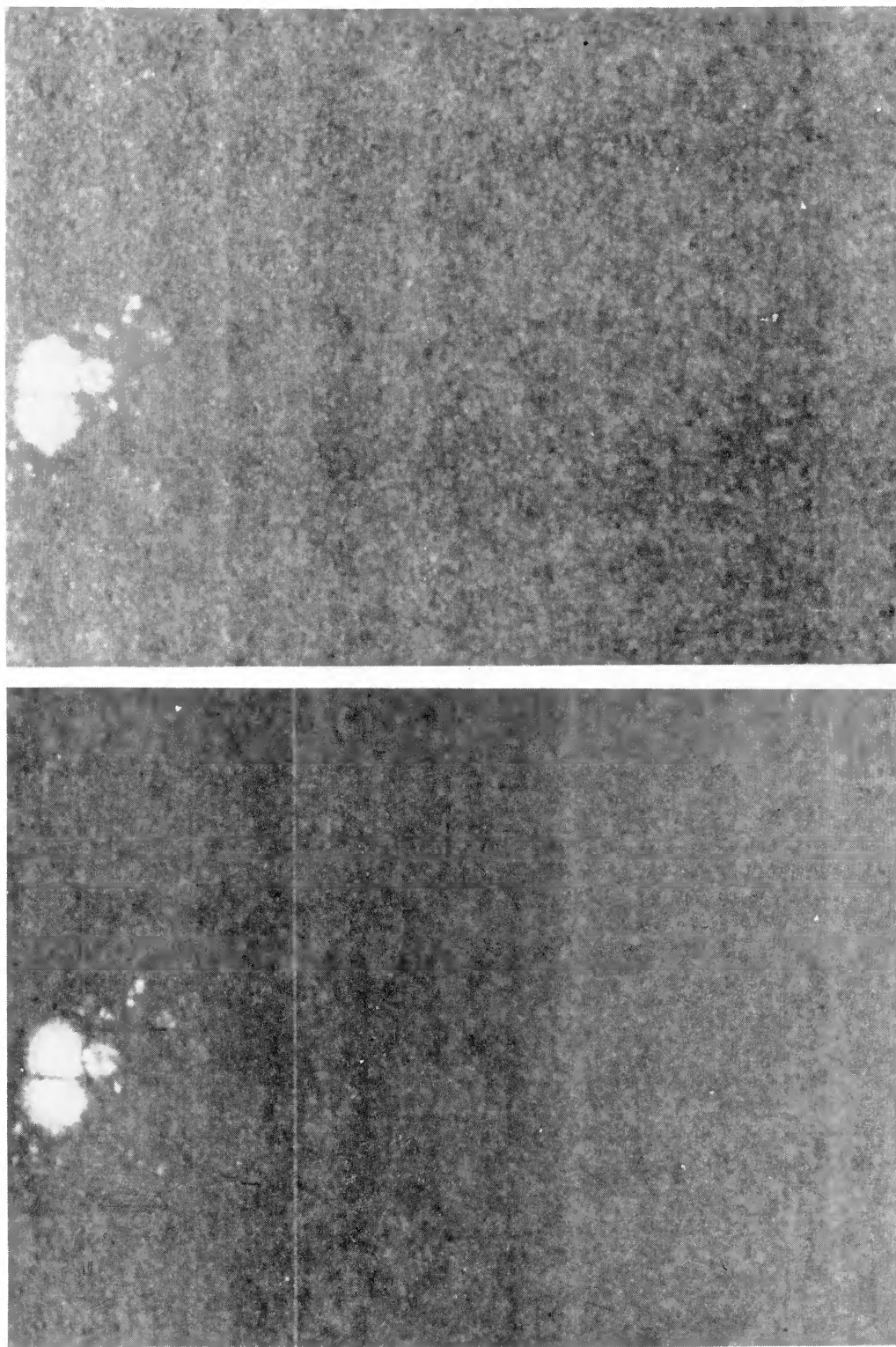


FIG. 9.4.—Reproduction of the two images of a Ca 6103 Doppler plate, showing the contrast difference attributed to a strong correlation between brightness and vertical velocity. *Left image:* violet wing; *right image:* red wing. June 17, 1961, 13^h30^m U.T.

Since the plates used in the A-C device are unity-gamma projection prints of the original plates, they have a transmission T related to the intensity I passed through the spectroheliograph slit by the equation $T = K I^\Gamma$, where Γ is the contrast of the original plate, generally about 2.5.

The A-C and C-C functions of the red and violet images may then be written:

a) $C_{rr}(s) = \langle T_r(x,y)T_r(x+s,y) \rangle = \langle [I_r(x,y)]^\Gamma [I_r(x+s,y)]^\Gamma \rangle,$

b) $C_{vv}(s) = \langle T_v(x,y)T_v(x+s,y) \rangle = \langle [I_v(x,y)]^\Gamma [I_v(x+s,y)]^\Gamma \rangle,$

c) $C_{rv}(s) = \langle [I_r(x,y)]^\Gamma [I_v(x+s,y)]^\Gamma \rangle.$

(2)

If we write the normalized height of the central peak of an A-C function as

$$H_{rr} = \frac{C_{rr}(0) - C_{rr}(\infty)}{C_{rr}(\infty)}, \text{ etc.,}$$

use equations (1), and drop terms above the second order in β and δ , we find

a) $H_{rr} = \Gamma^2 [\langle (\beta + \delta)^2 \rangle - \langle \delta^2 \rangle] = \Gamma^2 [\langle \beta^2 \rangle + \langle \delta^2 \rangle + 2\langle \beta \delta \rangle - \langle \delta^2 \rangle],$

b) $H_{vv} = \Gamma^2 \langle \beta^2 \rangle + \langle \delta^2 \rangle - 2\langle \beta \delta \rangle - \langle \delta^2 \rangle,$

c) $H_{rv} = \Gamma^2 [\langle \beta^2 \rangle - \langle \delta^2 \rangle + \langle \delta^2 \rangle].$

(3)

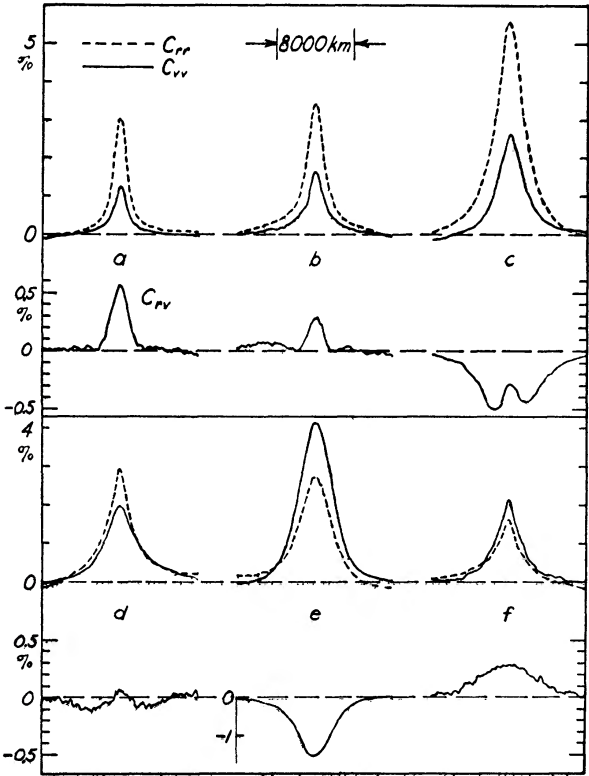


FIG. 9B.—A-C and C-C curves of various original plates, showing the brightness-velocity correlation discussed in the text. The C-C curves of *c* and *d* indicate that the brightness elements are smaller in size than the Doppler elements.

a) Fe 6102	$\Delta\lambda=0$ 10 A	June 14, 1961	d) Na 5896...	$\Delta\lambda=0$ 14 A	Sept 18, 1960
b) Ca 6103.	$\Delta\lambda=0$ 10 A	June 14, 1961	e) Na 5896...	$\Delta\lambda=0$ 10 A	Aug 1, 1961
c) Ba ⁺ 4554	$\Delta\lambda=0$ 07 A	July 1, 1961	f) Ca ⁺ 8542	$\Delta\lambda=0$ 21 A	Aug 30, 1960

Thus

$$\begin{aligned}
 a) \quad & \langle \beta^2 \rangle = \frac{(H_{rr} + H_{vv} + 2H_{rv})}{4\Gamma^2}, \\
 b) \quad & \langle \delta^2 \rangle - \langle \delta \rangle^2 = \frac{(H_{rr} + H_{vv} - 2H_{rv})}{4\Gamma^2}, \\
 c) \quad & \langle \beta \delta \rangle = \frac{(H_{rr} - H_{vv})}{4\Gamma^2}.
 \end{aligned} \tag{4}$$

Corresponding equations for $\langle \beta v \rangle$ and $\langle v^2 \rangle - \langle v \rangle^2$ may be obtained by observing that

$$\delta = \frac{1}{I_0} \frac{v}{c} \lambda \frac{dI}{d\lambda}$$

where $dI/d\lambda$ is the slope of the line profile at the position of the slit used. ($dI/d\lambda$ is found from the line-profile calibration procedure.) We may also write

$$\delta' = \delta - \langle \delta \rangle, \quad v' = v - \langle v \rangle. \tag{5}$$

Then $\langle \delta'^2 \rangle = \langle \delta^2 \rangle - \langle \delta \rangle^2$, $\langle v'^2 \rangle = \langle v^2 \rangle - \langle v \rangle^2$, and $\langle \beta v' \rangle = \langle \beta v \rangle$.

We may define the correlation coefficient C between the brightness and velocity as

$$C \equiv \frac{\langle \beta \delta' \rangle}{\langle \beta^2 \rangle^{1/2} \langle \delta'^2 \rangle^{1/2}} = \frac{\langle \beta v' \rangle}{\langle \beta^2 \rangle^{1/2} \langle v'^2 \rangle^{1/2}}. \tag{6}$$

Several A-C and C-C curves like those of Figure 9B were obtained for each line, using a number of areas on different plates. Table 1 lists the average values of $\langle v'^2 \rangle$, $\langle \beta^2 \rangle$, $\langle \beta v \rangle$, and C for each of the five lines.

TABLE 1*

Line	Offset (Å)	$\langle v'^2 \rangle^{1/2}$ (km sec ⁻¹)	$\langle (\Delta I/I)^2 \rangle^{1/2}$ $= \langle \beta^2 \rangle^{1/2}$	$\langle v(\Delta I/I) \rangle$ $= \langle \beta v \rangle$ (km sec ⁻¹)	C
Fe 6102	0 10	0 39	0 039	+0 0057	+0 38
Ca 6103	10	0 43	048	+ 0103	+ 50
Ba ⁺ 4554	07	0 61	068	+ 0166	+ 38
Na 5896	14	0 35	053	+ 0022	+ 12
Na 5896	11	0 50	045	- 0051	- 23
Ca ⁺ 8542	0.23	1 20	0 048	-0 0070	-0 12
		(±30 per cent)	(±30 per cent)	(±30 per cent)	(±20 per cent)

* Data for each spectral line were obtained from measurements of plates taken during a single set of observations. Such sets of measurements are usually self-consistent to within 10 per cent. However, systematic and random errors which vary from day to day arise from numerous sources; these errors may be correlated or uncorrelated in the various columns of the table. The uncertainties indicated at the foot of each column represent our best provisional estimates, based upon our experience with many plates reduced under similar conditions, but are not to be considered as independent statistical errors in the usual sense.

We may use the values of $\langle \beta v \rangle$ listed in Table 1 to estimate the total mechanical (i.e., non-radiative) energy transported upward by the velocity field at the altitude of formation of the weaker lines, if we assume $\beta = \Delta I/I = a(\Delta T/T)$, where $a \sim 4$ and T and ΔT are the temperature and temperature fluctuation in the region of line formation. A volume of gas of molecular weight μ , unit cross-sectional area, at a temperature T and moving upward with velocity v , transports (per second) an energy

$$E = \frac{1}{\gamma - 1} \frac{RT}{\mu} \rho v + P v = \frac{\gamma}{\gamma - 1} \frac{RT}{\mu} \rho v. \tag{7}$$

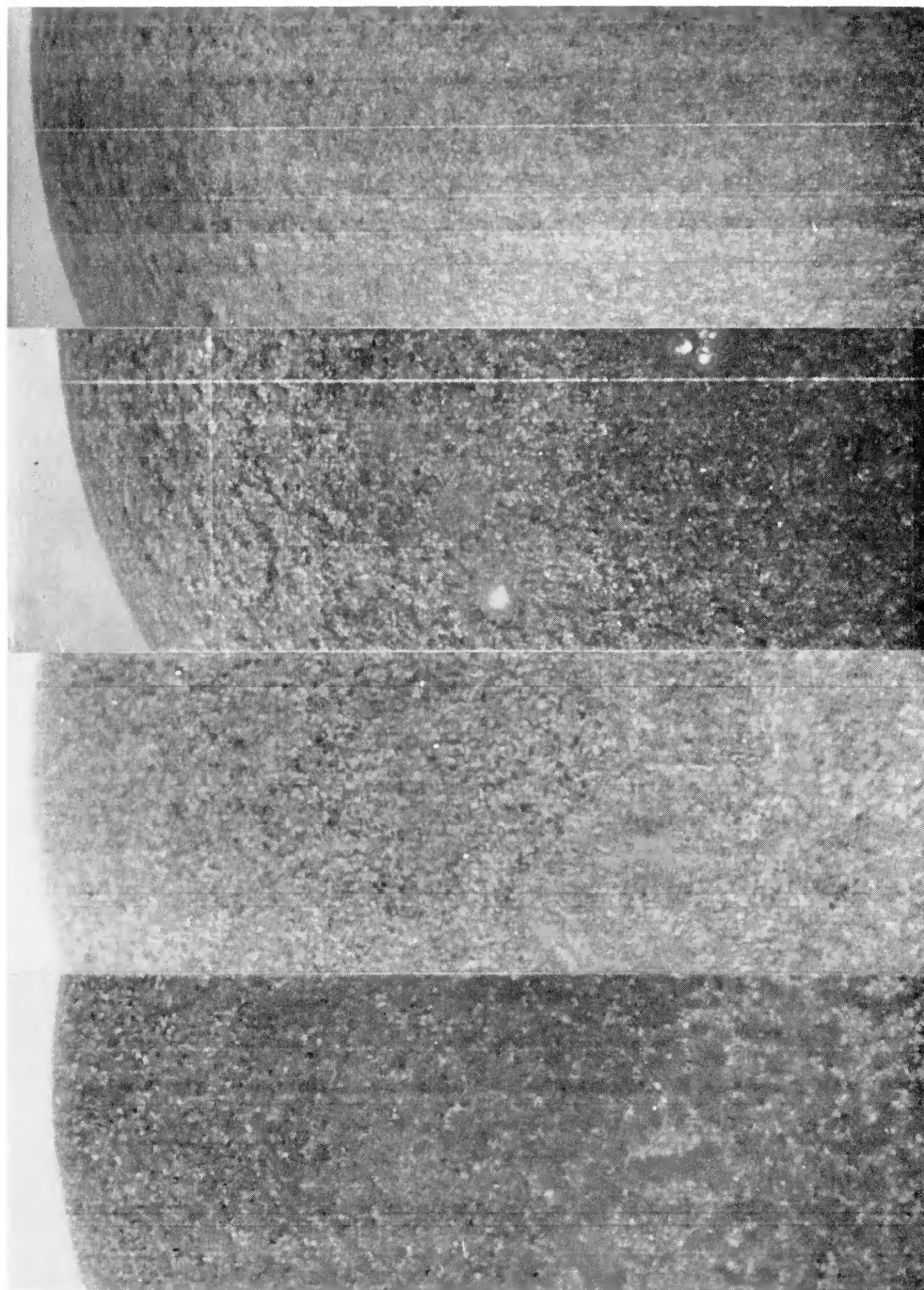


FIG. 10.—Examples of singly canceled Doppler plates. *From top to bottom:*

<i>a)</i> Ca 6103.....	June 22, 1960, 13 ^h 45 ^m U.T.	$\Delta\lambda = 0.1 \text{ \AA}$
<i>b)</i> Na 5896.....	July 3, 1960, 14 ^h 10 ^m U.T.	$\Delta\lambda = .1 \text{ \AA}$
<i>c)</i> H α 6563.....	June 22, 1960, 14 ^h 18 ^m U.T.	$\Delta\lambda = .35 \text{ \AA}$
<i>d)</i> H α 6563.....	June 22, 1960, 14 ^h 11 ^m U.T.	$\Delta\lambda = 0.7 \text{ \AA}$

In *a* and *b*, dark areas are receding; in *c* and *d*, dark areas are approaching.

Writing $T = T_0 + \Delta T$, where $T_0 = \langle T \rangle$, and noting that mass conservation requires that $\langle \rho v \rangle = 0$, we have

$$\langle E \rangle = \frac{\gamma}{\gamma - 1} \frac{R}{\mu} \langle \Delta T \rho v \rangle = \frac{\gamma}{\gamma - 1} \left\langle P \frac{\Delta T}{T} v \right\rangle. \quad (8)$$

Now write $P = P_0 + \Delta P$, where $P_0 = \langle P \rangle$. Then, neglecting third-degree correlations between small quantities, there remains, for the net energy transport,

$$\langle E \rangle = \frac{\gamma}{\gamma - 1} P_0 \left\langle \frac{\Delta T}{T} v \right\rangle. \quad (9)$$

The pressures in the region of formation of the wings of the Fe 6102 and Ca 6103 lines are estimated to be about 4×10^4 dynes cm^{-2} , which leads to values of $\langle E \rangle$ of ~ 2 W cm^{-2} at the levels of formation of these lines.

A further interesting feature revealed in the curves of Figure 9B concerns the *relative sizes* of the elements which contribute to the fields $\beta(x, y)$ and $\delta(x, y)$. The C-C curves $C_{rv}(s)$ for $\text{Ba}^+ 4554$ and $\text{Na} 5896$ ($\Delta\lambda = 0.14$ Å) have a definite **W** shape, which indicates that the larger features on the two images of these Doppler plates are negatively correlated and the smaller features are positively correlated. We conclude that the features which contribute to the field $\beta(x, y)$ are, on the average, *smaller* than those which contribute to $\delta(x, y)$. This property is difficult to measure quantitatively because of seeing limitations, but it seems fair to conclude that the effect is at least as great as it appears on any given plate.

c) The Small-Scale Doppler Field

In this section we shall describe the general features of the Doppler field revealed on singly canceled Doppler plates using the 17-cm image. Figure 10, *a-d*, shows typical examples of the Doppler field as seen in the lines Ca 6103, Na 5896, and H α . Visible on the first two plates are the large cells described above, but, in addition, a smaller-scale field is apparent because of the greater resolution available with the 17-cm image. This smaller-scale field appears rather uniform in its properties over the entire disk except near the limb and in the vicinity of sunspots. Near the limb, the velocity field is poorly revealed because of the unfavorable projection factor, the mixing of the light from adjacent regions along the line of sight, and the shallower line profile. Near sunspots, one characteristically finds that the velocity field is subdued in amplitude and “smeared out” in comparison with that in normal regions (Fig. 10, *b*). Over the sunspot umbra, velocities cannot be measured because these areas are generally underexposed. In the penumbra, however, velocities should be seen if they are present. In general, the penumbra is *remarkably quiescent*, the small-scale vertical velocities being essentially zero there (less than ~ 0.1 km sec^{-1}). There is some indication of outward (horizontal) streaming when a spot is seen obliquely and of a possible narrow region of higher velocity at the outer boundary of the penumbra.⁴

The general appearance of the small-scale Doppler field resembles that of the familiar brightness granulation, and, in view of the brightness-velocity correlation just discussed, the two are closely connected. Measurements of the r.m.s. velocities near the center of the solar disk at various offsets from the six spectral lines most often used are summarized in Table 2. Typical A-C curves for these lines are shown in Figure 11.

The large r.m.s. deviations in Table 2 are due primarily to certain effects which vary from plate to plate and from day to day. Chief among these are (*a*) seeing variations,

⁴ These features are more easily measurable by ordinary spectroscopic techniques, because of the sensitivity of the present method to small errors in registration near sharp boundaries (de Jager 1959).

with consequent variations in resolution of the solar velocity field,⁵ and (b) velocity-calibration errors, different for each set of observations.

Table 3 shows the results of attempts to explore the velocity structure within individual spectral lines by taking plates at different offsets. For each line, although the individual velocities are subject to the errors just mentioned, the *relative* sizes of the velocities are nearly free of such errors: (a) The effect of slow seeing variations is essentially eliminated by exposing an entire set of images with different offsets from a line during a single observational sequence and also by arranging the order of taking the images such that an image at every offset immediately precedes and follows an image at every other offset. (b) Since all images are part of the same observational sequence, the calibration is the same for all. The remaining variations which contribute to the r.m.s. deviations shown in Table 3 are mainly due to photographic and instrumental

⁵ We generally observe that plates with higher resolution show a higher r.m.s. velocity. The results quoted must be interpreted as representing the r.m.s. velocities after being smeared out by a resolution window of about 2'' on the average.

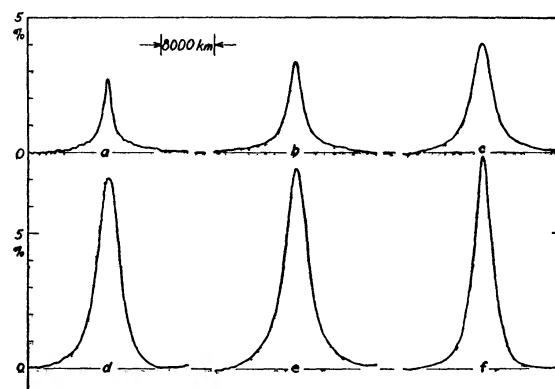


FIG. 11.—A-C curves of various singly canceled Doppler plates. The factor relating the ordinate to the mean-square velocity is different for each curve.

a) Fe 6102,	$\Delta\lambda = 0.10 \text{ \AA}$	June 14, 1961	$H = (0.65 \text{ km/sec})^2$
b) Ca 6103	$\Delta\lambda = 10 \text{ \AA}$	June 14, 1961	$H = (0.52 \text{ km/sec})^2$
c) Na 5896.	$\Delta\lambda = 10 \text{ \AA}$	Aug 1, 1961	$H = (0.58 \text{ km/sec})^2$
d) Ba ⁺ 4554	$\Delta\lambda = 0.7 \text{ \AA}$	July 1, 1961	$H = (0.49 \text{ km/sec})^2$
e) H α 6563	$\Delta\lambda = 50 \text{ \AA}$	June 14, 1961	$H = (1.6 \text{ km/sec})^2$
f) Ca ⁺ 8542	$\Delta\lambda = 0.21 \text{ \AA}$	Aug. 30, 1960	$H = (1.8 \text{ km/sec})^2$

The plate used in *a* had extremely fine resolution and thus a considerably larger than average value for the r.m.s. velocity. See n. 5.

TABLE 2*

Line	Offset (Å)	$\langle v^2 \rangle^{1/2}$ (km sec ⁻¹)	Line	Offset (Å)	$\langle v^2 \rangle^{1/2}$ (km sec ⁻¹)
Fe 6102	0.10	0.46 ± 0.08	Na 5896.	0.11	0.56 ± 0.07
Ca 6103	10	47 ± 0.08	Ca ⁺ 8542	23	1.8
Ba ⁺ 4554	0.07	0.50	H α 6563	0.35	1.6

* Deviations shown are r.m.s. deviations from the mean of a number of measurements of various areas on several (three or four) different plates, each plate taken on a different day. The measurements for the lines Ba⁺ 4554, Ca⁺ 8542, and H α 6563 were each made on plates from a *single* set of observations, and hence for these lines we have no estimate of probable errors due to seeing and calibration variations.

noise in the A-C curve-tracing process. In addition, there are probably small systematic errors remaining due to errors in measuring the difference in velocity calibration between different parts of a line profile. Nevertheless, we feel that these measurements do indicate a trend toward higher velocities in the core of a line than in its wings.

From Table 3 we see that typical r.m.s. velocities lie in the range 0.3–0.5 km sec⁻¹ and that there may be some variation with offset $\Delta\lambda$ and from line to line.

The stabilizing or damping effect of magnetic fields upon mechanical motions in the photosphere is visible on high-resolution direct photographs, where we have often seen the granules to be elongated and diffuse in plage areas (see also Edmonds 1960), and on Ca 6103 and Na 5896 Doppler plates, where we find the velocity field to be diminished in amplitude and diffuse in appearance in these areas (Fig. 10, *b*). The affected areas are relatively small on the direct photographs but quite large on the Na 5896 Doppler plates. Figure 12 shows A-C curves corresponding to plage areas and non-plage areas on the Na 5896 Doppler plate (Fig. 10, *b*).

TABLE 3*

Line	Offset (Å)	$\langle v^2 \rangle^{1/2}$ (km sec ⁻¹)
Fe 6102	0 13	0 35 ± 0 01
	10	37 ± 01
	07	40 ± 01
	04	49 ± 01
Ca 6103	13	43 ± 01
	10	40 ± 02
	07	43 ± 01
	04	45 ± 05
Na 5896	17	42 ± 01
	14	41 ± 01
	11	48 ± 01
	0 08	0 49 ± 0 01

* Eight measurements were made of four different images for each offset. Deviations shown are r.m.s. deviations from their mean. The values for the velocities disagree with those in Table 2 because they refer to one particular set of observations, while entries in Table 2 show the average of several sets of observations.

Turning now to the H α Doppler plates, we see on these a wealth of interesting phenomena. Unfortunately, the relation between the Doppler signal on H α Doppler plates and the actual velocities is rather complex because of the large variation in shape of the H α line profile from feature to feature, so that our observations are, at present, mostly qualitative. Our principal findings to date have to do with the velocity field near sunspots and over plage areas and the change of the field with height and with time in non-active areas.

Near sunspots, we find the region inside the outer boundary of the penumbra to be quiescent, just as for the lower levels seen in the Ca 6103 and Na 5896 plates. In H α , however, the area immediately *outside* this boundary is one of *enhanced* motions, which consists mainly of an *inward* flow of streams of material, accelerating as it approaches the penumbra and halting abruptly at the boundary. Occasionally, one sees *outward*-moving material, generally coming from this same boundary, traveling at relatively high velocity; the outward progress of this ejected matter can be followed on plates taken a few minutes apart. We are evidently seeing here, on the disk, motions which appear as quiescent and eruptive prominences on the limb. In a few cases, an eruptive feature will be light along one edge and dark along the other, as if the structure were in rapid *axial rotation*.

Farther from a sunspot but still within the associated active area, the pattern of velocities has a somewhat filamentary appearance but is relatively quiescent and diffuse and changes significantly only over many minutes of time. At places well removed from active areas, on the contrary, the velocity field is of large amplitude, shows quite fine, non-filamentary structure, and changes significantly within 20–40 sec (Fig. 13).

We have photographed the H α Doppler field at various offsets $\Delta\lambda$ from the line center, in order to study the changes in the properties of the velocity field with height. The most interesting changes are found within the range $0.35 \text{ \AA} < \Delta\lambda < 0.8 \text{ \AA}$ (Fig. 10, *c, d*). At high elevations ($\Delta\lambda \sim 0.3 \text{ \AA}$), one sees a rather uniform, fine-grained pattern of both upward and downward velocities, with a characteristic grain size of $\sim 3.6 \times 10^3 \text{ km}$, r.m.s. velocity amplitude $\sim 2 \text{ km sec}^{-1}$, and lifetime $\sim 30 \text{ sec}$. As one goes deeper into the atmosphere, this pattern gradually changes into a totally different one at $\Delta\lambda \sim 0.8 \text{ \AA}$. Here, most of the disk is *quiescent*, and the only sizable velocities present are confined to a network of narrow “tunnels,” through which material streams predominantly *downward* into the sun (Fig. 10, *d*). This network appears to correspond closely with the network seen on K $_2$ spectroheliograms.

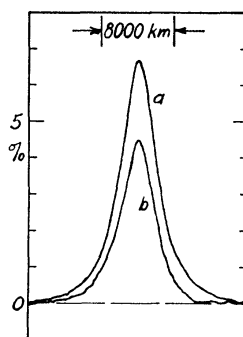


FIG. 12.—A-C curves of Na 5896 Doppler field inside and outside plage areas *a*, Outside plage; *b* inside plage Plate Na 5896, July 3, 1960.

When they are analyzed in greater detail, the H α Doppler plates should yield many interesting and important results concerning mass motions in the H α chromosphere. Such an analysis will require somewhat more precise velocity calibration than we have so far achieved, however. This matter is currently under study, and further work on the Balmer series lines is planned for the near future.

d) Oscillatory Motions in the Solar Atmosphere

We have used the “Doppler difference” procedure described in Section I to detect *changes* in the velocity field which take place over time intervals of a few minutes. On the basis of the few-minute “lifetime” of the solar granulation and because of the supposed “turbulent” nature of the velocities, it was expected that the appearance of such a velocity-difference plate would resemble that for H α shown in Figure 13, changing gradually from a uniform gray at one end of the plate (where $\Delta t = 0$) to a granular field characteristic of the superposition of the two (now uncorrelated) velocity fields at the other end, if the total elapsed time were many minutes.

Actually, a quite different and rather striking behavior is observed, which leads us to conclude that *the local vertical velocities in the solar atmosphere are not random, but quasi-oscillatory, in their time variation*: the “signal” on a Doppler difference plate grows from a uniform gray at the end where $\Delta t = 0$, passes through a *maximum* of “contrast” and “grain-size” at a time $\Delta t \sim 150 \text{ sec}$, diminishes to a *minimum* contrast and grain size at $\Delta t \sim 300 \text{ sec}$, and so on. This behavior is a consistent feature of Doppler difference

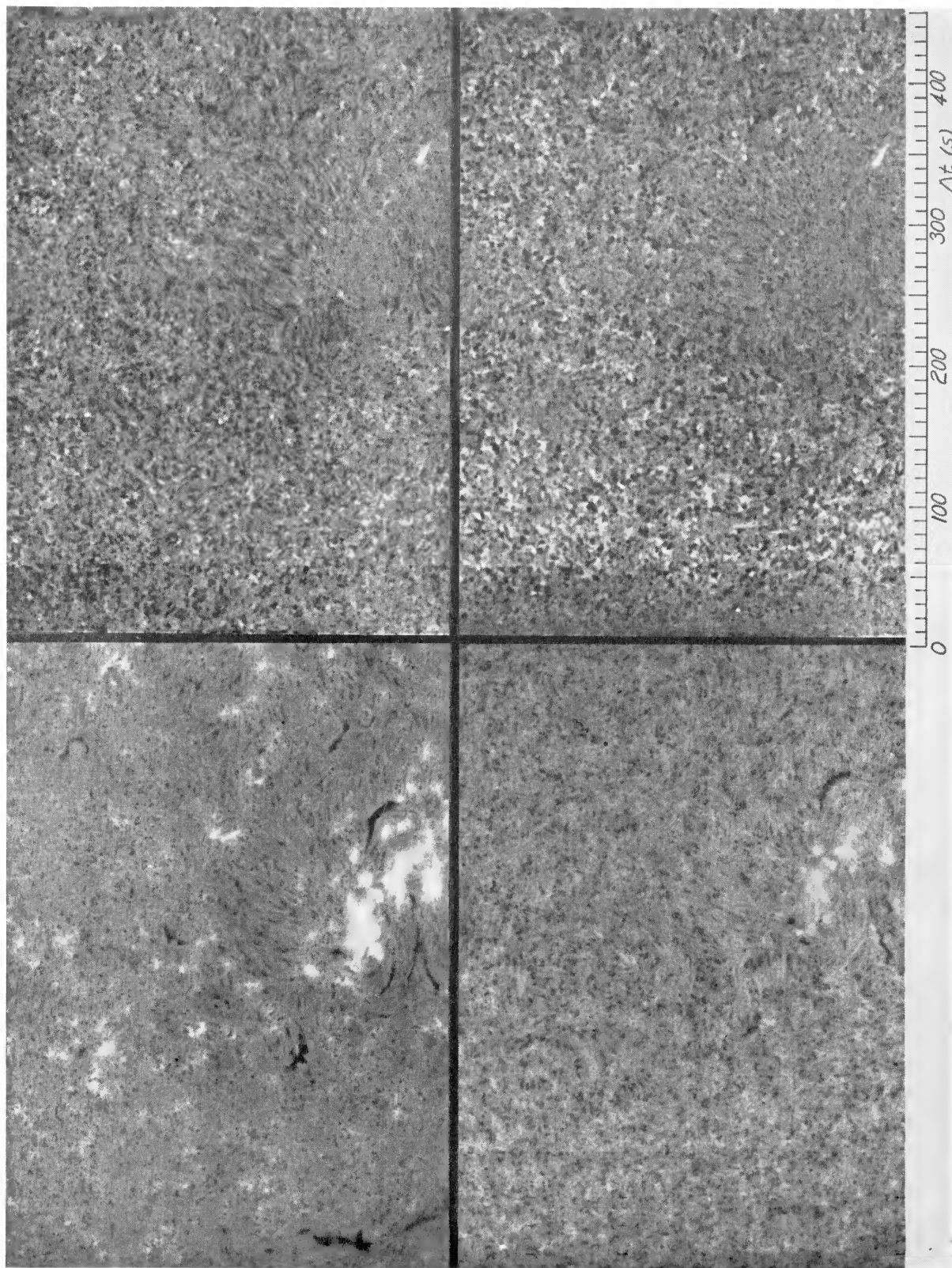


FIG. 13.—*Upper left:* original H α plate, at line core. *Lower left:* original H α plate of same area, $\Delta\lambda = 0.35$ Å. *Upper right:* H α Doppler field of same area, $\Delta\lambda = 0.35$ Å. *Lower right:* H α Doppler difference field, showing the rapidity with which the H α velocity field changes: the velocity loses its correlation in time in 20–40 seconds. June 24, 1961, 14^h16^m U.T.

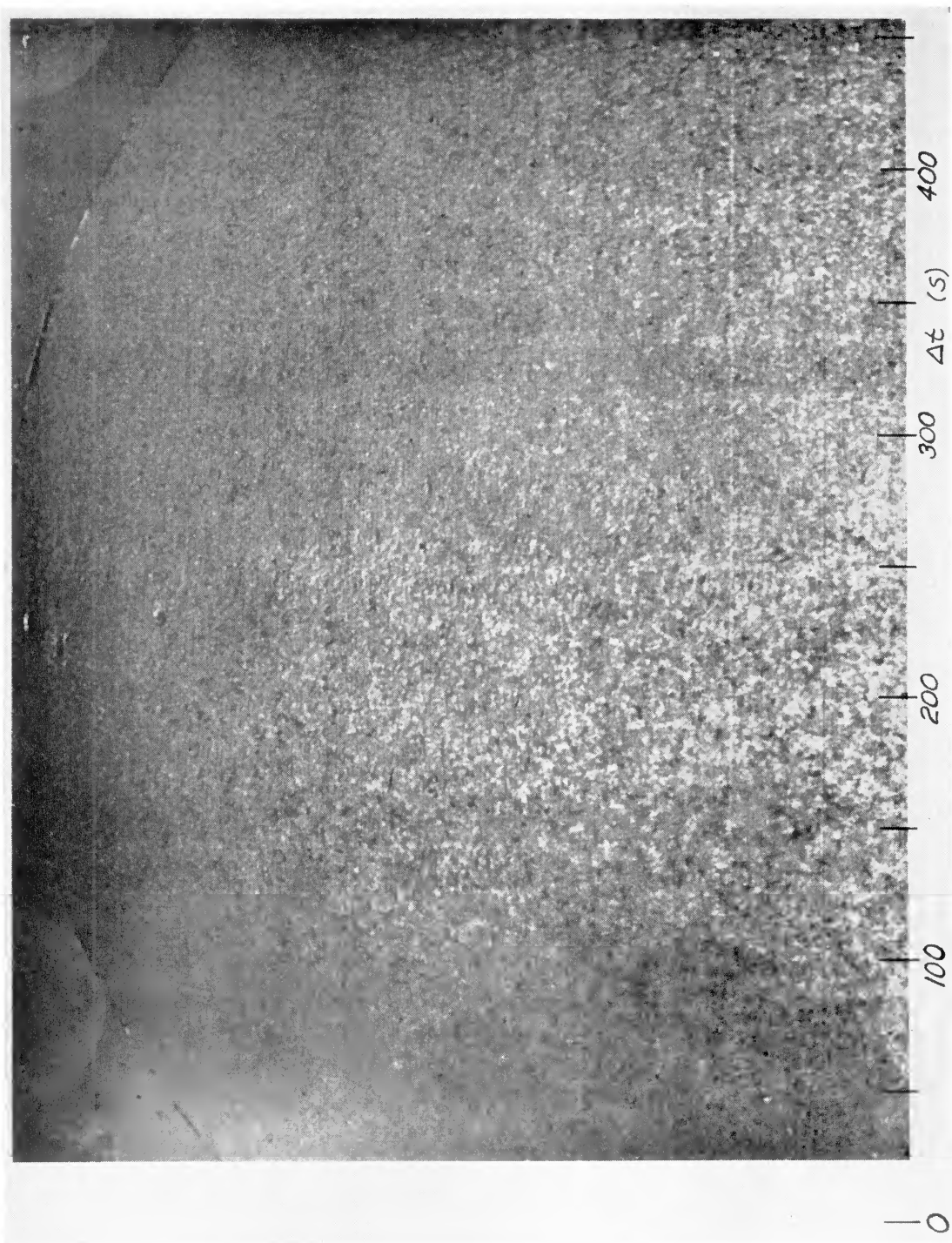


FIG. 14.—Doppler difference plate, showing the oscillatory time correlation of the small-scale velocity field. Ca 6103. June 10, 1960, 13^h40^m U.T.

plates taken in any of our lines except H α and Ca⁺ 8542 but is especially evident in Ca 6103, Ba⁺ 4554, and Na 5896 plates. Visual estimates of the period of this oscillation on twenty different Ca 6103 plates taken in 1960 give $T = 296 \pm 3$ sec. The stated uncertainty is indicative of the internal consistency of our eye-estimates and does not include possible systematic effects involved in judging where the "minimum" of the contrast pattern falls.

Figure 14 shows a Doppler difference plate for the Ca 6103 line; Figure 15, curve *D*, shows a plot of the central-peak heights of A-C functions corresponding to various areas on this plate.⁶ Each A-C function was evaluated for a long, narrow area whose long axis was parallel to the slit, so that Δt was nearly constant over each area of integration. The mean-square fluctuation is seen to be a minimum at $\Delta t = 0$ and to have a secondary minimum near $\Delta t = 300$ sec.

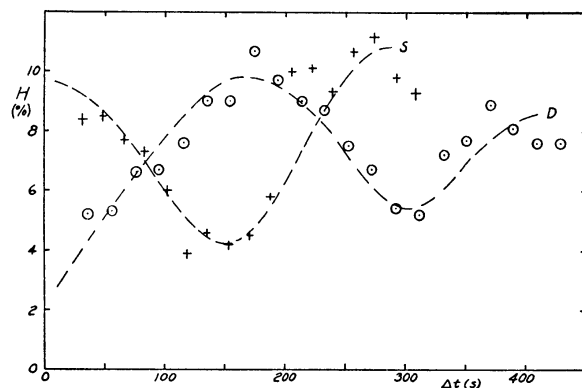


FIG. 15.—Plot of the peak heights of A-C curves (evaluated for long, narrow strips parallel to the slit) versus Δt for the Doppler difference plate of Fig. 14 (curve *D*) and the Doppler sum plate of Fig. 16 (curve *S*).

The features just described are sometimes difficult to see in Doppler difference plates such as Figure 14. Some of the reasons for this are as follows: In spite of the efforts of the photoelectric guider to keep the image stationary to within about $1''$, some motions do occur which are too fast to be followed. Over-all *distortions* of the image are common as well, so that even if the south and west limbs were held *stationary* by the guider, other points on the disk would move about. Thus, when two singly canceled Doppler plates are themselves canceled to make a Doppler difference or sum plate, corresponding points on the two *plates* are not necessarily the same point on the *sun*. In the actual process of placing one plate upon its partner, it is often possible to improve the registration in one area, but at the expense of losing register in another. Thus the observed oscillatory time

⁶ The meaning of the central-peak height of an A-C function for a Doppler difference plate may be seen as follows: At each point (x, y) of such a plate, the transmission fluctuation is proportional to $v(x, y, t) - v(x, y, t + \Delta t)$, where t and $(t + \Delta t)$ are the two times at which the slit scanned past that point on the two corresponding exposures. Thus the height of an A-C function evaluated for a long, narrow strip parallel to the slit will be

$$\begin{aligned} H(\Delta t) &\propto \langle [v(x, y, t) - v(x, y, t + \Delta t)]^2 \rangle \\ &= \langle [v(x, y, t)]^2 + [v(x, y, t + \Delta t)]^2 - 2v(x, y, t)v(x, y, t + \Delta t) \rangle \\ &= 2\langle v^2 \rangle - 2\langle v(t)v(t + \Delta t) \rangle. \end{aligned}$$

Thus $H(\Delta t)$ provides a measure of the *time correlation* of the local velocity, averaged over the corresponding spatial area, since $v(x, y, t)$ is, statistically, spatially homogeneous and stationary in time.

correlation is much more evident under laboratory conditions, wherein the effects of small relative motions of the plates may be seen at first hand. It is invariably true that, at this stage, suitable positions of the two plates can be found which *minimize* the difference signal at the places where $\Delta t = 0$ and $\Delta t \sim 300$ sec., but that *no position exists* which correspondingly minimizes the difference signal at $\Delta t \sim 150$ sec. A Doppler difference plate such as that of Figure 14 necessarily suffers from the fact that we must choose some *one* relative position in which the two plates match "best."

Interestingly enough, the oscillatory time correlation may also be seen on a Doppler *sum* plate, if the center of the solar disk lies near the strip where $\Delta t = 150$ sec. Figure 16 shows a Ca 6103 Doppler sum plate, and curve *S* of Figure 15 shows the corresponding plot of central-peak heights versus Δt for narrow strips whose long axis is parallel to the slit. A pronounced *minimum* of contrast is observed near $\Delta t \sim 150$ sec. This corresponds to a strong *anticorrelation* of velocities after such a time interval.

This anticorrelation on a Doppler sum plate is of importance in two respects. First, the fact that it is possible in this way *strongly to minimize* the sum of two velocity fields proves conclusively that the effect is *on the sun* and not in the earth's atmosphere, the instrument, or the photographic procedures. And, second, we learn that the oscillatory motion is not merely a small effect superimposed upon other, more energetic, velocity fields but is, instead, essentially *the only vertical motion present* in the range of linear dimensions resolved on our plates.

By observing the time correlation of velocity using spectral lines formed at different elevations, we may hope to study the properties of the oscillatory motions as a function of height. As mentioned previously, we have found the oscillation to be present in all lines so far studied except H α and Ca⁺ 8542. Figure 17 shows Doppler difference and sum fields for the line Ba⁺ 4554, in which the oscillatory motions are especially marked.

The presence of the oscillatory motions at the rather high elevations represented by the lines Na 5896 and Mg 5173 suggests that the oscillation might manifest itself in the chromosphere in other ways than through the Doppler effect. Accordingly, we have sought and apparently found a corresponding periodicity *in the small-scale bright elements characteristic of the lower chromosphere*. Figure 18 (*top*) shows an ordinary spectroheliogram taken in the center of the D₁ line Na 5896, and Figure 18 (*bottom*) shows a "Brightness difference" plate obtained by photographic subtraction of two such plates scanned in opposite directions in quick succession. This plate and the corresponding A-C function peak-height curve of Figure 19 exhibit the same characteristic maxima and minima of contrast, with about the same period, as are seen in the Doppler difference plates of Figures 14 and 17. If the effect seen on this single plate is confirmed by further observation and if the intensity fluctuations seen at the center of the mean profile are not significantly contributed to by the Doppler effect, then it would appear that the oscillatory motions may play a significant role, and perhaps a dominant one, in the transport of energy from the granulating layer into the chromosphere.

Further observation of the periodic time changes in these and other spectral lines are under way to determine whether there may be a dependence of period upon altitude in the atmosphere or upon horizontal wavelength, and to elucidate further the physical processes involved.

The velocity amplitude of the oscillation, as measured from A-C curves, appears to be greatest near the center of the disk and to fall off near the limb, which suggests that the associated motions are primary *vertical*.

In order to measure the *average duration* of a particular oscillation before it dies out, Doppler difference plates were obtained for which the time delay was held *constant* over the entire area at one of the values $\Delta t = T/2, T, 3T/2, \dots$, where $T = 296$ sec. This was done by scanning the spectroheliograph in the same direction at two times separated by the required interval, as explained earlier. Thus A-C curves for these plates may utilize nearly the whole area of the plate instead of only a small area, so that much im-

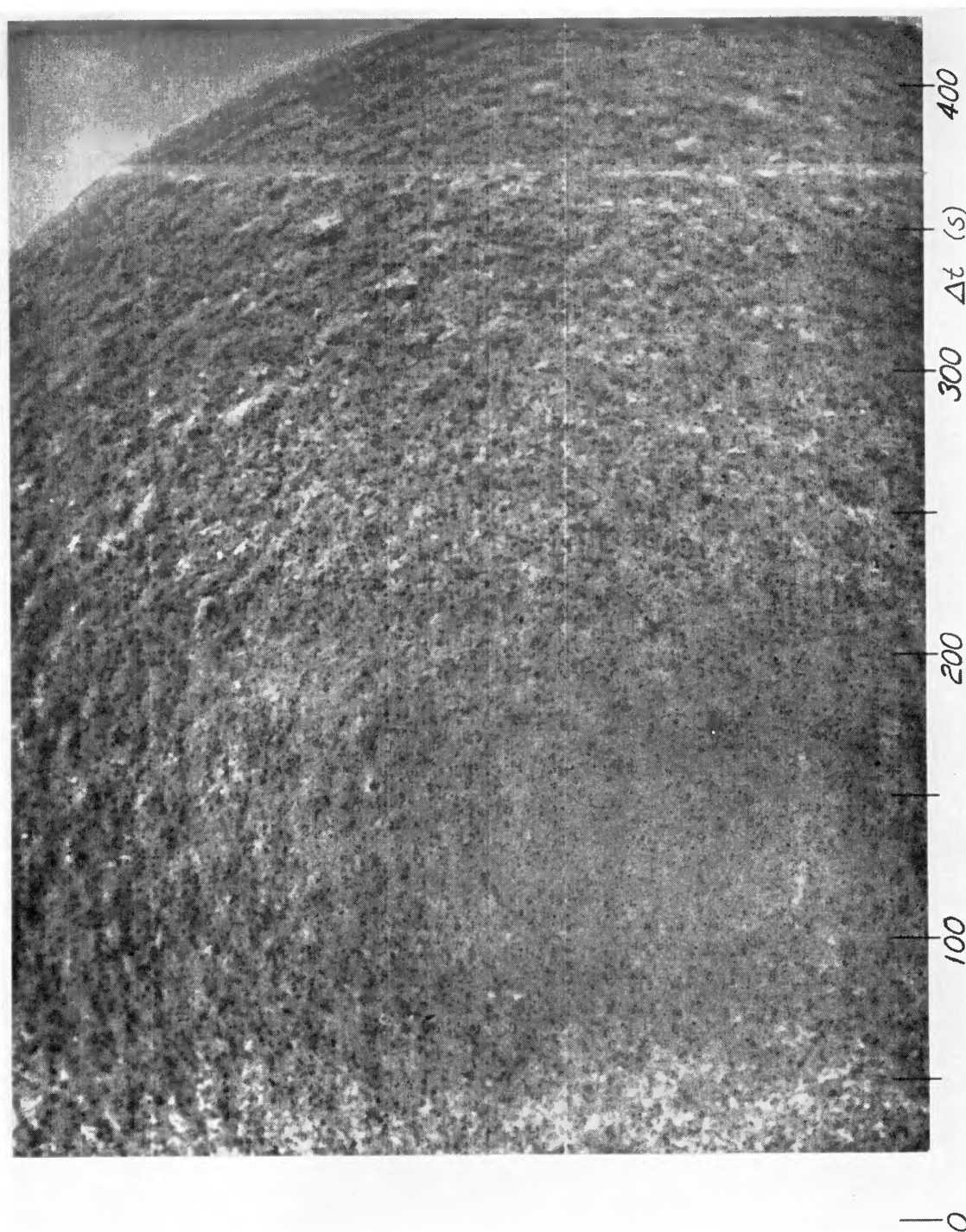


FIG. 16.—Doppler sum plate, showing the strong *anticorrelation* of the local velocities after a time interval $\frac{1}{2}T \sim 150$ sec. Ca 6103, June 22, 1960, 13^h49^m U.T. Note also the large velocity cells described in Sec. IVa. (Dark areas are approaching.)

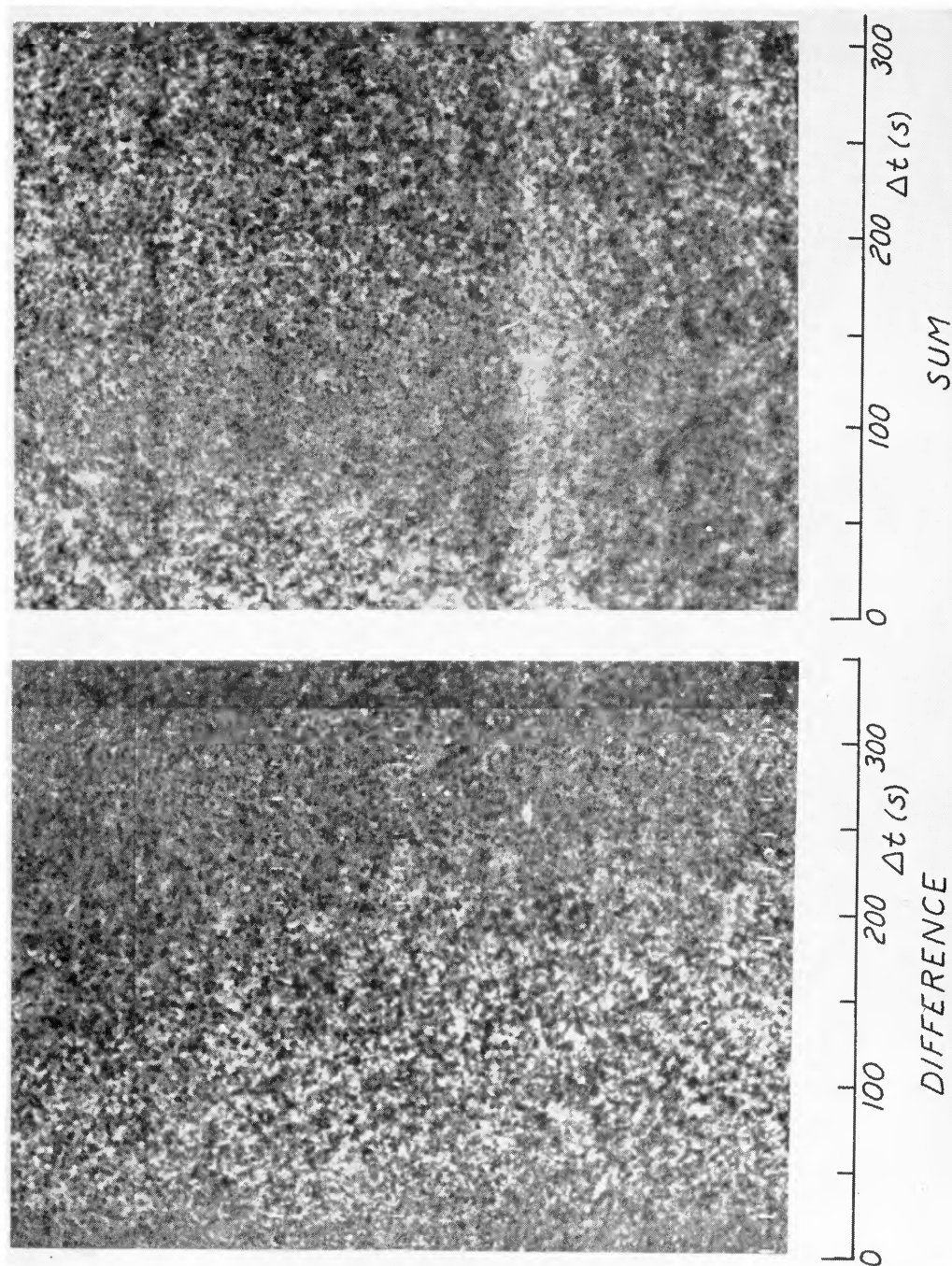


FIG. 17.—Doppler difference (*left*) and sum (*right*) plates, in the line $\text{Ba}^+ 4554$. July 1, 1961, 13^h55^m U.T.

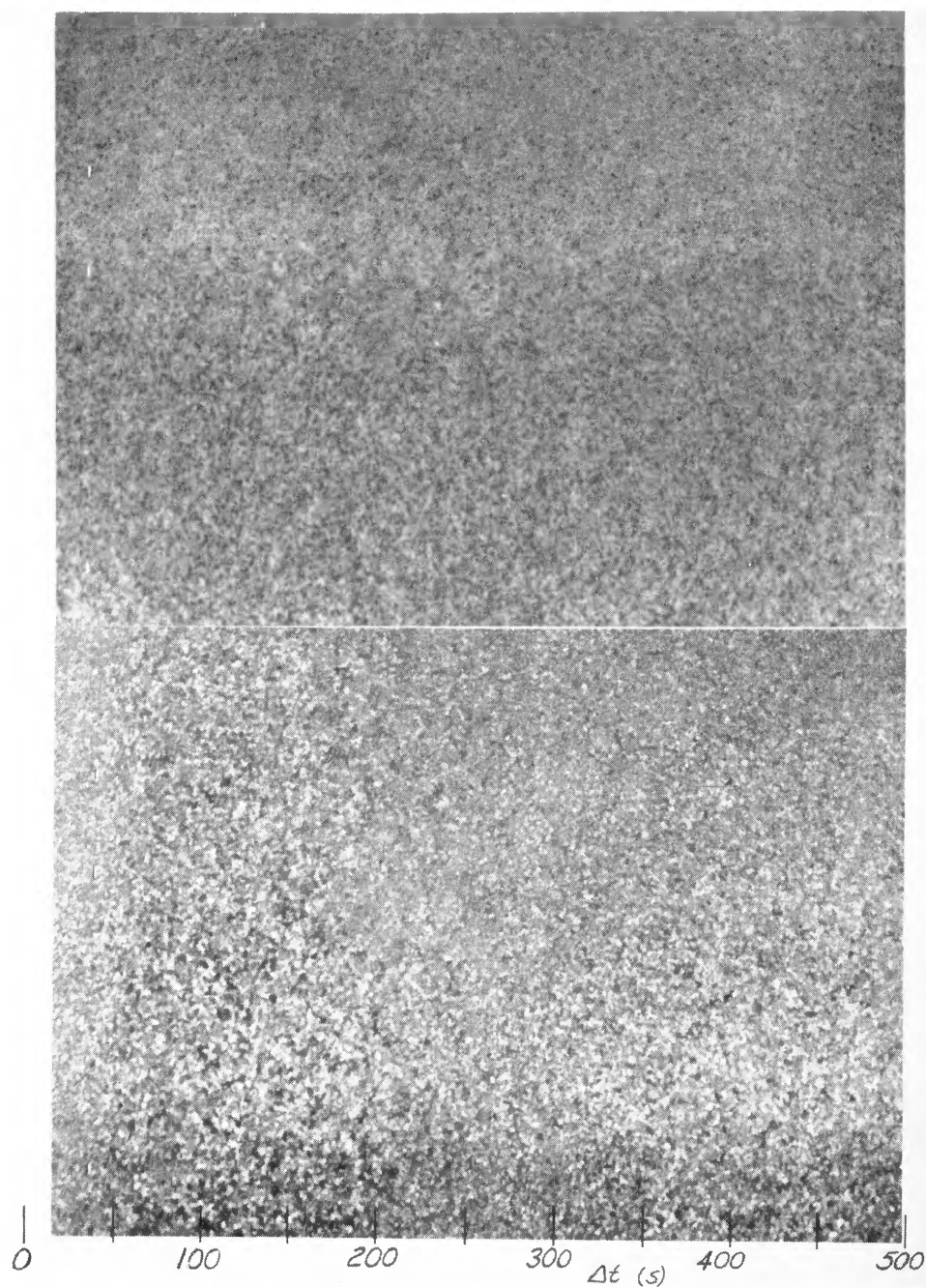


FIG. 18.—Ordinary spectroheliogram (*top*) and “Brightness Difference” plate (*bottom*) of the core of the D₁ line Na 5896. The brightness elements seem to show a tendency toward repetitive time correlation after an interval $T \sim 250$ sec. August 1, 1961, 14^h04^m U.T.

proved statistics are available. In Figure 20 are plotted A-C curves for four such plates; they illustrate the characteristic changes in cell size and contrast that occur as the oscillation progresses.

In Figure 21 the peak heights of such A-C curves are shown as a function of time delay Δt , expressed in units of the period T . It is seen that the characteristic maxima and minima of the oscillation may be followed out to at least three periods.

If we assume that the peak height of the A-C function varies sinusoidally in Δt with a period of 5 minutes and with an exponentially decaying amplitude, we may estimate the mean life τ of this "damped oscillation" by expressing the height of the A-C function as

$$H(\Delta t) = A e^{-\Delta t/\tau} (1 - \cos \omega \Delta t) = A e^{-nT/\tau} (1 - \cos n\omega T),$$

where n is the number of oscillations, T is the period, and τ is the mean life of the oscillation.

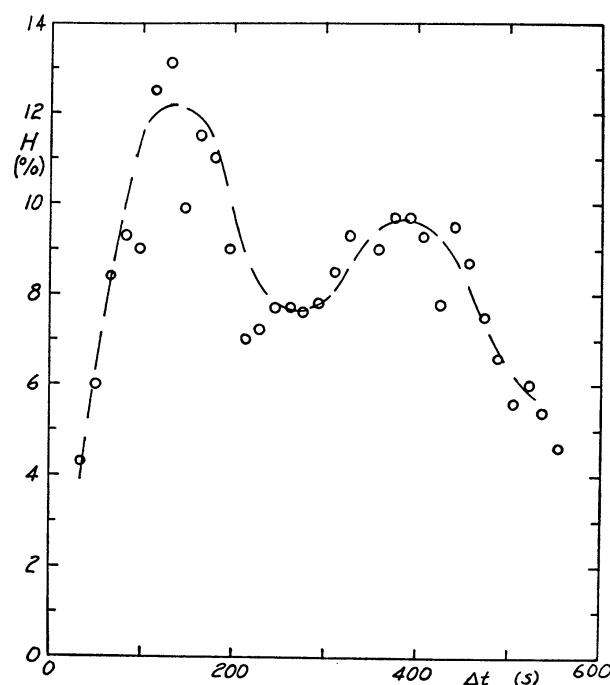


FIG. 19.—Plot of A-C function peak heights versus Δt for the "Brightness Difference" plate of Fig. 18. Part of the rather great dispersion of the measured points may be due to the fact that the brightness field is made up of a slowly changing coarse-grained component associated with plages and the chromospheric network and a rapidly changing fine-grained component.

Figure 22 shows semilog plots of $|H(nT) - H(nT - \frac{1}{2}T)|$ for the data of Figure 21. From the slopes of the two lines shown, which correspond to mean lives of 320 and 440 sec, we conclude that the data for the three lines Fe 6102, Ca 6103, and Na 5896 are all consistent with a mean life $\tau \sim 380$ sec.

Concerning the characteristic *sizes* of the moving elements which constitute the "granulation" Doppler field seen on a singly canceled plate, the oscillating elements which appear at the half-period point of a Doppler difference plate, and the familiar brightness granules, we observe a general trend of increasing apparent size in the order granulation, Doppler field, oscillating element. Perhaps a part, but certainly not all, of this trend is attributable to the loss of resolution to be expected due to the finite slit

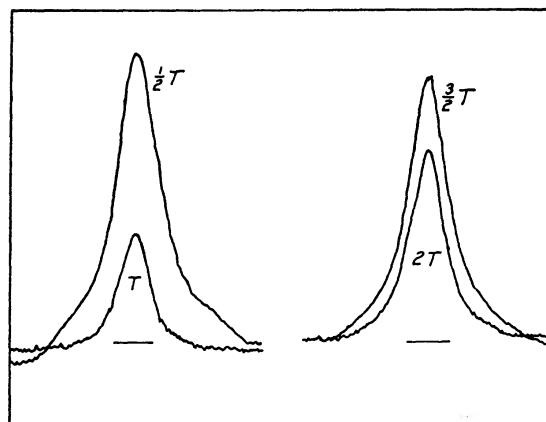


FIG. 20.—A-C curves for Ca 6103 Doppler difference plates for which the time differences are constant over the entire area and have the values $\Delta t = \frac{1}{2}T$, T , $\frac{3}{2}T$, and $2T$, where $T = 296$ sec. These curves show that, at integral periods, the curves are both narrower and less high than at half-integral periods.

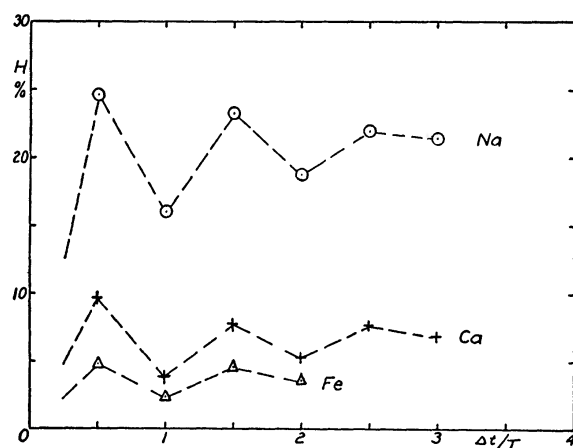


FIG. 21.—Plot of the A-C function peak heights versus Δt (in units of $T = 296$ sec) for Fe 6102, Ca 6103, and Na 5896.

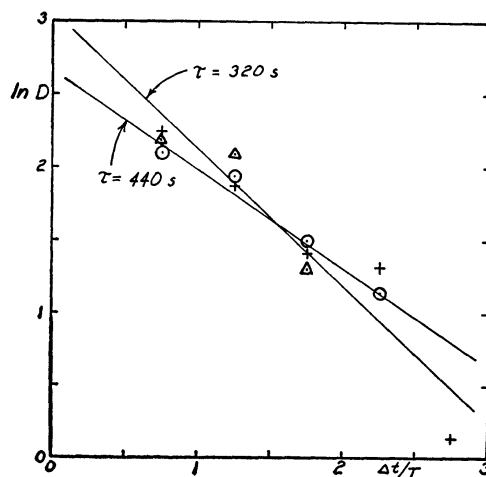


FIG. 22.—Semilog plot of successive differences in peak height versus Δt . The rate of decay of the oscillatory time correlation corresponds to a “mean life” $\tau \sim 380$ sec.

width of the spectroheliograph, the difficulties in attaining perfect registration at the two stages of cancellation, and the intentional defocusing of the image at each projection print step.

Another trend in size which seems indicated (Fig. 11) is that the lower-lying levels have smaller-diameter elements than the higher levels. Between the levels of Fe 6102 and Na 5896 the average size of a Doppler element grows from ~ 1700 to ~ 3500 km. Above the level of Na 5896, the Doppler elements remain roughly constant in size at ~ 3000 – 4000 km, up to the level of $H\alpha$ ($\Delta\lambda = 0.3$ Å).

V. DISCUSSION

The velocity field of the solar atmosphere in the region of line formation has been the subject of numerous investigations in which, up to the present time, two approaches have mainly been used. One of these is the analysis of the strengths and detailed shapes of the profiles of various spectral lines at various places on the solar disk and the other involves a point-by-point measurement of wavelengths of spectral lines on spectrograms on which sufficiently small structures are resolved.

The procedures used in the present investigation are somewhat related operationally to the latter approach, but there are some basic differences also. As compared with the measurement of wavelengths on spectrograms, which we may consider as referring to a one-dimensional segment of the solar surface at an instant of time, the present method introduces two additional dimensions—a second space dimension and (statistically) the time—and it also circumvents the laborious procedures connected with the precise measurement of wavelength. The results are directly amenable to statistical treatment without involved numerical computations and offer far more massive statistics than can ordinarily be attained by a procedure that uses data read at a finite number of points. Furthermore, the presentation of the data in *pictorial form* has proved of great value in discovering important qualitative relationships which have heretofore been hidden from us.

On the other hand, while the sensitivity of the present system to small velocity differences is comparable with that obtainable by direct measurement of wavelengths, it does have the drawbacks that *absolute* wavelengths are not obtained, that sufficient sensitivity can be attained only by using rather strong lines, and that the velocity sensitivity must be determined for each plate by a subsidiary calibration procedure which is not yet completely trustworthy in its precision. In addition, the rather involved photographic steps which enter into the present system are perhaps as laborious in their way as the measuring procedures that they make unnecessary.

Some of the results given here may be compared directly with measurements reported by other investigators. Richardson and Schwarzschild (1950) were the first to measure the “turbulent” velocities in the sun, using high-resolution spectrograms. Their value of 0.37 km sec $^{-1}$ for the r.m.s. velocity agrees quite satisfactorily with the values given in Tables 1 and 2. In a later statistical analysis of the same data, Frenkiel and Schwarzschild (1952) obtained a correlation-curve analogous to those shown in Figure 11. Their curve seemed to indicate a subsidiary maximum at a distance of about 1.5×10^4 km, which they tentatively attributed to large eddies of about 7×10^3 km in diameter. We find no evidence for eddies of this special size in the *vertical* motions. Vertical r.m.s. velocities in the range 0.3 – 0.7 km sec $^{-1}$ have also been found by Plaskett (1954) and by McMath *et al.* (1956).

The brightness-velocity correlation of the granulation has been studied by Stuart and Rush (1954) and by Plaskett (1954), who report correlation coefficients of about -0.30 . Our correlation coefficients are as large as 0.50 for the Ca 6103 line but decrease to zero and reverse sign in the Na 5896 line (Table 1). (In our work, we regard an upward velocity as being positive rather than negative, so that the sign of our correlation appears reversed with respect to those previously reported. All results indicate that brighter elements move *upward* in the lower levels of the atmosphere.) We must also bear in mind

that our "brightness" fluctuations refer to a rather steep part of a line profile and not to the continuum, which may well complicate the interpretation of some of our results concerning energy transport (Sec. IV, *b*).

Plaskett (1954) found that the part of the velocity field that is uncorrelated with the brightness shows a strong tendency toward spatial periodicity with a wavelength of about 4000 km and a velocity amplitude of about 0.5 km sec^{-1} . Possibly this residual field is to be identified with our time-oscillatory field as it decays following an impulsive excitation by the upward granule motions. (See the later discussion of the oscillatory motions.)

The large-scale horizontal velocity fields which we find are evidently the same as those reported by Hart (1956). Our findings provide a strong corroboration of her work and extend it by showing that the large-scale fields cover the entire solar surface rather than only the equatorial latitudes and by providing a clearer picture of the geometry of the flow.

The existence of the vertical oscillatory motions has recently been strongly confirmed by the beautiful work of Evans and Michard (1961), who measured the wavelength versus time at a large number of points on a long sequence of carefully guided, high-dispersion spectrograms taken at 40-sec intervals. Their period of $260 \pm 30 \text{ sec}$ is somewhat shorter than that reported here, but, in view of the different techniques and spectral lines involved, no real discrepancy is indicated. The oscillatory motions have also been detected by Howard (1961), with the Babcock magnetograph in its Doppler mode, guided carefully on a fixed point on the sun with a small aperture. His time correlation data are in close agreement with our results.

Let us now consider the over-all physical picture of the photospheric motions. The velocity field is clearly composed of two distinct, probably unrelated, parts: the large-scale cellular pattern of long-lived horizontal motions and the small-scale granular pattern of quasi-oscillatory vertical motions. What is the true nature of these two fields, and what agencies supply the energy which drives them?

With respect to the large-scale horizontal currents, the divergent nature of these imply a corresponding *vertical* current system which supplies matter to the center of each cell; but, so far, we see nothing within these layers that can be identified with such a current system. Observationally, we cannot yet say whether the matter comes from inside or outside the sun, but one can imagine that either could be the case.

Some of the properties of the large cells suggest that they may be a giant system of convective cells—a supergranulation—analogue to the ordinary granulation but originating in deeper layers where the scale height is relatively great. The rather uniform distribution of the cells over the solar surface, their many-hour lifetimes, and their quasi-regular spacing would seem to suggest such an interpretation. Indeed, if these currents circulate at 1 km sec^{-1} throughout a region extending to depths equal to the apparent cell size at the surface, the time required for one complete cycle would be about 10 hours. This would seem to be a minimum value for the lifetime, because the velocity should be considerably smaller at great depths where the density is high.

On the other hand, our $\text{H}\alpha$ observations show that there are localized *downward* motions from the chromosphere, and, while it seems unlikely that these currents could supply the required amounts of matter, it cannot be excluded observationally that these downward-moving currents could spread out horizontally as they reach the upper photosphere and become the large cells that we see. Further work is needed to clarify this matter.

If, as we tentatively suggest, the large cells do constitute a kind of supergranulation, the question arises as to what physical agency supplies the driving energy and sets the linear scale. Present evidence strongly suggests that the ordinary granulation and the supergranulation are quite distinct from each other. There is no indication, for instance, that the horizontal currents are merely the large-scale "tail" of a continuous spectrum

of eddy sizes, of which the ordinary granulation constitutes the major part. On the contrary, a great disparity in size—about a factor of 10—and even more in lifetime—about a factor of 100—seems to separate the two. The linear scale of the supergranulation is a hundred times, while that of the ordinary granulation is but five or ten times the scale height of the photosphere. If the scale of the supergranulation is to be a few times the “average” scale height in the layer where the currents flow, a scale height of perhaps 2000 km is indicated, which occurs at a depth of about 5000 km. A physical *discontinuity* associated with such a dimension could serve to define the linear scale, but at present we are unable to do more than suggest that a helium ionization zone might play such a role.

Turning now to the quasi-oscillatory small-scale motions, we shall evaluate the acceleration, vertical displacement amplitude, and total energy content of a column of unit cross-section. The angular frequency is $\omega = 2\pi/296 = 0.021 \text{ sec}^{-1}$, and if we take 0.40 km sec^{-1} as a typical r.m.s. velocity, we find the corresponding r.m.s. amplitude and acceleration to be $A = 19 \text{ km}$ and $a = 0.0084 \text{ km sec}^{-2}$, respectively. Thus a typical total excursion of a given volume element of the gas is only about 50–60 km, its maximum acceleration only about $0.04\text{--}0.05 g_{\odot}$, and its maximum velocity only about 10 per cent of the local speed of sound. To estimate the energy content of a vertical column of unit cross-section, we assume a density $\rho = 10^{-7} \text{ gm cm}^{-3}$ corresponding to $\tau \sim 0.1$ (Allen 1955) and a scale height of 100 km and thus find $E \sim \rho \langle v^2 \rangle H \sim 160 \text{ J cm}^{-2}$.

We now note a possibly significant relation between the brightness-velocity correlation, the measured lifetime of a given oscillation, and the energy content just calculated. On the one hand, our observations indicate an upward transport of non-radiative energy in the amount of about 2 W cm^{-2} , about half of which is heat energy being carried upward by the bodily motion of the gas and half is mechanical work done on the gas by the pressure. On the other hand, the oscillatory motions “decay” with a characteristic lifetime of about 400 sec. While this “decay” appears as a loss of time correlation and does not directly imply an actual dissipative damping mechanism, it does imply some sort of *flow* of energy through the oscillatory mode, with an essential difference in mechanism, time, or place between the “input” and “loss” of mechanical energy. (Of course, the observation of periodic effects in the brightness elements of the lower chromosphere indicates that an important part of this loss of correlation may result from damping of the waves.) Now the “loss” of energy, as indicated by the decay of the time correlation, seems to occur at about the same rate as that at which mechanical work is supplied through the brightness-velocity correlation, namely, about 1 W cm^{-2} . It thus appears quite plausible that the driving force for the oscillatory motion is the buoyancy of the hot granules.

If we next consider the fact that the small-scale brightness fluctuations in the lower chromosphere (and perhaps in higher layers as well) seem to exhibit the same periodic time correlation as the Doppler velocities, we may conclude that the oscillatory motions are probably responsible for these brightness fluctuations. Thus it seems possible that we are actually observing the essential chain of events by which energy is transferred from the granulating layer into the chromosphere: Gravitational energy in the form of the buoyancy of hot granules is converted into kinetic energy in the lower and middle photosphere, as evidenced by the brightness-velocity correlation, and thence, through the elastic properties of the atmosphere, into an oscillatory wave of rather definite frequency. This wave, propagating upward, eventually deposits a part (or all) of its energy in the chromosphere. On the basis of the numerical results so far obtained, it seems quite possible that the oscillatory motions contribute a major part of the energy which heats the chromosphere in non-active areas.

One of the most interesting results so far obtained in the present investigation is the numerical value of the oscillatory period itself. This newly measured property not only presents us with a challenge to understand its origin quantitatively but also, potentially,

offers a new means of determining certain other local properties of the solar atmosphere, such as the temperature, the vertical temperature gradient, or the mean molecular weight.

What can we say about the physical nature of the oscillatory motion? Dimensional considerations strongly suggest that the motion involves both elastic and gravitational forces, for if we evaluate the quantity $T = 2\pi c/g$, where $c \approx 6.8 \text{ km sec}^{-1}$ is the speed of sound and g is the acceleration of gravity, we find $T \approx 150 \text{ sec}$. An analysis (Lamb 1945) of the vertical propagation of elastic waves in an isothermal atmosphere reveals that such an atmosphere may indeed undergo free oscillations with a period equal to $2/\gamma$ times the above, or $\sim 190 \text{ sec}$ for the solar photosphere. (γ is the ratio of specific heats of the gas, assumed equal to $\frac{5}{3}$.) (See Whitney 1958.)

One can improve the agreement with the observed period somewhat by introducing a linear temperature gradient, but, in order to derive the observed period precisely, it will very likely be necessary to introduce the actual temperature gradient, as well as the molecular weight and γ variations due to hydrogen ionization and radiative transfer into the problem.⁷ Furthermore, the driving forces and boundary conditions may significantly affect the calculated period, and these are exceedingly difficult to specify precisely, especially as the dissipation of the wave energy into heat in the chromosphere not only damps the wave but also affects the local propagation properties of the medium. Thus it appears that an accurate calculation of the observed period may be hopelessly difficult or even impossible.

Nevertheless, it seems worthwhile to consider some of the possible abstractions of the actual physical situation which may provide a usefully accurate basis for further calculation. The following tentative list outlines some of the more attractive possibilities:

1. It is currently believed that the upper photosphere where the stronger spectral lines are formed is convectively stable and that a thin region just below $\tau_{5000} \approx 1$ is highly unstable. According to this picture, the granulation we observe is at about the uppermost limit of the unstable region. It seems most unlikely that the behavior of the upper stable layers can affect the motions within the unstable region to any appreciable extent. Therefore, it might be fruitful to consider the observed Doppler motions not as a free oscillation but as the response of a filter system—the upper atmosphere—to a broad-band “noise” spectrum introduced by the violent convective motions below. The atmosphere will then preferentially transmit those frequencies that are less attenuated. One difficulty with such a view is, of course, that the vertical extent of the atmosphere from the “input layer” to the line-forming layers is not very many attenuation lengths, even at frequencies some octaves removed from the nominal “resonance” frequency. Thus it is difficult to see how the atmosphere can greatly modify the input spectrum.

2. We have seen that there is a significant upward flux of thermal energy—about 2 W cm^{-2} —which is energetically capable of supporting the oscillatory motion. Perhaps the atmosphere is, in fact, a kind of thermodynamical engine which is transferring heat from the hot interior to the cold exterior of the sun, by a mechanism such as the following: if one investigates the properties of *standing waves* of various horizontal wave numbers, there appears a certain coupling between the horizontal and vertical velocity components, such that a vertically rising gas element may undergo a lateral expansion or compression as it rises and the reverse as it falls. This net compression or expansion is a function of the horizontal wave number and the frequency. Now, inasmuch as the $\sim 50\text{-km}$ total vertical excursion is a significant fraction of a scale height, it seems possible that the radiative properties of a given gas element may be sufficiently different at its uppermost and lowermost positions to contribute to the motion itself. Thus, if an element is relatively cool at its lower position and is then also shielded from radiating by the temporary presence of higher elevation material nearby, it may become overheated.

⁷ Since the radiative relaxation time is very short compared with the period of the oscillation, the effective value of λ should be very nearly unity.

ed because of its proximity to the hot interior. It may then become buoyant, rise, and, in rising, perhaps remain hotter if it is laterally compressed. It may then arrive at its upper position both superheated and also, by its additional height, able to radiate more efficiently. In radiating, it contracts, becomes relatively dense, and thus falls again, to repeat the process. In this picture the frequency would be fixed by the condition that the thermodynamic cycle should entail a *maximum net output* of work.

3. The solar atmosphere is characterized by a temperature profile as a function of height which passes through a minimum in the upper photosphere and increases at both greater and lesser heights (de Jager 1959). Now the propagation of high-frequency (acoustic) waves in such a medium would be characterized by a bending of the ray trajectory *away* from the vertical, both above and below the plane of minimum temperature (Kahn 1961). Thus acoustical energy would tend to become concentrated near this level. As we follow this property of the atmosphere for lower and lower frequencies, we eventually find that, for *very* low frequencies, the region of minimum temperatures no longer *transmits* waves but *attenuates* them. The atmosphere may therefore act as a *wave guide* for laterally moving waves, and the observed oscillation may correspond to the lower "cutoff" frequency of the wave guide.

4. While there is no observational evidence known to us to suggest a 5-minute periodicity in the granulation *brightness* field, neither can this be completely excluded at the present time. It seems unlikely, but perhaps possible, that the 5-minute period is actually a property of the convection zone rather than the upper atmosphere and that this periodicity is revealed in the upper atmosphere only in virtue of the larger velocity amplitudes called for by the relatively lower density there.

It is perhaps worthwhile to observe here that the existence of a brightness-velocity correlation does not necessarily imply an oscillation in the photospheric brightness field corresponding to that observed in the velocity field. In fact, it seems more reasonable to suppose that the brightness elements constitute a temporally random driving force for the upper atmosphere and that only the *immediate* responding motion of the atmosphere is well correlated with this driving field. The subsequent motion of the atmosphere—which may be wholly uncorrelated with the driving field—may then be the "ringing" after-response of the resonant atmosphere. Thus the brightness-velocity correlation might well only express the fact that the brightness elements influence the *phase* of the subsequent oscillatory response.

We shall not analyze the above ideas here in any greater detail, for to do so is not the purpose of this paper and would, in any case, be premature in view of the rudimentary state of our present knowledge of the physical situation. However, the preceding discussion should serve to suggest certain kinds of observations which could provide a firmer basis for theoretical attack upon the problem.

Finally, let us consider briefly the small-scale motions that appear in the Doppler plates taken near the core of the H α line. The linear scale of these motions—about 3.6×10^3 km—and their short lifetime—about 30 sec—suggest to us that they are connected physically with the oscillatory motions seen at lower levels. However, it seems clear that the rather different physical state of the upper chromospheric medium should rather drastically modify the dynamics of the waves in this region. In the photosphere, we have little doubt that the motions involve only the total mass density, the elastic compressibility, and the surface gravity. In the upper chromosphere, however, we have equally little doubt that even rather weak magnetic fields may enter into the dynamical situation in an essential way through their action upon the ionized component of the medium.

It is interesting to consider two aspects of the rapid time changes which we find in the upper H α chromosphere. On the one hand, the magnitude of the acceleration required to change the velocity by, say, 2 km sec^{-1} in 30 sec amounts to about one-fourth the solar acceleration of gravity. Thus the motions may probably be considered as having a rather small amplitude if acoustical forces only are involved. On the other hand, if we

regard these accelerations as being associated with horizontally propagating (hydro-magnetic) waves whose wavelength is on the order of 3.6×10^3 km (i.e., the linear scale of the motions themselves), the velocity of propagation of these waves must have the rather large value of about 100 km sec^{-1} .

If the upper chromospheric motions are connected with the oscillatory motions in the lower levels, we should perhaps expect at least a vestige of the periodic time correlation to appear in H α Doppler difference plates, but none has been found so far. Of course, if the wave energy which reaches the upper chromosphere propagates laterally at a sufficiently high velocity, a time correlation might easily be masked, even if it were present, because the motion at a given point could be predominantly determined by the earlier motion at a large number of surrounding points and only relatively slightly affected by the local motions in the lower chromosphere beneath it.

In concluding this discussion, we should emphasize that most of our observations and our interpretation of them must be regarded as preliminary in the sense that more complete measurements, as well as improvement of the apparatus and procedures, will almost certainly lead to more detailed—and probably more precise—results. Certain improvements in the method have already been made, particularly in connection with the calibration procedure, and others are planned. Further reports on work now in progress will be forthcoming as new results are obtained.

VI. SUMMARY

Preliminary measurements, obtained by a new method, provide a new and clearer picture of the motions in undisturbed regions of the solar atmosphere. In the photosphere, two distinct velocity fields exist. One of these is a large-scale, long-lived cellular pattern of horizontal currents, and the other is a smaller-scale, quasi-oscillatory system of vertical (and perhaps horizontal) motions. The large cells, about 5000 of which are distributed rather uniformly over the solar surface, have “diameters” of about 1.6×10^4 km and lifetimes of several hours, and the flow within each cell is from the center toward the outer boundary. Typical velocities are about 0.5 km sec^{-1} . There appears to be a geometrical relationship between the large cells and the chromospheric network. We tentatively suggest that this cellular pattern and the chromospheric network are surface manifestations of a supersystem of convective currents originating at rather great depths within the sun.

The smaller-scale velocity field is closely related geometrically to the brightness granulation, and probably the two are but different aspects of a single entity. The distinctive feature of this velocity field is its quasi-oscillatory character. Surface elements larger than $\sim 2\text{--}3 \times 10^3$ km independently undergo an oscillation with a period of 296 ± 3 sec, a velocity amplitude of about 0.4 km sec^{-1} , and a mean life of about 380 sec. We are as yet unable to state whether this mean life corresponds entirely to a gradual decay of the velocity amplitude, or whether it also involves abrupt changes in phase or other decohering processes. The oscillatory motion is prominent in the lines Ca 6103, Ba⁺ 4554, and Na 5896, and can be seen also in the weaker line Fe 6102 and the stronger lines Mg 5528 and Mg 5173. A corresponding oscillation in the small-scale bright elements of the lower chromosphere is also indicated. There is no strong indication of a variation in the period with altitude or horizontal “cell size,” although a dependence upon such factors cannot be excluded.

A distinct brightness-velocity correlation is observed, with brighter elements moving upward at lower levels and downward at higher levels. The upward transport of energy amounts to about 2 W cm^{-2} at the level of Ca 6103, and it is suggested that the buoyancy of the hot granules provides the energy needed to maintain the oscillatory motions. It seems possible that the phenomena reported here may account for a major part of the transfer of energy from the granulating layer into the chromosphere.

In the H α chromosphere, there is a strong variation in the nature of the velocity field with altitude. At higher elevations ($\Delta\lambda \sim 0.3 \text{ \AA}$ from the line center) one sees a granular

field of upward and downward motions. Typical sizes are $\sim 3.6 \times 10^3$ km; velocities, ~ 2 km sec $^{-1}$; lifetimes, ~ 30 sec. There is no strong indication of association with local magnetic fields at this elevation, but their presence is by no means excluded.

At lower elevations ($\Delta\lambda \sim 0.8$ Å) the greater part of the solar surface is relatively quiescent, the only significant motions being confined to a network of "funnels," geometrically similar to the well-known chromospheric network observed in Ca $^+$ K $_2$ spectroheliograms. Motion is predominantly downward through these "funnels," and the participation of magnetic fields is strongly suggested at this level. The "lifetime" of the velocity pattern may be several hours, although significant changes do occur within a few minutes.

VII. CONCLUSION

While the measurements reported here seem in quite satisfactory agreement with results obtained by other investigators by other methods wherever direct comparisons can be made, the present method has considerably extended previous results and has provided a new and more coherent picture of the solar atmospheric motions. However, we feel that it has not yet reached its full capabilities. The least satisfactory aspect of the present procedure—the method of calibrating the velocity sensitivity of the plate at various stages of reduction—seems greatly improved by the newly adopted system of introducing artificial Doppler shifts of known magnitude by moving the exit slit a precisely prescribed amount. This and other improvements having to do with the elimination of certain optical aberrations of the present system should further enhance the capabilities of the method and perhaps bring even more subtle phenomena within its range of sensitivity. We are hopeful that work now in progress, together with the more refined data that should be available later, will further elucidate the general nature and detailed properties of motions throughout the solar atmosphere. In addition, it should be clear that the basic procedures can also be applied in still other ways to study various features of the sun's surface. Work is now under way in some of these other areas also.

We take this opportunity to extend our sincere thanks to Dr. I. S. Bowen and the Carnegie Institution of Washington for undertaking an extensive modification of the spectroheliograph at the 65-foot tower telescope of the Mount Wilson Observatory and for providing observing time and facilities. Our thanks are also due the Observatory optical and engineering staff for their part in the modification program. We gratefully acknowledge the able assistance of Mr. Warren L. Simmons in the observation and measurement program.

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