OBSERVATIONAL STUDY OF MACROSCOPIC INHOMOGENEITIES IN THE SOLAR ATMOSPHERE

II. BRIGHTNESS FLUCTUATIONS IN FRAUNHOFER LINES AND THE CONTINUUM

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ABSTRACT

Large brightness fluctuations are observed at the centers of Fraunhofer lines of average and great strength. Their character is described for different lines and different parts of line profiles. Root-mean-square values are given for a number of cases. The scale of these features is comparable to the size of photospheric granulation. There are no simple relations between the brightness fluctuations in Fraunhofer lines, Doppler displacements of the lines, and continuum granulation. The bearing of these observations on recent inhomogeneous models of the photosphere is briefly discussed.

I. INTRODUCTION

The Fraunhofer lines of Rowland intensity \( \geq 3 \) show both Doppler shifts and fluctuations in brightness as a function of position along the slit, both of which are identical in position and sign for all lines. This paper is a study of the brightness fluctuations and their relation to the granulation seen in the continuum and to the Doppler shifts. The observational material is described in Paper I of this series (Evans and Michard 1962).

The spectroheliographic aspects of brightness fluctuations of strong chromospheric lines were first discussed by d’Azambuja (1930), and de Jager (1959) has reviewed the more recent work. The presence of similar fluctuations in the weaker lines from lower levels indicates that the inhomogeneities that are so evident in the photospheric granulation and in the chromosphere actually prevail through the intervening levels.

II. INTENSITY FLUCTUATIONS IN THE FRAUNHOFER LINES

An examination of the spectra shows at once that the brightness fluctuations, like the Doppler shifts, are identical in all lines inspected, except \( \text{H} \alpha \) and \( \text{Ca II} \ 8498, 8542 \). The contrast, however, is variable. In faint lines like \( \text{Ni} \ 5168.66 \) and \( \text{Fe} \ 5170.77 \), the fluctuations are practically invisible. They are conspicuous, however, in all lines brighter than Rowland intensity 2. The nature of the fluctuations is apparent in Figure 1. The fluctuation contrast is very perceptibly reduced in lines of ionized atoms, like \( \text{Fe} \ II \ 5169.05 \). These qualitative observations are confirmed by the photometric studies described below.

a) R.M.S. Intensity Fluctuations

We have determined the r.m.s. intensity fluctuations along seven lines at their centers and in two of the lines at various distances, \( \Delta \lambda \), from the line centers. The measurements were made from microphotometer traces parallel to the length of the line. The length of the scanning slit in the direction of dispersion varied from 0.02 to 0.04 Å for lines of differing width. In the steep parts of the profiles, the disturbing effects of the small Doppler shifts of the quiet photosphere were essentially eliminated by averaging the traces at \( + \Delta \lambda \) and \( - \Delta \lambda \). At the line center, a few traces at small \( \Delta \lambda \)'s demonstrated that the intensities were not measurably affected by the Doppler shifts.

The intensity fluctuations, \( \Delta I \), unlike the intensities themselves, were practically unaffected by instrumental scattered light, and could be expressed at once in terms of the
Fig. 1.—Sample of brightness fluctuations in part of a high-quality spectrum. The continuum is shown twice, for easier comparison with other curves. The lower one shows fluctuations at the center of the line Fe I 5168.910 (Rowland intensity 3). Four curves refer to the $b_2$ line of Mg I 5172.700, at various distances from the center of the line (given in Å). The arbitrary intensity scales are different for the different curves. The fluctuations relative to local intensity, $I_0$, appear in Table 1. Note the absence of relation between the continuum and the centers of the two lines. The feature marked $M$ is an example of the type that we call "micromoustache."
nearby continuum, \( I_c \). In critical cases, such as the cores of the b lines, Dr. J. Waddell (1961) directly determined the true line profile, \( I_\lambda / I_c \), using the spectrograph as a scatter-free double-pass monochromator (see Evans and Waddell 1962). His measurements enable us to calculate the fluctuations in terms of the local intensities, \( \Delta I_\lambda / I_\lambda \).

The results are gathered in Table 1, where both the r.m.s. fluctuations and the extremes are listed. The figure of 3 per cent for the continuum is appreciably lower than the 5 per cent determined from Stratoscope photographs by Schwarzschild and Bahng (1961), presumably because of less perfect image quality. Similarly, the measured r.m.s. values in the lines are certainly underestimates, but the comparisons at different wavelengths are still significant.

b) The Magnesium b Line

The characteristics of the b\(_2\) line, Mg 5172.70, have been described qualitatively by Michard (1961). The photometric measurements confirm his description, showing the following conditions.

**TABLE 1**

<table>
<thead>
<tr>
<th>Line</th>
<th>( \Delta \lambda (\text{A}) )</th>
<th>Rowland Intensity</th>
<th>( I_\lambda / I_c ) (Per Cent)</th>
<th>r.m.s. ( \Delta I_\lambda / I_c ) (Per Cent)</th>
<th>r.m.s. ( \Delta I_\lambda / I_\lambda )</th>
<th>Extremes; (±) of ( \Delta I_\lambda / I_\lambda )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuum</td>
<td>5170</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5168.910 Fe I . . . .</td>
<td>0</td>
<td>3</td>
<td>100</td>
<td>3.05</td>
<td>3.05</td>
<td>8.8</td>
</tr>
<tr>
<td>5171 612 Fe I . .</td>
<td>0</td>
<td>6</td>
<td>20</td>
<td>2.04</td>
<td>12.0</td>
<td>33.0</td>
</tr>
<tr>
<td>5169 052 Fe II . .</td>
<td>0</td>
<td>4</td>
<td>21</td>
<td>1.85</td>
<td>8.8</td>
<td>22.0</td>
</tr>
<tr>
<td>( ±0.027 )</td>
<td>( ±0.066 )</td>
<td></td>
<td>( ±0.156 )</td>
<td>( ±0.312 )</td>
<td>( ±0.625 )</td>
<td></td>
</tr>
<tr>
<td>5172.700 Mg I . . .</td>
<td>( ±0.027 )</td>
<td>20</td>
<td>6.8</td>
<td>0.75</td>
<td>11.0</td>
<td>36.0</td>
</tr>
<tr>
<td>8498 Ca II . . . .</td>
<td>( ±0.183 )</td>
<td>12</td>
<td>28</td>
<td>3.03</td>
<td>10.8</td>
<td>25.5</td>
</tr>
<tr>
<td>8542 Ca II . . . .</td>
<td>0</td>
<td>16</td>
<td>20</td>
<td>2.36</td>
<td>11.8</td>
<td>26.0</td>
</tr>
<tr>
<td>6563 Hα . . . . .</td>
<td>0</td>
<td>40</td>
<td>15.4</td>
<td>1.20</td>
<td>7.8</td>
<td>21.0</td>
</tr>
</tbody>
</table>

1. Features of the continuum are unrelated to the strong fluctuations in the line core. Beyond the steepest part of the profile (\( \Delta \lambda \approx 0.1 \text{ A} \)), however, a correlation between fluctuations in the line and the continuum is evident, as shown in Figure 1, increasing with \( \Delta \lambda \).

2. The contrast of brightness fluctuations decreases outward from the line core to the continuum.

3. Occasional short-lived “micromoustaches,” bright features a few seconds in extent, appear in the wings of the b lines in the range \( \Delta \lambda = 0.1-0.6 \text{ A} \) and occasionally extend into the line core. Such a micromoustache is shown in Figure 1.

c) Fluctuations in Steep Parts of the Line Profiles

Previous work has shown that the fluctuations often have more contrast, for a given \( \Delta \lambda \), on the violet side than on the red side of a line. This was found by d’Azambuja (1930) for various strong lines. Just the reverse asymmetry has been reported by R. Leighton (1961) for the line Ca i 6103.

This phenomenon is also seen on our tracings along most, but not all, of the lines. In strong lines (b lines, infrared triplet of Ca ii, Fe i 5171.612, etc. . . .), fluctuations on the
violet side tend to show more contrast than on the red side. For fainter lines, the two sides have fluctuations of equal amplitude (Ti i 5173.75, Rowland intensity 2), or the red side shows the larger fluctuations (Ni i 5168.665, Fe i 5170.77 of Rowland intensities 1 and 0). Leighton, Noyes, and Simon (1962) came to the same conclusion from their study of five lines of various intensities.

The simplest explanation of this asymmetry in fluctuations is that, for strong lines, violet shifts are associated with widening and/or strengthening of the line, the reverse being true for faint lines. Detailed studies of local changes in profiles of various Fraunhofer lines will probably become an important problem in the near future.

d) Sizes of the Elements

Dark knots in Fraunhofer lines as small as 1000 km can be seen on our spectra. A statistical estimate of the size of this structure has been made by counting maxima and minima of brightness on microphotometer tracings. In a length of 290'' on the sun, we found 125 maxima and minima at the center of Fe 5168.91 and 105 in the continuum. Accordingly, the scale of structure at the centers of lines appears to be roughly the same as the scale in photospheric granulation. Of course, the resolution of such details is limited by "seeing" in our observations.

III. RELATIONS BETWEEN BRIGHTNESS AND WAVELENGTH FLUCTUATIONS

As a guide for more accurate and laborious photometric investigations, a careful qualitative study was made of the relation between brightness fluctuations and velocity, with the results described below.

a) Continuum Features and Wavelength Shifts

Much work has already been devoted to this question. As is well known, the coefficients of correlation are very small, in the range 0.2-0.4 (see Richardson and Schwarzschild 1950; Plaskett 1954; Fellgett 1959; Servajean 1961). Recent measurements on very good Pic du Midi spectra (to be published) confirm these results and show the correlation to be still smaller when comparing granulation and wavelength shifts in very strong lines such as b2.

We find, however, that about 70 per cent of bright continuum features are associated with violet shifts, and, conversely, 70 per cent of the dark features show red shifts (see also Servajean 1961). The significant association in sign, but with low quantitative correlation, suggests a more complicated relation between granulation and upward motions at the level of line absorption than that expected of a simple convective model.

b) Wavelength Shifts of Bright and Dark Elements in the Centers of Fraunhofer Lines

The association of bright and dark elements in the line centers with velocity shifts is summarized as follows: (1) about 70 per cent of the strong line-shifts of either sign are associated with dark elements; (2) dark elements are usually associated with violet shifts (55 per cent) or red shifts (30 per cent), the number of no clear associations being small; (3) only about half the bright elements are shifted, more often to the red.

c) Continuum Features Compared with Line Core Features

The comparison of microphotometric scans for line centers and continuum shows the fluctuations to be generally unrelated, although bright regions in the line core may coincide with bright continuum features more often than would be expected by chance.

IV. DISCUSSION

The combination of our results on the random turbulent velocities in Fraunhofer lines (Evans and Michard 1962) and the present study of brightness fluctuations in lines of
Rowland intensity $\geq 3$ lead to some interesting conclusions concerning the "columnar" inhomogeneous models of the photosphere (see de Jager 1959).

1. Brightness fluctuations in the centers of the Fraunhofer lines are unrelated to the fluctuations in the continuum. Hence the thermal inhomogeneities at the level of line formation are not directly related to those responsible for granulation (about 300 km lower in the photosphere), and the photospheric columns do not extend radially through the intervening layers.

2. Identity of both velocity and brightness features in different lines of widely varying Rowland intensities (from 3 to 20) indicates that the photospheric structure is at least roughly columnar through the height range within which these lines are formed. For the lines of neutral atoms this height range is probably restricted to the region around the temperature minimum (a very sharp minimum, according to Pagel 1961). However, the fact that the same velocity and brightness features appear in the lines of ionized metals like Fe $\Pi$ 5169.05, which absorb over a much larger range of temperature and height, suggests that the columns extend over this larger range. The lower contrast in these lines could be due either to diffusion introduced by some shearing of the columns through the height range of line absorption or simply to the lesser temperature sensitivity of these lines.

3. A comparison of microphotometer traces at the centers of Ha and Fe 6569.23 shows that the brightness structure of the photospheric lines definitely does not extend to the height of origin of the center of Ha. Many of the larger velocity features in Fe 6569.23 do appear in the Ha velocities measured at $\Delta \lambda = \pm 0.42 \text{Å}$, however. We conclude that the columns lose their identity in the lower chromosphere somewhere between the levels of absorption of the cores of the b lines and Ha.

4. The contrast in the brightness fluctuations is low for the weakest lines, increasing to a maximum at Rowland intensity $\approx 4$ and possibly decreasing slightly for the stronger lines up to Rowland intensity 20. This behavior is not consistent with a reduction of temperature differences between hot and cold columns with increasing height, as pictured in most of the columnar models.

As an alternative, one might think of pressure inhomogeneities produced by the passage of acoustic waves in the layer where the lines are formed. We have made an order-of-magnitude calculation of the possible brightness fluctuations in the strong lines induced by such waves, supposing them to satisfy the conditions (Unsöld 1955).

$$\frac{1}{\gamma} \frac{\Delta \rho}{\rho} = \frac{1}{\gamma - 1} \frac{\Delta T}{T} = \frac{v}{c_s} \approx \frac{1}{10},$$

where $\Delta \rho$, $\Delta T$, and $v$ are the pressure, temperature, and velocity amplitudes of the wave and $c_s$ is the velocity of sound. The value $1/10$ was chosen in agreement with observations. Further, it was assumed that the line was formed according to the Schuster-Schwarzschild model and that the source function in the line was identical with the Planck function.

It was found that, although the pressure and temperature changes tend to compensate, an increase in both does produce a marked increase in optical thickness in the line-forming layer, with a decrease in brightness. Should the change in temperature be smaller than adiabatic or the source function vary more slowly with $T$ than the Planck function (non L.T.E.), the tendency of temperature and pressure effects to compensate would be lessened, and features as dark as, or darker than, observed could be explained by temperature-pressure maxima in waves. An unsatisfactory feature of this explanation, however, is that dark knots in lines seem to be associated with maxima in velocity, while, for ordinary sound waves, pressure and velocity maxima are in quadrature.

It seems that a more complete explanation of both brightness and velocity fluctuations, possibly in terms of pressure waves, should wait for a detailed study of the time...
changes of these fluctuations and their phase relations. Such a study is in progress and will be reported in further papers of this series.

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REFERENCES

Leighton, R. B. 1961, communication at Berkeley Meeting of I.A.U.