ON CORRELATIONS BETWEEN BRIGHTNESS, VELOCITY, AND MAGNETIC FIELDS IN THE SOLAR PHOTOSPHERE

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1. Introduction

Modern observations indicate that the solar atmosphere is a region of confluence for many kinds of gas motions, both radial and transverse, some oscillatory, possessing a wide range in amplitude and physical size. The basic driving force behind these motions is the escape of energy from the sun's interior. Therefore, associated with the above velocity field (V) may be expected a brightness field (I) because the last free path of outward energy flux takes the form of radiation. The constraints on the motions near the surface include gravity and magnetic fields (H). Magnetism can be expected to play a role because solar material is highly ionized and therefore a good electrical conductor. Induction currents tend to oppose gas motion across existing magnetic lines of force. Ultimately the desire is to understand the structure and dynamics of the solar atmosphere.

Toward this end, accurate and properly analyzed observations are needed. The apparent stochastic nature of the VIH fields, together with the inadequacy of even the best optical image resolution, requires that the data receive a statistical treatment. Thus, the appropriateness of this subject for this symposium.

In this paper we shall outline the available observational data on velocity and brightness fields. We shall restrict ourselves to the lowest atmospheric level, the "photosphere," and also to aspects of the normal or "quiet" sun. Additional new, and preliminary, observations on the relation of (longitudinal) magnetic fields to the V and I structure are given. We emphasize the preliminary nature of this new data because our effective image resolution is uncertain, and it is difficult to say how the fine detail is attenuated. The fine detail is most important because the scale height of the photosphere is the order of 100 km, or about 0.15 arc seconds viewed from the earth.

1.1. *Methods of observation.* Wide band direct photographs, high dispersion

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line spectra taken with the image focused on the slit, spectroheliograms, narrow band "filtergrams," and several photoelectric techniques all contribute different information on aspects of the *VIH* fields.

Two factors to be kept in mind in the design and interpretation of different observational techniques are the extreme thinness of the photosphere and the role of the continuous and line absorption coefficients which lead to a variation of visible geometric depth with wavelength. The photosphere comes close to being a discontinuity—it is estimated to have a total extent of only 250 km—or about 10^{-4} times the solar diameter. This limited extent of the photosphere is relevant when considering transverse motions (Evans' "inclined inhomogeneities"), level effects in the magnetic fields, and oscillatory motion. The variation of the sun's atmospheric transparency with wavelength provides a means to probe for *VIH* field effects with depth. Over the visible spectral region the continuous absorption varies only a small amount with a minimum (75 per cent of maximum) near 4000 A. But as we cross a spectrum line, going from the continuum to the line center, the depth of the layer that contributes to the residual intensity passes from the lowest (~ 0 km) to perhaps 100 km for a weak line, to thousands of km for strong lines such as the K line of calcium and the principal Balmer lines Hα, Hβ, and so forth. (Because the photosphere is but 250 km high, it is then invisible in the core of Hα and lines of this strength are referred to as chromospheric lines.)

The observations then take the following forms. Direct photographs of the solar disk show the brightness field of the base of the photosphere. Subjectively one sees on good records a fine grain pattern, the "granulation" (figure 1a, 1b),

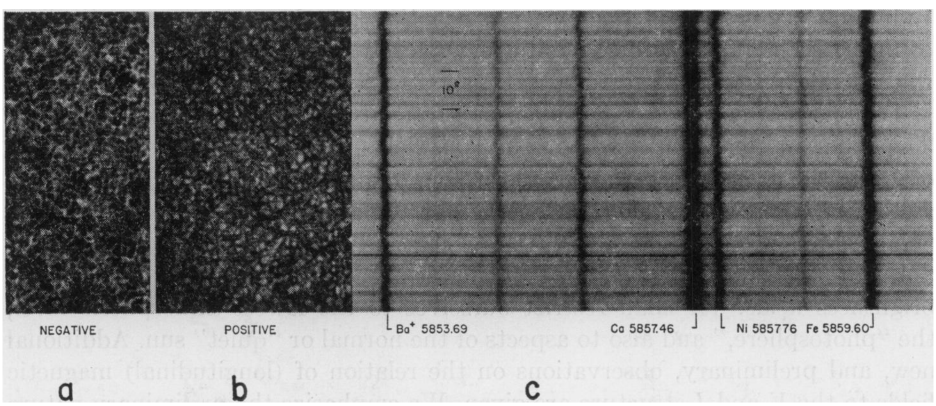


FIGURE 1

(a)(b) White light granulation photograph, negative and positive print to show asymmetry of the bright-dark. Six inch refractor, 649-GW film, exposure 1/1750 sec, June 29, 1965 at 0935 PST, Van Norman Lake, Aerospace Corp. Solar Observatory.

(*c*) Sixty inch McMath Solar Telescope, Linagraph Sellburst film, exposure 1 sec, August 25, 1965.

plus a larger scale mottling and a fall off of intensity toward the limb. Such white light photographs reveal the smallest details we can resolve because the exposure times are short ($\sim 0.001^s$) and detrimental image motion originating in the earth's atmosphere is at a minimum. The radial velocity field is revealed by Doppler shifts in the Fraunhofer lines. High dispersion stigmatic spectra (figure 1c) indicate a sample across the elements imaged on the spectrograph slit. The special value of such spectra is that, simultaneously, one has a record of the lower photosphere brightness field, indicated by the uneven intensity of the continuum, plus the velocity (and brightness) field at different depths according to line strength.

A technique used to advantage by Evans and Michard [1] involves the tracing of isophotal contours along medium strong lines to study in an objective way the *VI* variation with depth. The limitation of the spectrogram recording is that it is a one-dimensional sample of a two-dimension field. Two-dimensional anisotropic fields are liable to misinterpretation (see Fellgett [2], p. 490) when examined in one dimension. But the best argument in favor of two-dimensional observations is given by the success of R. Leighton and his colleagues at Mount Wilson in the use of Doppler spectroheliograms. In a conventional spectroheliograph, a certain wavelength interval $\Delta\lambda$ is selected by an exit slit and focused onto a photographic plate. This plate moves past the exit slit synchronously with the movement of the sun's image past the entrance slit of the spectrograph. A two-dimensional picture results with a time delay along the direction of image travel. In a conventional spectroheliogram, Doppler effects and the line brightness field are inextricable. In Leighton's scheme, two spectroheliograms are taken simultaneously, using light from the red wing for one and light from the blue wing for the other. These two records suitably combined, possibly with intervening photographic processes, can yield either the pure velocity field (figure 2) or the line brightness field.

Possible limitations in the spectroheliogram technique include the time delay effects accompanied by relatively long exposure times, an averaging of contributions from several layers depending on width of $\Delta\lambda$, and an accuracy set by the photographic process. Greatly decreased exposure time and freedom from time delay are afforded by the monochromatic Lyot type filter. Because the band pass of the Lyot filter has so far been at best about 0.5 A, its use is restricted to the strong chromospheric lines and so it is not applicable to photospheric lines which have a width of about 0.1 A.

Magnetic fields may be detected by means of the spectroscopic Zeeman effect. An atomic Fraunhofer line, when formed in the presence of a line of sight (or longitudinal) magnetic field, will split into two components which are oppositely circularly polarized. In the region of a sunspot, where the field strength may be thousands of gauss, certain magnetically sensitive lines will split into two well resolved components. But over most of the solar disk the fields are much weaker, the order of a few gauss, and the line is just slightly broadened. Leighton [4] has devised techniques for making high resolution magnetic spectroheliograms.

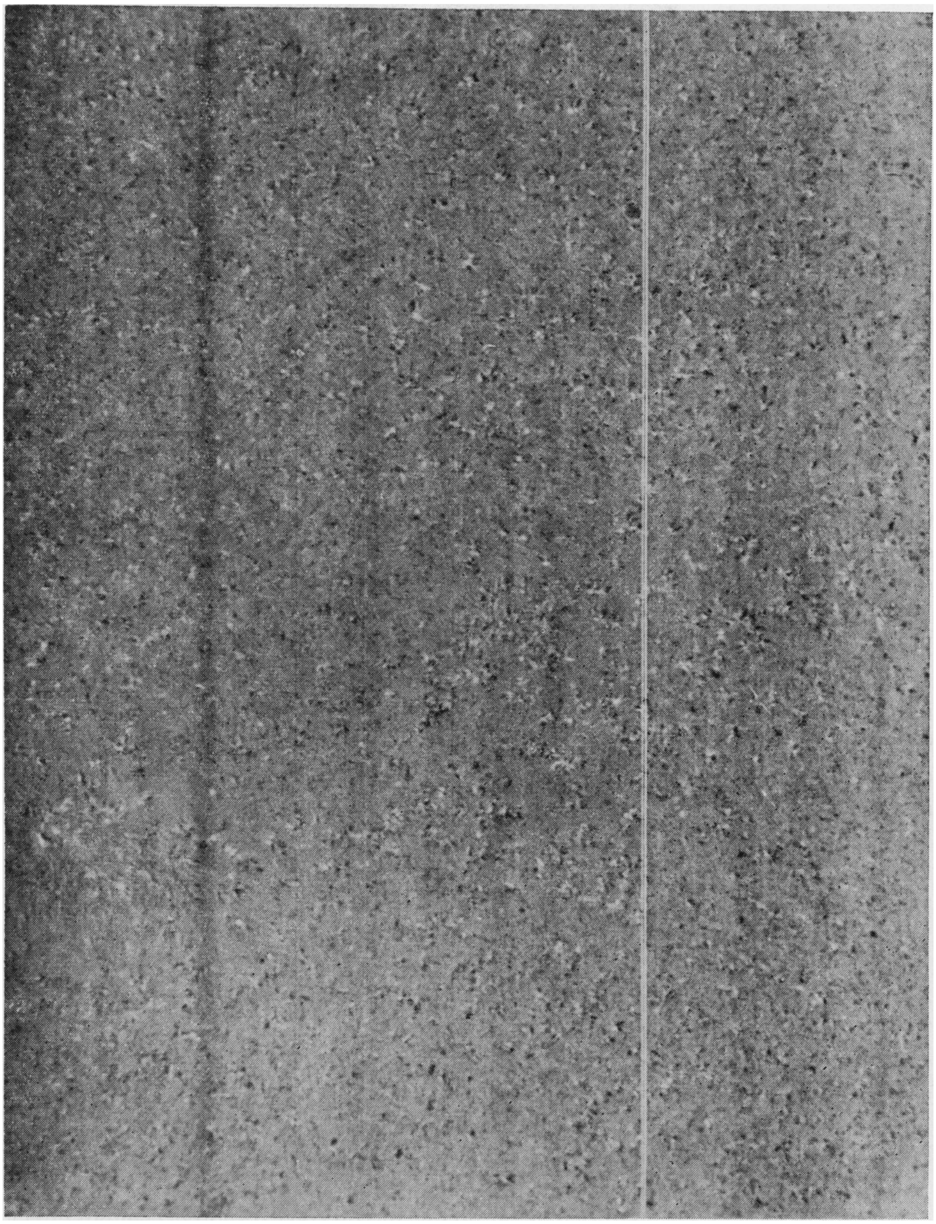


FIGURE 2

Doppler spectroheliogram in which line brightness has been canceled leaving only the velocity field. Dark indicates upward flow, bright downward. *H*-alpha 0.7 A from core, 0.08 A window. Record suggests material flows upward from photosphere through ($\sim$ 1 arc sec) dark dots and returns through the bright whisps which are thought to coincide with the bright calcium network.
Taken by Dr. N. R. Sheeley, Jr. at Mount Wilson.

Because of the limitations of the photographic process his noise level is 10 to 20 gauss. The best way to detect and measure weak fields is by photoelectric means, using an instrument developed by Babcock [5]—the magnetograph. Fortunately, it is possible to derive simultaneous velocity and brightness data in addition to magnetic information (figure 3); and as the outputs are electrical,

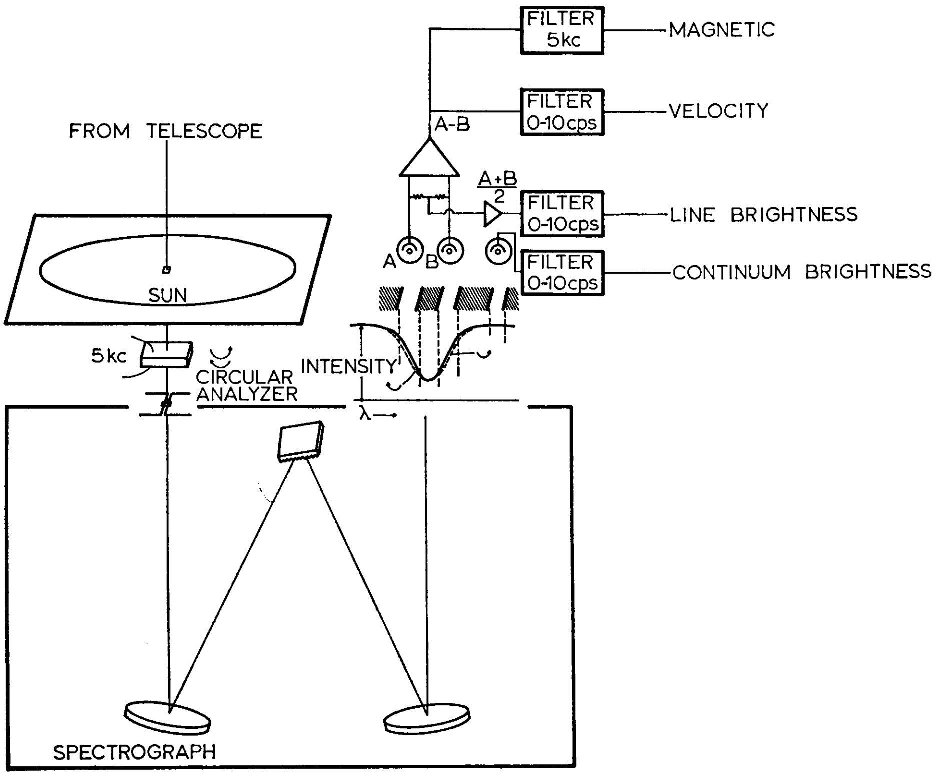


FIGURE 3

Magnetograph arrangement at McMath Solar Telescope which provides simultaneous channels of *VIH* information. For details on principles of operation, see Babcock [5].

modern data storage and processing methods are applicable. The principal limitation of the magnetograph is its point scan which results in low efficiency and, therefore, long exposure time compared to the line scan of the spectroheliograph and the entire field record of the filtergram.

In principle, one can determine the complete magnetic vector from the magnitude of the transverse and longitudinal components and the azimuth angle for maximum transverse effect. Evans [6] has shown, however, that in the case of weak fields ($H < 500$ gauss) at least 50 times more light is required for equivalent sensitivity to the transverse field. Techniques have not yet been developed for their measurement.

1.2. *Methods for the reduction of observations.* Correlation functions provide an objective measure of certain interrelated properties of the *VIH* fields. Suppose we wish to investigate the spatial correlation between velocity and brightness fields. Assuming a polar coordinate system centered on the solar disk, we have $V(r, \theta)$ and $I(r, \theta)$. The two-dimensional spatial correlation $Q(r', \theta')$ is given by

$$Q(r', \theta') = \frac{K}{A} \iint V(r, \theta) I(r + r', \theta + \theta')\, dA, \tag{1.1}$$

where A is the area covered by the observation and K a normalizing constant. Such correlations can be machine computed, but Leighton [3] has demonstrated the utility of a simple analogue correlation technique. Assume that $V(r, \theta)$ can be represented by corresponding transmission variations $T_V(r, \theta)$ on a photographic plate. Similarly, and to the same scale, $I(r, \theta)$ is printed on a separate plate as $T_I(r, \theta)$. Of course, such plates are the natural product of spectroheliograms, but they can be prepared from other forms of data including numerical tabulations. Then according to Leighton

$$\begin{aligned} Q_{VI}(r', \theta') &= \frac{K_T}{A} \iint T_V(r, \theta) T_I(r + r', \theta + \theta')\, dA \\ &\equiv K_T \langle T_V(r, \theta) T_I(r + r', \theta + \theta') \rangle. \end{aligned} \tag{1.2}$$

Given the described transmission plates T_V and T_I, Leighton describes a simple instrument for obtaining the indicated two-dimensional spatial averages. The plates are superimposed initially with $r' = \theta' = 0$. Collimated light is passed through the plates and brought to a focus on a phototube. Output from the phototube is amplified and presented on a strip chart recorder. Then one plate is moved with respect to the other in increments corresponding to the dA and in total amount to cover the range of spatial frequencies under investigation. The function $Q_{VI}(r', \theta')$ is given on the strip chart trace. It can be interpreted in terms of the correlation between the Fourier components of the spatial details contained on the plates.

The autocorrelation function $Q_s(r', \theta')$ provides a description of the spatial properties of a field, for example,

$$Q_s(r', \theta') = \frac{K_S}{A} \iint I(r, \theta) I(r + r', \theta + \theta')\, dA. \tag{1.3}$$

And the time correlation function can indicate the lifetime of field elements as a function of size,

$$Q_t(r', \theta', t') = \frac{K_t}{A} \iiint I(r, \theta, t) I(r + r', \theta + \theta', t + t')\, dA\, dt. \tag{1.4}$$

If $r' = \theta' = 0$, we obtain the lifetime of some average element size.

The analysis of one-dimensional spectrum plates involves first a photometric reduction to isophotal maps followed by detailed measurement for amplitude and crosscorrelation study [1], [7].

1.3. *Interpretation of observations; the physical picture.* The following is an outline of the current picture of the dynamic structure of the photosphere as given by de Jager [8] in 1959. Below the visible surface (that is, the white light photosphere) is an extended zone in which energy transport is mainly by convection. Hot cells of gas rise, surrounded by cooler cells that move downward. Cells have diameters the order of the local scale height and rise, or fall, over a distance equal to their diameter after which they dissolve and exchange energy with the surroundings. As we approach the surface the scale height decreases and so does the cell diameter. The theory of Vitense predicts a cell diameter around 500 km near the surface. Apparently the near discontinuity in scale height at the photosphere (where it falls to 100 km) plays little role, however, in breaking apart the cells. Matter in the cells overshoots to spill into the photosphere and radiate.

In this convective zone, hydrodynamic forces are expected to dominate the gas motions over any magnetic force. As the gas pressure decreases through the photosphere and into the chromosphere, the relative importance of magnetic fields increases.

The photosphere itself is thought to be a relatively stable layer not subject to convection. Excited from below by the pumping action of the convective cells, it would seem to respond by propagating upward selective frequencies of pressure or acoustical waves.

The discovery by Leighton and his colleagues of the "supergranulation," the large, long lived, and apparently well-ordered horizontal flow patterns, suggests that there may exist deep seated, very slow moving convective currents. Such circulating currents might penetrate deep into the convective layer or, alternatively, into the chromosphere. There is also the possibility that the interior and chromospheric circulating currents may coexist synchronously.

2. White light granulation; the lower photosphere

A few exceptional photographic records of the granulation exist: the wet plate taken by Janssen [9] at Meudon on July 5, 1885, and certain select frames from the Princeton Observatory Project Stratoscope balloon flights in 1957 and 1959.

The Stratoscope pictures have been extensively studied and yield the following information. The lifetime of the granules (Bahng and Schwarzschild [10]) as given by the time correlation function shows an exponential decay with a time constant (e^{-1} point) of 6.27 minutes. As the time correlation is 0.5 at 4.3 minutes, the average lifetime is taken to be 8.6 minutes. This same lifetime is found in magnetic regions, near sunspots, as in nonmagnetic regions, which is direct evidence that magnetic fields do not inhibit motion in the convective zone. The autocorrelation function shows an average correlation distance of 640 km [11].

The r.m.s. intensity fluctuation ($\Delta I/I$) corrected for instrumental effects is 0.14 in the center of the disk [12]. This fluctuation increases to a maximum of 0.20 at $r/R = 0.766$ and then decreases to become zero near $r/R = 0.987$.

This visibility of the granulation near the limb, in a region of significant limb darkening, is of special interest because it indicates a projection of the white light structure into the higher levels of the photosphere where the weak to intermediate strength lines are formed. This point will be discussed further in connection with the interpretation of figure 1c.

The above statistical description says nothing, of course, about the quasi-polygon shapes of the individual granules (see figure 1a, 1b) and the extreme narrowness of the dark lines between the granules. In the study of the dark grain boundaries we definitely lack optical resolving power. Leighton concludes that the dark lines are 0".45 wide. But this is based on observations with a telescope whose diffraction limit is 0".38 and neglects the effects of optical imperfections and scattered light. Assuming constant mass transport and the condition that the downward flow is confined to the narrow dark lanes, velocity must increase as the lanes become narrow. Higher resolution granulation pictures are needed to correctly interpret the spectrum of figure 1c.

Besides the fine 2 inch granulation there is another somewhat less prominent aspect to the brightness field—the large scale mottling. The photograph plate is inappropriate for the recording of this mottling because all emulsions show increasing granularity for large spatial frequencies (see figure 4 in Livingston

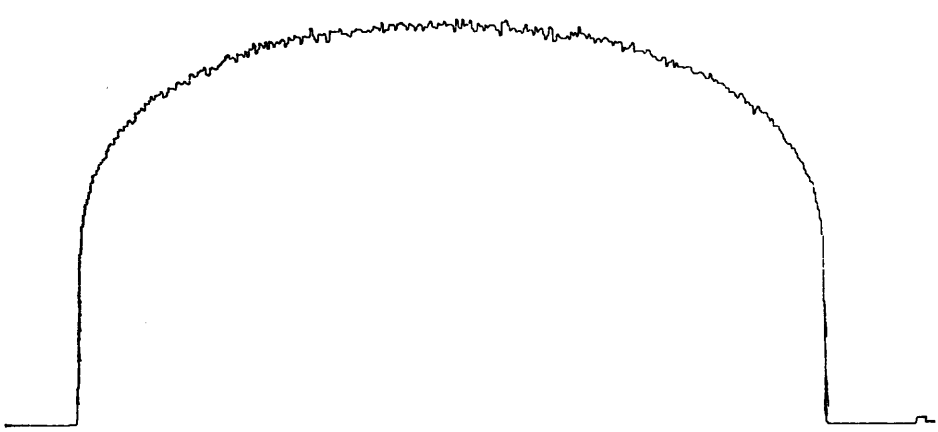


FIGURE 4

"Limb darkening" scan across extremely quiet sun at a wavelength of 6700 A, June 23, 1964. Consists of 400 adjacent deflections, each covering 23 × 5 arc sec. Illustrates the large scale mottling.

[13]) and thus have a mottling of their own. Photoelectric scans of the disk are required to show the mottling properly. Figure 4 is a high speed scan across a diameter of the sun's disk that was completely free of visible spots or faculae.

The r.m.s. $\Delta I/I$ is about 0.03 neglecting limb darkening. The presence of this mottling may account, at least in part, for the low VI crosscorrelation obtained when the large area Fourier components are included in the analysis [14], [15].

The physical interpretation of the mottling remains uncertain. Possibly related are the large scale patterns very near the limb ($r/R > 0.94$) as noted by Edmonds. The mottling may simply represent the statistical fluctuations resulting from aggregate collections of the variable brightness granules.

3. Spectroscopic structure; the middle and high photosphere

Modern interest in photospheric velocity and brightness fields seems to have begun with the 1950 paper of Richardson and Schwarzschild [16] in which a plate showing minute Doppler shifts was analyzed. This was followed by the 1956 work of McMath, Mohler, Pierce, and Goldberg [17] (see also [18]) in which greatly improved spectra showing the Doppler shifts, now called the "wiggly lines," were clearly seen. But the greatest impetus to this topic has probably come from the Mount Wilson observers—Leighton, Noyes, and Simon—with their discovery that the sun appears to be pulsating with a five minute period. Evans and Michard [1] then verified the Mount Wilson work, which was based on spectroheliograms, by more conventional spectroscopic analysis.

From these several investigations the following statistical data has developed. Measurements of Doppler displacements in lines of different strength [1] show that the r.m.s. velocity amplitude varies from around 0.3 km/sec in weak lines to 0.6 km/sec in strong photospheric lines. The element size for these velocities lies between 1000 and 5000 km, or somewhat larger than the scale of the white light granulation. Leighton, *et al.*, find that the time correlation function, for this small scale velocity field, has the form of a damped sine wave with a period of 296 sec and damping leading to a mean life of 380 sec. This almost precisely five minute oscillation period has so far proved to be an exclusive property of the photosphere and may well characterize this layer better than any other single parameter.

Evans and Michard [18] find no simple correlation between line brightness fluctuations, Doppler displacement, and the continuum granulation. They refer to lines of moderate strength.

Figure 1c clearly shows that for weak lines there is a one to one correspondence between the redward shifts of the lines and the dark intergranule spaces displayed in the streaked continuum.

We expect this condition because of the previously noted observation that the white light granulation retains some visibility near the limb. If there is this unity correlation between the downward component of the velocity field and the granulation brightness, why is there not a corresponding five minute periodicity in the brightness field? None has been observed. The answer would seem to be that, in objective correlation analysis, the bowed side of the lines dominates and this portion of the line is independent of the granular field. This will be the case particularly with lower spatial resolution, for the fine dark threads will be lost relative to the bright streaks and bowed displacements. The fact that measured r.m.s. velocities show only a slight dependence on plate quality (as judged by visibility of the threads) supports this view. Again, we see the need for higher image resolution in connection with the problem of the dark intergranule lines. Velocity shifts of these dark lanes may well prove to be many km/sec with improved definition.

Apparently independent from the small scale velocity field is a system of large scale transverse flow patterns called by Leighton the "supergranulation." These flows are revealed on Doppler spectroheliograms as well-ordered cells about 15,000 km in diameter with a preferred spacing, as shown by a secondary maximum (in the θ component) of the autocorrelation function of 35,000 km. No related brightness field has been found. The average velocity of (the radial) flow is about 0.5 km/sec. The lifetime is uncertain but at least ten hours. Simon has shown that the edges of the supergranulation cells coincide with the so called "calcium network" of the chromosphere. Howard finds that calcium network emission patches coincide with magnetic fields of ten or more gauss in strength. Simon and Sheeley have found that matter is ascending from the photosphere in small patches between the network and then descending in the network as in figure 2. Thus, we can expect some relation between the supergranulation, magnetic, and velocity fields in the photosphere, but the picture is not yet clear in detail.

4. The magnetic fields

Figure 5 is a magnetic record of the full disk of the sun taken at a time when there were no visible sunspots. The resolution is about 10×10 arc sec and the noise level about 0.5 gauss. The observational technique is that indicated schematically in figure 3. The line used was the intermediate strong line of neutral iron at 5250.2 A so we are examining the upper photosphere. We see several "bipolar" regions as well as a predominance of S fields at high northern latitudes and N fields in the southern polar regions.

The quiet sun aspects of this record follow. The sun is covered with fields which have an r.m.s. amplitude of 4.9 gauss, excluding pronounced active regions and the polar latitudes. The magnetic structure shows no center to limb variation. Because at the center we see "longitudinal" fields and at the limb "transverse" fields, we conclude the magnetic vector distribution is isotropic.

To examine the magnetic fine structure with high resolution, maps of restricted areas have been made in the VIH components and with a scanning aperture of 1.8×1.8 arc sec. Over a particular area taken near the center of disk and well away from signs of activity (figure 6a, 6b), the r.m.s. magnetic field is 2.8 gauss. Peak fields of 10 gauss are common. This result may be compared with findings of Howard [19] who, with similar resolution but higher noise, describes an r.m.s. field of 8.2 ± 4.4 gauss.

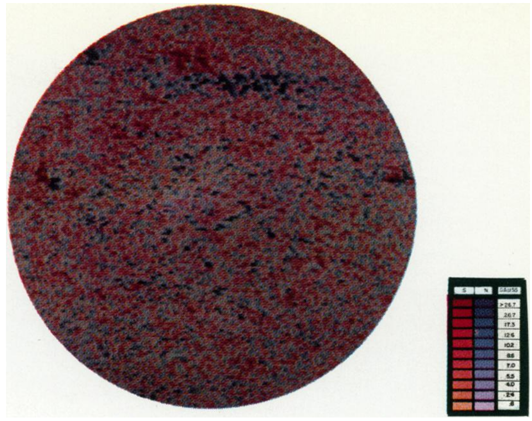


FIGURE 5
Full disk magnetogram for November 5, 1964. Corrected for limb darkening, 10×10 arc sec aperture.

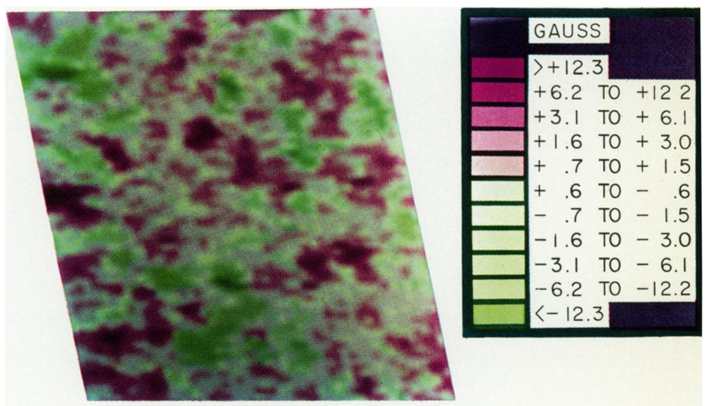
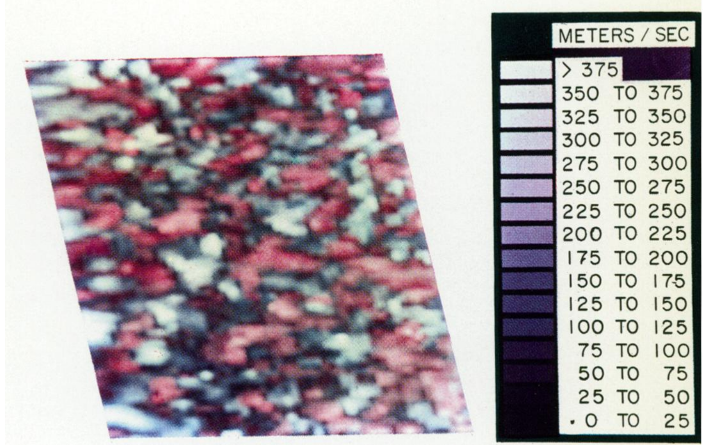


FIGURE 6
(a) Magnetic map, center disk, quiet sun, with 1.8×1.8 arc sec aperture. Total size 90×100 arc sec. Seeing: very good. October 2, 1964.



(b) Velocity map recorder simultaneous to (a). Toned gray scale indicates velocity with minimum to maximum, dark to light, respectively.

Red tone is away from observer (downward flow), blue toward observer.

Objective correlation analysis has not been undertaken, but certain relations between the *V* and *H* fields are noticeable. On the magnetic record, *x* marks have been placed over points of maximum intensity. When a map of these *x* marks is transferred to the velocity field, we see that peak *H* fields fall on lines of zero, or near zero, velocity. Dr. N. F. Ness points out (at this symposium) that the locus of the field reversal points also tends to coincide with zero velocity lines. Assuming that the peak *H* field points coincide with the calcium network, and thus with the edges of the supergranulation, we may have some evidence here for an interaction between the supergranulation at its boundary and the vertical velocity field.

The associated brightness field (not shown) does not resolve the granulation nor do we see features on the *V* record that correspond to the red displaced intergranule dark spaces. Therefore, before such records as these are studied in greater detail, high resolution maps are needed. Observations of this kind are planned for Kitt Peak.

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