INCLINED INHOMOGENEITIES IN THE SOLAR PHOTOSPHERE

BY JOHN W. EVANS

Sacramento Peak Observatory of
Air Force Cambridge Research Laboratories, Sunspot, New Mexico.

Abstract: The threads of the solar spectrum are the bright and dark streaks parallel to dispersion due to bright and dark inhomogeneities ~ 1000 km wide in the solar atmosphere. They are prominent in the continuum and are traceable with varying contrast through some or all of the Fraunhofer lines. In the wings of very strong lines, many of the bright threads are curved, with x-displacements (perpendicular to dispersion) up to 1000 km on the sun. At $\Delta \lambda = 0.2\AA$ from the center of Fe 4383.6 the rms x-deviation of threads from their positions in the continuum is $\bar{x} = 500$ km. If we assume that the height observed in the photosphere is an inverse function of $\Delta \lambda$, the curved threads correspond to strongly inclined bright elements in the solar atmosphere. If also we observe a specific height, $h$, at the center of a weaker line, the thread displacements in this line should be the same as at the corresponding $\Delta \lambda_A$ in Fe 4383.6. A comparison of the x coordinates of 6 threads in 15 weaker lines shows that for each of the lines this exception is fulfilled. There is a difficulty with the inclined element explanation, however. The x-deviations of threads are large at $\Delta \lambda$'s greater than 5 Doppler widths in Fe 4383.6, $\Delta \lambda$'s at which we might expect the height observed to be indistinguishable from the level of continuous absorption. One alternative explanation is suggested, but does not appear promising.

Introduction. Many small scale phenomena in the photosphere of the sun are evident in good stigmatic solar spectrograms. The most conspicuous of these are the quasi periodic vertical motions in 3000 km elements manifested in the wiggly lines, (Leighton, 1960; Leighton, Noyes, and Simon, 1962; Evans and Michard, 1962c, and Evans, Michard and Servajean, 1963), and the diverging horizontal motions in the 30,000 km cells of supergranulation found by Leighton Noyes and Simon in their velocity spectroheliograms (Leighton, Noyes, and Simon, 1962). In addition to the line wiggles, the spectrograms show sharply defined bright and dark threads, typically 1000 km wide, running parallel to dispersion. The threads are quite apparent in Figure 1. In the continuum the threads are simply the result of brightness fluctuations in the solar granulation. In the Fraunhofer lines, however, we presumably see the brightness fluctuations at higher levels in the solar atmosphere, and Evans and Michard (1962b) found that the pattern is quite different. This paper is a study of the differences as they appear at the center of the solar disk.

On microdensitometer tracings in the $X$ direction, perpendicular to the dispersion, most of the bright and dark threads appear as alternate positive and negative peaks, with no sign of an intermediate mean background. See the tracings of Figure 2. The bright
Fig. 2. Microdensitometer traces from the spectrogram of Figure 1, scanned across the dispersion at various \( \Delta \lambda \)'s in the wings of Fe 4383.6. The loci of a number of curved threads have been marked. The ordinate scale is approximately logarithmic.
Fig. 1. The solar spectrum near Fe 4383.6, showing the threads.
Fig. 3. Photograph of solar granulation in green light.
and dark threads appear to be quite symmetrical in the sense that a tracing looks statistically the same, whether right side up (brightness increasing upward) or upside down. That the symmetry in the intensity fluctuations along the line of the slit does not imply a two dimensional symmetry of brightness fluctuations on the surface of the sun is evident from high resolution photographs of granulation like Figure 3. Here the typical bright elements are clearly separated islands in a singly connected dark sea. It is likely that a similar difference between bright and dark elements persists at the higher levels seen in the absorption lines. It is perhaps somewhat more meaningful, therefore, to consider the bright elements and the relatively rare very dark pores as the perturbations on a loosely defined mean background. For this reason I have given more attention to bright threads than dark threads.

The distortion of relative line intensities in the spectrum of Figure 1 require explanation. The spectra were printed through a mask which reduced the unprintable depths of the absorption lines without affecting the contrast and detail in the direction perpendicular to dispersion. The mask was a positive contact print of a mean spectrum, exposed while the solar image was in rapid motion across the spectrograph slit. It is quite without structure perpendicular to the dispersion. The illustrations were printed with the original film and mask in contact. The results are ugly, with gross distortions of relative line strengths, and even reversals. However, they show the geometry of the threads quite faithfully, although with a considerable loss in detail. All of the results described below depend, of course, on studies of the original spectra, which are much clearer and show more detail than the prints.

**Observed characteristics of threads.** A careful examination of many spectra in the region between $\lambda$ 4000 and $\lambda$ 6000 has established the qualitative character of the spectrum threads at the center of the solar disk. The results were as follows.

a) In general the intensity contrast of a given bright or dark thread is very different in the continuum and at the centers of the Fraunhofer lines. This difference tends to increase with line strength. In the wings of very strong lines the transition is easily visible and appears to be a smooth function of $\Delta \lambda$, the distance from line center.

b) The intensity behaviour of different threads is very diverse. At one extreme we find the most numerous class, *continuum threads*, which are very strong in the continuum and fade into near or complete invisibility at the centers of strong lines. At the other extreme are *line threads*, strong at the centers of strong lines, and weak or invisible in the continuum. Between the extremes are less numerous *uniform threads* of approximately constant contrast in the continuum and the wings and centers of all lines (except $H\alpha$, $H\beta$, $H$ and $K$) and *wing threads* in which maximum contrast occurs in the wings of the strong lines and decreases or vanishes at line center or in the continuum or both. Both bright and dark threads of all four classes are found. The predominance of continuum and line threads leads to the low correlation found by Evans and Michard (1962b) between intensities in the continuum and at the centers of lines. The micromoustaches found by Evans and Michard (1962b) are identical with the bright wing threads.
c) About a third of the threads are visibly curved in the wings of strong lines, showing marked displacements in the $X$ direction perpendicular to dispersion. The $X$-displacements usually vary smoothly with $\Delta \lambda$, and are symmetrical about the line center, with the same sign on the blue and red sides. Some of these curved threads are visible in Figure 1. The largest displacements are about one second of arc along the slit, and are very conspicuous in good spectrograms. There does not appear to be any systematic loss of sharpness of the threads in their curved portions, nor any difference in sharpness between curved and straight threads, although some threads are decidedly sharper than others.

d) The Doppler shift at the $X$ position of a thread has a profound effect on its appearance as it crosses a Fraunhofer line. This effect complicates the interpretation of both the $\lambda$ variations of contrast and the thread curves, and is a considerable nuisance for the main purposes of this paper. Since it does affect our conclusions, however, a short dissertation on the influence of local Doppler shifts is required, and should be endured patiently.

As a sample, consider an absorption line with a Gaussian profile, in which the central intensity is 0.28 and the $1/e$ points are at $\Delta \lambda = \pm 0.07 \, \AA$. This is an approximation to the line $V\, 4378.24$ in Figure 1. The logarithms of the intensities in the profile are shown in Figure 4a where curve 1 represents the normal photosphere with no Doppler shift and average intensity.

Now suppose profile 1 represents the intensities at two points $X_1$ and $X_3$, but the profile is Doppler shifted $\Delta \lambda = \pm 0.01 \, \AA$ at the intermediate $X_2$, represented by profile 2. We see a bright thread at $X_2$ at negative $\Delta \lambda$'s within the line and a dark thread at positive $\Delta \lambda$'s, with maximum contrast (the ordinate difference between the profiles) near the inflection points in the lg$I$ profile. The eye sees this as an apparent line shift much larger than the actual 0.01 $\AA$, and a surprising asymmetry in brightness. Figure 5B shows the effect on the $X$-profile through $X_1$, $X_2$, and $X_3$ at various $\Delta \lambda$'s.

Next, suppose in Figure 4b there is an unshifted bright thread at $X_2$, profile 3, between relatively dark threads at $X_1$ and $X_3$, profile 1. Let the difference in lg$I$ be 0.04 at all $\Delta \lambda$'s. The contrast is constant at all $\Delta \lambda$'s, and the $X$-profiles are those of Figure 5C. Now Doppler shift profile 3 by $+0.01 \, \AA$ to profile 4. Again the contrast represented by the ordinate difference between 1 and 4 becomes very asymmetrical about the line center and in this instance reverses sign between $\Delta \lambda \sim +0.005$ and $+0.07 \, \AA$. With a smaller Doppler shift the contrast at positive $\Delta \lambda$'s would simply be diminished or vanish. In any event the contrast at negative $\Delta \lambda$'s is greatly enhanced. As before, the apparent line shift is much larger than the actual 0.01 $\AA$ and the thread contrast looks even more asymmetrical. The effect on the $X$-profiles is shown in Figure 5D.

Finally, suppose we have a bright thread at $X_2$ between two dark threads with an $X$ velocity gradient at $X_2$ as shown at the bottom of Figure 5E. Here the effect is rather more complicated. The dark threads, where $\frac{dv}{dx} = 0$ (where $v =$ sightline velocity) become
Fig. 4. The effect of Doppler shifts on line profiles.
(a) 1 Profile of undisturbed line
2 Doppler shifted 0.01 A.
(b) 1 Profile of undisturbed line.
3 Profile of thread brighter than Profile 1 by 0.04 in $\log I$.
4 Profile 3 Doppler shifted 0.01 A.

The $\log I$ curves were calculated for a Gaussian line profile with central intensity of 0.28 and the

$$ I = \frac{1}{e} \quad \text{at} \quad \Delta \lambda = 0.07 \, \text{A}. $$
Fig. 5. Changes in contrast and apparent position of threads in an absorption line induced by Doppler shifts. Abscissae are distances perpendicular to dispersion. Ordinates are $\lg I$ at the various $\Delta \lambda$'s. The spacing between $\Delta \lambda$'s represents 0.06 in $\lg I$. Ordinates in the bottom row represent sightline velocity. The columns refer to: A, $\Delta \lg I$ constant, $V = 0$; B, $\Delta \lg I = 0$, $V = 0.67 \cos \pi x$; C, $\Delta \lg I = 0.02 \cos \pi x$, $V = 0$; D, $\Delta \lg I = 0.02 \cos \pi x$, $V = 0.67 \cos \pi x$; E, $\Delta \lg I = 0.02 \cos \pi x$, $V = 0.67 \sin \left(\frac{\pi}{2} x\right)$. The heavy curve in E is the locus of maximum brightness.
asymmetrical in contrast in opposite senses (since the Doppler shift is opposite at $X_1$ and $X_3$) but retain their $X$-positions. The bright thread at $X_3$, however, shows a change in $X$ with $\Delta \lambda$, of opposite sign on the two sides of line center. It appears as an inclined thread across the line profile, a very common phenomenon. If in addition there is a Doppler shift at $X_2$, contrast asymmetry is introduced as in D.

As a rule of thumb, within an absorption line a Doppler shift results in an asymmetry in contrast, and a gradient in Doppler shift produces an inclined thread. The two effects can combine, and often do. The asymmetry in contrast amplifies the apparent displacement due to the Doppler shift. The exaggeration, always large, varies with the rapidity of the change of $v$ with $X$. Thus a series of closely spaced line wiggles of opposite sign appear to have a much larger amplitude than if they are spaced farther apart in $X$. If the apparent wiggles were no larger than the actual Doppler shifts, they would be on the verge of invisibility in most lines.

All of the effects demonstrated in Figure 5 are quite commonly found in spectrograms like those of Figure 1. These are the simplest cases. When we consider the additional complications of Doppler shifts varying with $\Delta \lambda$ (see Evans, 1963), inherent contrast varying with $\Delta \lambda$ (Evans and Michard, 1962b), and inherently curved threads, the possibilities seem endless. Fortunately, however, all of these velocity effects differ from the photometric and geometrical characteristics of interest in this paper in being unsymmetrical in sign about the line center.

From this qualitative study emerge two significant properties of threads in transition between the continuum and the cores of strong Fraunhofer lines. First, many threads are curved, a geometrical effect. Secondly, thread contrast varies with distance from line center, $\Delta \lambda$, and varies differently in different threads, a photometric effect. Like the earlier studies of the velocity inhomogeneities in the solar atmosphere, these facts reinforce the generally accepted idea that in an absorption line the height of origin of the light at a given $\lambda \Delta$ is an inverse function of $\Delta \lambda$. The observations do not define this function, but common sense indicates that the center of an absorption line originates at the highest level, and that the height of origin decreases with increasing $\Delta \lambda$ down to the level of continuous absorption where we see the granulation. By the same reasoning, strong lines originate at higher levels than weak lines.

The invariable decrease in $\xi^2$, the mean square velocity measured in line wiggles, with increasing $\Delta \lambda$ (Evans, 1963), and the increase of $\xi^2$ with line strength (Evans and Michard, 1962a) become comprehensible in this context if we assume that $\xi^2$ increases with height.

Similarly, the bright and dark threads are due to bright and dark inhomogeneities in the solar atmosphere, many of which persist through a rather limited range in height (or $\Delta \lambda$). The bright or dark elements at low, intermediate, and high levels produce the continuum, wing and line threads, and the rarer elements extending from top to bottom of the photospheric layer produce the uniform threads. As we shall see further on, however,
the top-to-bottom inhomogeneities are probably more numerous than they appear to be. Some of the inhomogeneities are sharply inclined to the vertical. At different $\Delta \lambda$'s we see the cross sections of such elements at different heights, and hence observe curved threads. Figure 6 shows the geometry.

If this picture is correct, we should expect to find certain consistencies in the thread characteristics and the $\xi$'s in different lines. Consider a medium strength line, $A$, and a very strong line, $B$. Suppose the light at the center of $A$ and at $\pm \Delta \lambda_{A,B}$ (in the profile of $B$) originates at the same height in the solar atmosphere and in the same body of material. Then the $X$ coordinate of any given thread should be the same at the center of $A$ and at $\pm \Delta \lambda_{A,B}$. Thus if the thread is curved, a measurement of $X(A)$ and its $X(\Delta \lambda)$ curve in $B$ permits the determination of $\Delta \lambda_{A,B}$. All curved threads should yield the same $\Delta \lambda_{A,B}$. We should also be able to relate the common level $\Delta \lambda$'s in the profiles of two or more strong lines by a comparison of the $X(\Delta \lambda)$ curves of threads in the two lines. In like manner $\xi(A)$ should equal $\xi(\Delta \lambda_{A,B})$. Note that these relations depend on pure geometry and mass motion. They are quite independent of theories of line absorption or model atmospheres, other than the premise relating $\Delta \lambda$ and line strength to height in the solar atmosphere.

We may also expect, less confidently, that the contrast should be similar in line $A$ and at $\pm \Delta \lambda_{A,B}$.

This is admittedly an idealization, since it is likely that the level of origin is different in threads of different brightness, both in $A$ and at $\Delta \lambda_{A,B}$. Furthermore, the sharpness of this level may be very different in $A$ and at $\Delta \lambda_{A,B}$. Finally, both contrast and $X$ position of a thread in the core of $A$ can be seriously affected by the distortions introduced by velocity shifts as discussed above.

In spite of these mitigating effects, further examination of the spectra confirmed that both thread contrast and $X$-position appear to behave approximately in the expected fashion.

There is one doubtful feature in this simple picture. Measured in terms of the total range of height observed between the continuum and the center of a strong line, the resolution in height at a given $\Delta \lambda$ seems surprisingly sharp. This is indicated by two observed facts. Some strong wing threads are practically invisible in both the continuum and line center. More importantly, most curved threads retain their sharpness at $\Delta \lambda$'s where their slopes, $\frac{dX}{d\Delta \lambda}$, are greatest. Neither of these things could be if the light at $\Delta \lambda$ came from a range in depth much greater than about a third of the total height range. It is difficult to be too positive, however, about estimates of any photometric effects or of the relative sharpness of threads. Hence these considerations deserve much less weight than the quite definite and compelling fact that many threads are strongly curved.
Fig. 6. Geometry of the formation of a curved thread. \( A \) is an inclined inhomogeneity rising in the solar atmosphere above the granulation layer \( G \). Several levels are numbered. \( B \) is the same inhomogeneity seen from above, with the projection of the spectrograph slit. To the right is the line profile, with numbered \( \Delta \lambda \)'s corresponding to the numbered heights in \( A \). \( T \) is the curved thread that results from this configuration.
In sum, the spectrum threads seem to fit very well into the accepted picture of an inhomogeneous solar atmosphere. The contrast fluctuations and thread curvatures add the fact that the inhomogeneities vary greatly with height in both brightness and position, and that these variations are different in different inhomogeneous elements.

**Measurements of curved threads.** The thread curvatures apparently exist and have significance for the study of the structure of the solar atmosphere. They will be useful when we know something quantitative about the frequency distribution and shapes of the \(X\)-displacements of the threads. It will then be possible to determine whether for each weak Fraunhofer line, \(A\), there is a definite \(\Delta \lambda_{A,B}\) in a strong line \(B\) that is the same for all curved threads. I have measured the \(X\) coordinates of enough threads to give the required information in small measure, in the strong line Fe 4383.6 and weaker lines nearby. To confirm the value of \(\Delta \lambda_{A,B}\), I also determined the \(\xi(\Delta \lambda)\) curve of Fe 4383.6 and \(\xi\)'s in the weaker lines.

**Observational material.** The measurements were made on a single spectrogram shown in Figure 1, number 898–21 in the Sacramento Peak system. It includes the region from \(\lambda 4377\) to 4386, with a dispersion of 14.0 mm/\(A\). The spectrogram was one of a time series taken with the ccelostat fed 12 inch telescope and 13 meter Littrow spectrograph, in the 14th order of a 25 cm, 300 groove/mm Harrison grating. The technical data are as follows: Eastman IV–0 35 mm film developed 6 minutes in Acufine at 18 °C to \(\gamma = 2.1\); densities above clear film, 1.4 in the continuum and 0.1 at the center of Fe 4383.6; exposure, 15 seconds, slit width 150 \(\mu\), through the birefringent monochromator (Evans, 1962). The resolution of solar detail is sufficient to just separate bright threads 600 km apart, on a scale of 5400 km/mm.

**Method of measurement.** The array of cross dispersion microdensitometer tracings shown (much reduced) in Figure 2, showed the existence of curved threads unambiguously, but the accuracy of measurements on the tracings was disappointing. Direct measurement with an old fashioned comparator was very much more satisfactory. The standard deviation of thread measurements repeated on different days varied from \(\pm 3\mu\) for sharply defined threads to \(\pm 7\mu\) for very fuzzy ones. All of the measurements discussed below were made with the comparator.

In the remainder of this paper, all lengths in the \(X\) direction are given in terms of kilometers along the projection of the slit on the sun. The coordinates \(X\) and \(x\) are measured, respectively, from the fiducial line on the spectrogram (produced by a hair across the slit during exposure), and from the adopted \(X\)-position of a thread in the continuum. Coordinates in \(y\) refer to distances on the sun, measured from the center of the projected slit, perpendicular to \(X\). Threads are identified in the form \(T\left(\frac{1}{1000}X\right)\), like \(T(13.2)\) for a thread at \(X = 13,200\) km in the continuum.
Unless otherwise stated, $\Delta \lambda$ always refers to distance from the center of the line Fe 4383.6. The expressions $x(\Delta \lambda)$ and $x(\lambda)$ represent the variation of $x$ in a thread with $\Delta \lambda$ or $\lambda$.

As in the earlier work (Evans and Michael, 1962a), $\xi^2 = 2\sigma^2$ where $\sigma^2$ is the mean square sightline velocity derived from a $v(X)$ curve. The $v(X)$ curves for different $\Delta \lambda$'s in Fe 4383.6 and for $\Delta \lambda = 0.014 \lambda$ or $0.021 \lambda$ in the weaker lines were traced on the Sacramento Peak recording Doppler comparator. This machine simultaneously produces a $v(X)$ curve from a chart recorder and a deck of punched IBM cards with 228 $(v, X)$ data points across the width of the spectrogram (135,000 km in X). An IBM 1620 computer calculated the values of $\xi$.

Mr. Horst Mauter traced the intensity curve of the spectrum shown in Figures 8 and 9 with the spectrograph in its scatter free double pass configuration (see Evans and Waddell, 1962). The tracing is reproduced without correction for the finite resolving power of the grating (~500,000) or slit width (equivalent to 0.016 $\lambda$). The recorded central intensity of Fe 4383.6 is 0.034.

**Frequency of thread displacements.** In the width of 135,000 km shown in the spectrogram, 58 bright threads appear in the continuum. All of them are traceable to within $\Delta \lambda = 0.2 \lambda$. In order to determine the frequency distribution of $x_t$, the total $x$-displacement of a thread, the $x$ coordinate of each thread was measured in the continuum at $\lambda$ 4381.4 and at $\Delta \lambda = 0.2 \lambda$ in Fe 4384.6. The resulting histogram appears in Figure 7.

Half of the threads in this sample show curves with $x_t > 320$ km on the sun. The largest $x_t$ is 1200 km. The rms deviation is $\bar{x} = 500$ km. The histogram represents only the $x$ component of displacement seen through a slit 810 km wide. If the actual displacements are in fact equally distributed in all directions about the line of sight, the histogram underestimates the true relative frequencies of the larger displacements. The observed distribution shows about 40% of the threads with displacements greater than the half width of the slit. Hence many of the bright solar inhomogeneities extending from top to bottom of the height range covered by Fe 4383.6 are doubtless inclined sufficiently in the $y$ direction to be visible in the slit through only a limited range of height. These give the appearance of a continuum or a wing or a line thread, when in fact, they would have been curved uniform threads if the spectrograph slit had been oriented parallel to their inclinations. I conclude therefore that highly inclined inhomogeneities in the solar atmosphere and inhomogeneities extending through a great height range are both relatively more numerous than the uncorrected observations would indicate.

**Measured thread $x$-displacements.** Six threads were then selected which were strongly curved and suitable for measurement both in the continuum and in most of the lines on the spectrogram. I measured them at short intervals of $\Delta \lambda$ in the wings of Fe 4383.6, in the continuum near $\lambda$ 4381.4, and in the centers of 15 lines. The purpose was to define the $x(\Delta \lambda)$ profiles of the curved threads, and to determine the $\Delta \lambda_{A,B}$ in Fe 4383.6 at which the $x$ is equal to $x$ at the center of each of the weaker lines.
Fig. 7. Histogram of the number of threads with $\Delta x_T$ between stated limits. $\Delta x_T$ is the total deviation of a thread between the continuum and $\Delta \lambda = 0.2 \AA$.

Figure 8 shows the $x(\Delta \lambda)$ profiles, with the intensity profile of Fe 4383.6 taken from Mr. Mauter's tracing. Since the $x(\Delta \lambda)$ curve is always symmetrical except near the core of the line, I have folded the long (dots) and short (open circles) wavelength branches on top of each other about the center of symmetry. Three of the threads showed decided asymmetries in the line core due to velocity gradients in the $X$ direction. Within the $\Delta \lambda$ limits indicated by the vertical lines, I have shown the two sides of the line separately. All of the $x$-displacements are plotted in the same direction in the interest of compactness in the figure, although the signs of $x$ in the first two (from the top) were opposite to those of the remaining four.

These six $x(\Delta \lambda)$ curves vary in total $x$-displacement and shape. Generally the curve is fairly flat in the continuum and breaks into its «curved» portion rather abruptly. In most instances the accuracy of measurements is not sufficient to decide whether the curved portion is in fact definitely curved or straight. The break comes at different $\Delta \lambda$'s in different threads, from $\sim .3 \AA$ in $T(-11.1)$ to $\sim .75 \AA$ in $T(+47.8)$. This can only mean that a bright inhomogeneity in the solar atmosphere tends to be vertical up to a given height, which is different for different threads, and is inclined above this height. The
Fig. 8. Measured $x(\Delta \lambda)$ curves for six threads in Fe 4383.6. The thread in the red wing is reflected in the $\Delta \lambda = 0$ axis onto the blue wing. Dots are measurements in the red wing, and o's in the blue wing. The red and blue sides are plotted separately near the line center for threads with unsymmetrical Doppler distortions. For comparison, the line profile is shown at the bottom.
Fig. 9. The $x(\Delta \lambda)$ curve of thread $T(+ 17.1)$ with an intensity tracing from $\lambda$ 4377 to 4386. Note the coincidences between thread deviations and the stronger absorption lines.

time dependence of the $\Delta \lambda$ of the break point will be the next step in the study of threads, and should be interesting.

The thread $T(- 27.5)$ is particularly interesting. It was selected for measurement because it showed a quite visible reversal of the $x(\Delta \lambda)$ curve at $\Delta \lambda \sim 0.2 \, \AA$. The measured curve shows this. In addition it shows another slower reversal between 0.8 and 2.0 $\AA$ which was not evident to the eye. Although not very large, the sharp reversal at 0.17 $\AA$ suggests that the levels in the solar atmosphere seen at $\Delta \lambda = 0.0$, 0.17, and 0.3 are quite distinct. In other words, the light from the level that is seen at $\Delta \lambda = 0.17$ is not very seriously contaminated by light from the levels corresponding to $\Delta \lambda = 0.0$ and 0.3. The steepness of the curved portions of all of the measured threads, particularly $T(+ 15.7)$, leads to a similar conclusion.

The thread $T(+ 17.1)$ is very sharply defined in the spectrogram, reasonably bright, and easily measurable in the continuum and most lines. It has a strong curve with the break at a fairly large $\Delta \lambda$ in Fe 4383.6 and the velocity $X$-gradient is small. It was therefore measured in detail throughout the whole length of the spectrogram. Figure 9 shows the measured points, along with a photograph of Mr. Mauter's intensity tracing. Measured $x$'s separated by $\leq 0.02 \, \AA$ in $\lambda$ have usually been averaged. They are plotted at the mean $\lambda$, open circles representing averages of two points and plus signs of three points. Points of low weight are in parentheses.

With due allowance for errors of measurement, the $x(\lambda)$ curve of Figure 9 agrees well with our conception of a curved thread caused by the inclination in $x$ of a bright inhomogeneity in the solar atmosphere. In every adequately measured line of equivalent width, $W > 20$ mA, and in many of the fainter lines, the thread is unmistakably displaced. The expected correlation between the central intensities of lines and their $x$-displacements.
Fig. 10. Correlation for $T(\pm 17.1)$ between the central intensities of lines of equivalent width $\geq 20 \, m\AA$ (except for Ce II 4382.2 of $W = 8 \, m\AA$) and the thread deviations. Solid dots are lines of neutral atoms, crosses are neutral blends, open circles are lines of ionized atoms, and the square is an ionized line and a neutral line blended (La II + Fe 4385.0). The $x$'s are the $(I, x)$ relation in the profile of Fe 4383.56.

is clearly present. It is shown in Figure 10. The central intensities of the lines, $I_0$, were determined from the tracing of Figure 9 with no corrections for instrumental effects.

Measurements of $\Delta\lambda_{A,B}$. Assume that at the center of a relatively weak line $\lambda_A$ and at a corresponding $\Delta\lambda_{A,B}$ in a strong line, like Fe 4383.6, the light comes from a very thin layer at height $h_A$ in the solar atmosphere. Then a given thread should have the same $X$ coordinate at $\lambda_A$ and at $\Delta\lambda_{A,B}$, because we are looking at the same bright element at the same height in the two wavelengths. Different threads will have different curves, but in thread $j$, $X_j(\lambda_A) = X_j(\Delta\lambda_{AB})$ invariably. On the assumption that this is an approximation to the truth, I have tried to determine the $\Delta\lambda_{AB}$ for 15 lines on the spectrogram of Figure 1,
to see whether the six threads of Figure 8 give a single well-defined value of \( \Delta \lambda_{AB} \) for each line. The method is simply to measure thread \( j \) in line \( A \), obtaining \( X_j(\lambda_A) \) and read the corresponding \( \Delta \lambda_{A,B} \) from the \( X_j(\Delta \lambda) \) curve in Figure 8.

The results are listed in Table I. The numbers in the top row are the \( X \) coordinates of the 6 threads. The first column lists the various lines, \( A \). The column under each thread gives the \( \Delta \lambda_{A,B} \) for each line. Determinations of low weight are in parentheses. The weighted mean \( \Delta \lambda_{A,B} \)’s are in column 8, and the standard deviations, \( \sigma \), of a single determination are in column 9. Values in parentheses have been given half weight.

The \( \sigma \)’s, which are really the test of the concept of inclined inhomogeneities, are a sizable fraction of the range of 0.37 between the smallest and largest \( \Delta \lambda_{AB} \). The question, then, is to what extent \( \sigma \) represents real fluctuations in \( \Delta \lambda_{AB} \) rather than observational errors.

The observational error in \( \Delta \lambda_{AB} \) is approximately 
\[
\delta(\Delta \lambda_{AB}) = \frac{d(\Delta \lambda)}{dX_B} (\delta X_A + \delta X_B)
\]

where \( \delta \) signifies the error of measurement. The threads are more difficult to measure in lines other than Fe 4383.6, and are often complicated by inclinations due to Doppler gradients. I have assumed, therefore, that the mean error of \( \delta X_A + \delta X_B \) is 54 km, corresponding to 10\( \mu \) on the spectrogram. For each thread in each line I have determined the errors in \( \Delta \lambda_{AB} \) induced by a positive and a negative 10\( \mu \) error of measurement, (which are appreciably different in the neighborhood of the «break» in the \( X(\Delta \lambda) \) curve). From these, the estimated standard deviation \( \Delta \lambda_{AB} \), \( \sigma_m \), due to observational error, was calculated. The result for each spectrum line appears in column 10, and for each thread in the last row of Table I. The over-all values are \( \sigma = 0.10 A \) and \( \sigma_m = 0.09 A \).

While it appears that the errors of measurement can well account for the observed \( \sigma \)’s, there is no justification for assuming that the real value of \( \Delta \lambda_{AB} \) has no dispersion in a large number of threads. Such behavior would be very surprising. It would imply that we see each bright element in the solar atmosphere at exactly the same height in line \( A \) as at \( \Delta \lambda_{AB} \). However, the observations do show that the dispersion in \( \Delta \lambda_{AB} \) corresponding to a given line, \( A \), does not, on the average, exceed about 25 % of the total range found. In short, the threads behave exactly as they should if they are due to highly inclined bright inhomogeneities in the solar atmosphere, which are seen at a quite specific height in a given line or at a given \( \Delta \lambda \) in a very broad strong line.

**Velocity measurements.** The attempt to determine \( \Delta \lambda_{AB} \) by comparing \( \xi \)’s in 12 of the lines studied above with the \( \xi(\Delta \lambda) \) curve for Fe 4383.6 was a disappointment. The measured \( \xi(\Delta \lambda) \) curve showed a smooth decrease in \( \xi \) from 0.72 km/sec at \( \Delta \lambda = 0.014 A \) to 0.28 at \( \Delta \lambda = 0.31 A \). Beyond this the measurements become unreliable because of the decreasing slope of the lgI profile, which determines the signal to noise ratio in velocity measurement. In the weaker lines, the velocities had to be determined at \( \Delta \lambda = 0.014 A \), again to have a usable slope in the lgI profile. Hence the measured velocities correspond
### Table I

$\Delta \lambda_{A,B}$ for 6 threads in 15 lines, in Angstroms

<table>
<thead>
<tr>
<th>Line</th>
<th>X/1000</th>
<th>+47.8</th>
<th>+17.1</th>
<th>+15.7</th>
<th>−11.1</th>
<th>−26.5</th>
<th>−27.5</th>
<th>$\Delta \lambda_{A,B}$</th>
<th>$\sigma$</th>
<th>$\sigma_m$</th>
</tr>
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<tr>
<td>Fe 4377.8</td>
<td>.45</td>
<td>.58</td>
<td>.65</td>
<td></td>
<td>.45</td>
<td>.53</td>
<td>.53</td>
<td>±.07</td>
<td>±.08</td>
<td></td>
</tr>
<tr>
<td>CH 4378.3</td>
<td>.51</td>
<td>.51</td>
<td>.43</td>
<td>.60</td>
<td>.44</td>
<td>.50</td>
<td>.07</td>
<td>.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V 4379.2</td>
<td>.30</td>
<td>(.20)</td>
<td>(.15)</td>
<td>.30</td>
<td>.24</td>
<td>.23</td>
<td>.06</td>
<td>.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V 4379.8</td>
<td>.65</td>
<td>.43</td>
<td>(.40)</td>
<td>.30</td>
<td>.24</td>
<td>.49</td>
<td>.42</td>
<td>.14</td>
<td>.08</td>
<td></td>
</tr>
<tr>
<td>V 4380.1</td>
<td>.44</td>
<td>.39</td>
<td>(.65)</td>
<td>.29</td>
<td>.61</td>
<td>.40</td>
<td>.44</td>
<td>.12</td>
<td>.07</td>
<td></td>
</tr>
<tr>
<td>CH 4380.7</td>
<td>.34</td>
<td>.31</td>
<td>.43</td>
<td>.26</td>
<td>(.52)</td>
<td>.41</td>
<td>.37</td>
<td>.08</td>
<td>.08</td>
<td></td>
</tr>
<tr>
<td>Cr 4381.1</td>
<td>.63</td>
<td>.56</td>
<td>.50</td>
<td>.32</td>
<td>.70</td>
<td>.54</td>
<td>.54</td>
<td>.12</td>
<td>.13</td>
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<tr>
<td>Ce II 4382.2</td>
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<td>.88</td>
<td>.45</td>
<td>.60</td>
<td>.48</td>
<td>.62</td>
<td>.17</td>
<td>.16</td>
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<tr>
<td>Ce II 4382.5</td>
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<td>.63</td>
<td>(.65)</td>
<td>.44</td>
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<td>.08</td>
<td>.07</td>
<td>.06</td>
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<td>.31</td>
<td>.07</td>
<td>.07</td>
<td>.07</td>
<td></td>
</tr>
<tr>
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<td>.49</td>
<td>(.32)</td>
<td>.28</td>
<td>.59</td>
<td>.46</td>
<td>.48</td>
<td>.09</td>
<td>.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ni 4384.5</td>
<td>.44</td>
<td>.44</td>
<td>.34</td>
<td>.43</td>
<td>.42</td>
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<td>.10</td>
<td></td>
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<tr>
<td>V 4384.7</td>
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<td>.20</td>
<td>.29</td>
<td>(.35)</td>
<td>.26</td>
<td>.28</td>
<td>.27</td>
<td>.04</td>
<td>.07</td>
<td></td>
</tr>
<tr>
<td>Cr 4385.0</td>
<td>.34</td>
<td>.20</td>
<td>.26</td>
<td>.41</td>
<td>.30</td>
<td>.30</td>
<td>.08</td>
<td>.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe II 4385.4</td>
<td>.42</td>
<td>(.45)</td>
<td>.30</td>
<td>.32</td>
<td>.39</td>
<td>.37</td>
<td>.08</td>
<td>.07</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$\sigma$ | .09 | .11 | .10 | .12 | .11 | .06 | .10 |

$\sigma_m$ | .11 | .10 | .14 | .07 | .07 | .04 | .10 |

To a somewhat lower level in the solar atmosphere than the thread measurements at the line centers. The final problem was the fact that the variation of $\xi$ with the strength flattens out at about 0.25 km/sec, and is constant within observational accuracy for all lines with equivalent widths less than 150 mA. See Evans and Michard, (1962a). The 12 lines measured all showed $\xi$ between 0.28 and 0.33 km/sec, with no detectable correlation between line strength and $\xi$. The only result of the velocity measurements, therefore, is that $\Delta \lambda_{AB} \geq 0.25 \, \lambda$.

In Fe 4383.6, $\xi$ is a rapidly varying function of $\Delta \lambda$ out to $\sim 0.25 \, \lambda$, while the $X(\Delta \lambda)$ curves of favourable threads are steep and unconfused by Doppler shifts in the range $\Delta \lambda = 0.15$ to $\sim 0.7 \, \lambda$. 

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Discussion

*Threads as a tool for height discrimination.* The measurements show that the \( x \)-deviations of curved threads uniquely relate weak and medium strong lines with corresponding \( \Delta \lambda \)'s in very strong lines. This observed fact is understandable if we assume that a thread is radiation from an inclined bright element in the solar atmosphere. The \( x \) coordinate of a thread is then a function of the height at which the element is seen, either at different \( \Delta \lambda \)'s in the very strong lines or at the centers of less strong lines.

If this assumption is correct, the curved threads are potentially quite useful. By comparing \( x \)-deviations of threads at the centers and in the wings of the Fraunhofer lines, we can order them according to height. Since the deviations are measurable in kilometers, the curved threads may even give some inkling of the magnitude of height differences in kilometers. This application has the merit of using a purely geometrical effect, \( x \) as a function of height in a bright element, which is uninfluenced by any uncertainties in the model atmosphere, the process of line formation, or atomic properties. The analogous use of the \( \xi \)'s, which are a measure of mass motion rather than geometrical position, has the same merit.

If the six threads of Figure 8 are typical, the threads are most useful in the height range corresponding to \( 0.15 \ A < \Delta \lambda < 0.7 \ A \) in Fe 4383.6. The useful range of the \( \xi \)'s seems to be limited to \( \xi > 0.3 \ \text{km/sec} \), which corresponds to \( \Delta \lambda < 0.25 \ A \), or to lines of equivalent width greater than 100 or 150 mA. Analyses based on both the \( x \)-deviations of threads and \( \xi \)'s should give reliable results over the whole height range from that seen at the centers of the strong lines down to the level of continuous absorption.

Figure 10 might be considered a first application, although it needs strengthening with more data. It shows that the relation between the \( x \)-deviations in a given thread and the central intensity of a line is remarkably close. To the extent that \( x \) is a function of height, the central intensity of a line appears to be an excellent index of its height of origin.

In the study presented here, I have been able to compare displacements of individual threads in different lines and at different \( \Delta \lambda \)'s on a single spectrogram. This could certainly be done also with the Doppler shifts (as it has in several instances). Such point by point comparisons are sure to lead to the most reliable results. However, it is not always possible to obtain spectra of adequate dispersion showing simultaneously lines of interest in different spectral regions. It should still be possible to compare thread characteristics in such lines by determining the \( \text{rms} \ x \)-displacements, \( \bar{x} \), of the threads in each from a distribution similar to that of Figure 7. This is analogous to determining \( \xi \) from the velocities.

*Heights in the lower photosphere.* One of the characteristics of threads shown by the measurements is particularly surprising. In Fe 4383.6 the large \( X \)-displacements of threads occur between the continuum and \( \Delta \lambda = 0.2 \ A \). This \( \Delta \lambda \) is at least five Doppler widths from the center of the line. Unno (1959) found that Doppler width increases with depth in the photosphere. For lines in the \( \lambda 4400 \) region, \( \Delta \lambda_D = 0.022 \ A \) at optical depth
\[ \tau_e = 0.6 \] in the continuum at \( \lambda 5000 \). The Doppler width could hardly increase to more than 0.04 at \( \tau_e = 1.0 \).

One would expect that at \( \Delta \lambda = 5 \Delta \lambda_D \), the level of origin of the light would be indistinguishable from the level of continuous absorption at the same wave-length. Athay’s study of \( Mg \) lines (1963) specifies a height of \(< 100 \) km at \( \Delta \lambda = 3 \Delta \lambda_D \) for such strong lines as \( Mg 5172.7 \) and 5183.6, and still less at \( 5 \Delta \lambda_D \). Yet the \( X(\Delta \lambda) \) curves show their large variations in \( X \) between \( \Delta \lambda = 0.2 \) and \( \Delta \lambda = 0.8 \), and the \textit{rms} value \( \hat{x} \), at 0.2 \( \Delta \) is 500 km.

If we hold to the interpretation of curved threads as evidence of inclined bright elements in the solar atmosphere, we are faced with a peculiar geometrical situation somewhat as follows. The bright elements trail out nearly horizontally from their bases in the granulation layer, like smoke from a chimney in a high wind. In a horizontal distance of 500 km on the average they rise less than 100 km above the floor of continuous absorption. Even more remarkable, the height resolution of the threads is sufficient to distinguish the intermediate levels quite clearly. The threads follow generally smooth \( \hat{x}(\Delta \lambda) \) curves, implying that the sloping bright elements increase in height along their length quite monotonically with no appreciable up and down ripples. This is not a convincing picture. The only alternatives I can see, however, are to conclude that at \( \Delta \lambda = 0.2 \) in Fe 4383.6 the height observed is very much greater than 100 km, or to find some other interpretation of the undoubtedly curved threads.

It is conceivable that the \( x \)-displacements of threads are simply progressive changes along the \( x \)-direction in the wing profiles of Fe 4383.6 produced by a change in the \( \Delta \lambda \) dependence of radiative transfer in material all at the same level. To account for the larger thread curves (> 700 km), however, there must be some mechanism for increasing the intensity at \( \Delta \lambda = 0.2 \) without affecting the profile at \( \Delta \lambda > 0.8 \), as well as the reverse. Furthermore, whatever perturbation of the profile occurs at \( \Delta \lambda_{AB} \) must also occur at the center of the profile of line \( A \) to account for the results of Table I, even when line \( A \) has an abnormal local continuum like that of CH 4383.0 in the wing of Fe 4383.6.

This explanation seems more artificial than the simple concept of inclined elements seen at different heights. However, it does avoid the embarrassing problem of large height differences corresponding to \( \Delta \lambda \)'s beyond \( 5 \Delta \lambda_D \), and provides a natural explanation for the stationary value of \( \xi \) in lines fainter than \( W \sim 150 \) mA and at \( \Delta \lambda > 0.2 \) in Fe 4383.6. There does not seem to be any obvious observational criterion to distinguish between the two hypotheses, and the question will have to be considered in terms of radiative transfer.

In closing, I wish to thank Mr. Horst Mauter for his expeditious production of the spectrum tracing of Figure 9, Mr. Patrick McIntosh for the photograph of solar granulation in Figure 3, and Mrs. Elisabeth Evans for calculating and plotting the \( x \) profiles of Figure 5, and carefully matching scales and plotting Figure 9.

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