SPECTRA-SPECTROHELIOGRAPH OBSERVATIONS

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Abstract. This paper describes a photographic technique for recording solar spectra. The technique, which we call spectra-spectroheliography, requires the same amount of observing time as conventional spectroheliography but yields much more information. Data reduction techniques have been developed to use this information for the construction of spectroheliograms and other contour maps. Parameters investigated by this method include the vector magnetic field, line-of-sight velocity, continuum intensity, and line strength. Results indicate (1) good correlation between bright regions in spectroheliograms and small vertical magnetic fields; (2) poorer correlation between larger magnetic fields and bright regions; (3) a feature in the continuum resembling a pore but having no vertical magnetic field; and (4) a gradient in the vertical magnetic field of 12 kG/arc s.

1. Introduction

We would like to discuss a technique for recording and analyzing solar spectra that is similar to spectroheliography (SHG) but yields much more information. This technique, which we call spectra-spectroheliography (S^{2}HG), appreciably extends the number of physical parameters that can be studied from a single observation. It also eliminates many of the difficulties encountered in interpreting conventional spectroheliograms, and achieves these results without introducing any additional complexity during observation. After outlining the principles underlying this technique, we will present some representative spectroheliograms and contour maps of magnetic fields and continua reconstructed from S^{2}HG spectra obtained at the Kitt Peak Solar Tower in 1969.

2. System Description

S^{2}HG is an extension of SHG and, as such, is closely related to it. In both instances, the Sun's image is moved with respect to the entrance slit of a spectrograph and recorded on film that is simultaneously being moved with respect to the exit slit. The most important difference between S^{2}HG and SHG is that S^{2}HG records a wide spectral region and SHG records only a narrow wavelength band.

Ordinarily, spectroheliograms are made by fixing both the film and the Sun's image and moving the spectrograph. Exposure is made through a narrow exit slit. The result is a photograph of the Sun with variations in density representing variations in the intensity of solar radiation (integrated over a small fixed wavelength band). It is difficult to determine from a single spectroheliogram whether these changes in density are due to Doppler shifts, Zeeman splittings, or variations in continuum intensity or line strength. Various techniques using combinations of spectroheliograms have been developed in an attempt to distinguish these different physical effects.

The S^{2}HG spectrograph (Figure 1) has a wide exit aperture and a specially constructed movie camera capable of rapidly advancing the film. In recording spectra,

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the spectrograph remains stationary and the Sun's image is allowed to drift past the entrance slit. A single frame of the film is exposed while the Sun moves a distance Δ with respect to the entrance slit. The film is then rapidly advanced and the next frame is exposed. Except for the time required to advance the film, exposure times are the same as in making conventional spectroheliograms. (Our film advance times were typically 2 to 5% of our exposure times.) Thus, S^2HG spectra are frames on the film, each frame containing the entire spectral profile along a line on the Sun's disk (Figure 2, a and b). Since successive frames contain spectral profiles for adjacent regions on the Sun, the film contains the spectral line profile for each position on a two-dimensional grid on the solar disk. The grid spacing is Δ perpendicular to the slit and the resolution of the spectrograph along the slit. By inserting quarter- or half-wave plates and a polarization-dependent beam splitter into the system, we obtain spectral profiles in polarization pairs, as shown in Figure 2c.

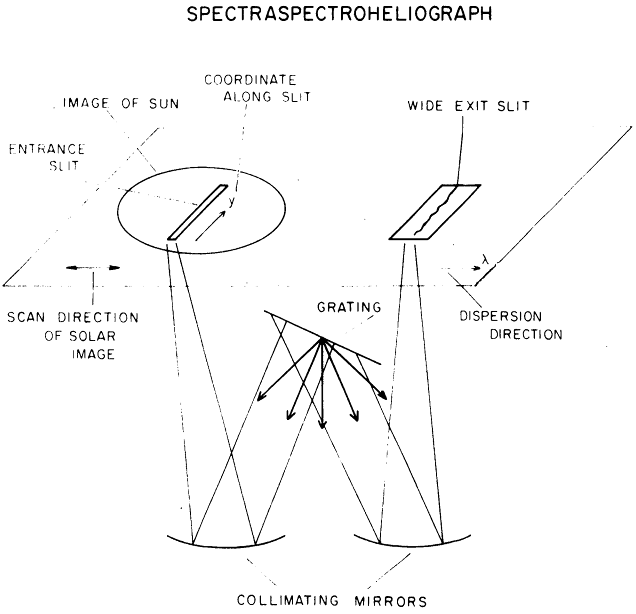

Fig. 1. Schematic of S^2HG optics.

Figure 3 illustrates how conventional spectroheliograms can be constructed from S^2HG film strips. The wavy line represents a particular spectral line as it appears in each frame. In principle, to produce a spectroheliogram at a given wavelength, we need only remove a thin strip of film from each frame at the appropriate position for that wavelength. The desired spectroheliogram can then be built up merely by placing adjacent strips side by side. In practice, of course, we do not cut up our original film. The only information we require is the relative intensity of the original solar radiation at the given wavelength for each position on the Sun. To obtain this, we microdensitometer the film and digitally record the output on tape. We then construct the spectroheliogram from the data on the tape.

Since the tape contains far more information than we need for the spectroheliogram, we can use the remaining information to construct contour maps of other interesting physical parameters. For example, by selecting different positions in each frame, we can vary wavelength and produce a spectroheliogram of the center of a line even in the presence of large Doppler shifts. Moreover, we can make contour maps of the Doppler shift itself as well as of the continuum intensity and the total absorption of the line. If a line displays a Zeeman effect and we take spectra in right and left circular polarizations, then we can construct longitudinal magnetic field maps. If Zeeman sensitive lines are taken in several pairs of linear polarizations, then transverse magnetic field maps can be constructed.

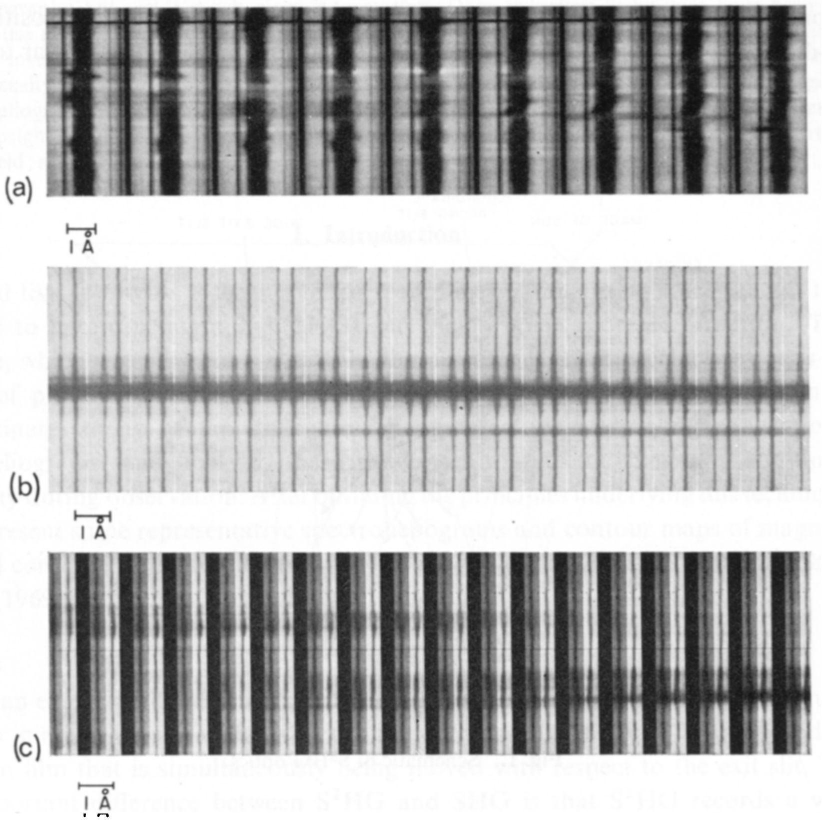

Fig. 2. Representative S^{2}HG spectra. The film strips are positives. (a) Hα spectra. Adjacent frames are separated by one arc second on the solar disk. (b) Fe I (λ 5250.2) spectra (left line). Adjacent frames are separated by one-half arc second on the solar disk. (c) Fe I (λ 5250.2) spectra in right and left circular polarization. Adjacent frames are separated by one-half arc second on the solar disk.

Whenever the magnetic field is small, our computer program is essentially a digital analog of an Evans magnetograph. For fields above a kilogauss, however, the program directly measures the splitting of the Zeeman components. It adjusts the separation of the peak-detecting slits to detect peculiar line profiles, thus alerting us to those interesting regions of the Sun where the profile of an observed line turns out to be different from the theoretical prediction. Such discrepancies can only be detected by examining an entire line profile. An important advantage of S^{2}HG spectrograms is that if subsequent theoretical work should suggest other spectral measurements, we could immediately investigate these by rewriting the S^{2}HG computer program and analyzing existing data. We would not need additional observing time for new data.

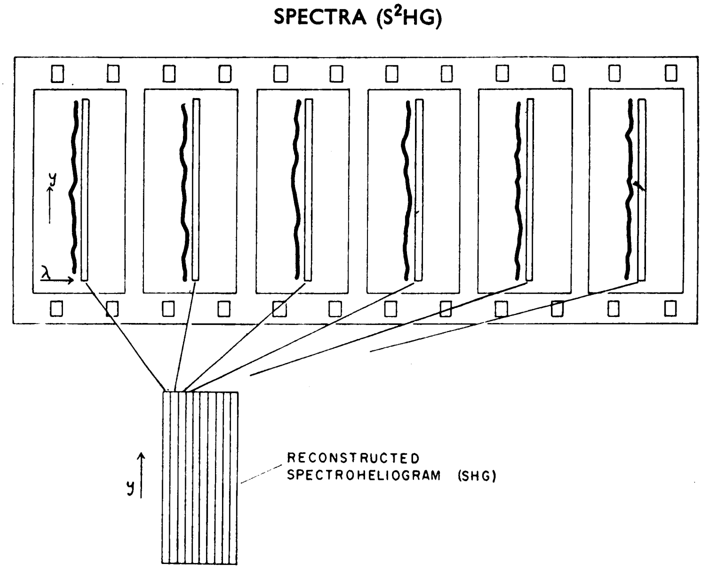

Fig. 3. Principle of constructing spectroheliograms from S^{2}HG spectra.

An important practical feature of S^{2}HG is that it does not require the precise mechanical motion nor delicate operation of a spectroheliograph. Thus, the increased rate of data acquisition and variety of physical parameters investigated are achieved concurrently with simplification of the process of solar observation.

3. Observations

In August 1969 we used the S^{2}HG system to make observations in λ5250.2 (Fe I) using the Kitt Peak Solar Tower. Spectra were photographed on 70 mm Linagraph Shellburst film approximately once a second, during which time the Sun moved one-half arc second relative to the entrance slit. Seeing was often better than one-half arc second, so we were able to record the spectrum of λ5250.2 at every point on a one-half arc second grid. Since we photographed the Sun's surface at a rate of one-half square arc minutes per minute, we were able to record a complex spot group three or four times in 15 min, alternately analyzing for linear and circular polarizations.

4. Reproducibility of Results

Most of the data reduced so far are from gap and pore regions rather than from well-developed spots. To make certain that our data reduction procedures were free from ambiguities, the films of these regions were subjected to two tests: (1) Different individuals independently analyzed the same strip of film, from setting up the microdensitometer to generating the digital data for construction of contour maps. In each case the contours generated agreed to better than one-half second of arc. The magnitudes of the longitudinal magnetic field, for example, agreed to a few gauss in quiet regions and to a few percent in fields of 500 to 1000 G. This small difference could easily be due to differences in positioning of the data grids with respect to the solar features. (2) Contour maps constructed from two different films of the same pore taken one-half hour apart were compared. The central longitudinal magnetic field differed by 5%; the contours agreed to better than one-half arc second. We do not know how much of this 5% difference is due to positioning of the data grids, to a change in the seeing conditions or to an actual change in the field of the pore.

5. Experimental Results

A. CONTOUR MAPS

We would like to present some spectroheliograms and contour maps of magnetic fields of corresponding regions. The spectra are from gaps and pores up to two arc seconds in diameter. A 9 × 12 arc s region around one such gap is shown in Figure 4. In contrast to a map of the continuum (not presented here), which had no particularly distinguishing features, the spectroheliogram (Figure 4a) clearly shows a very bright region (A) and several smaller bright regions nearby. A comparison of this spectroheliogram and the corresponding vertical magnetic field map (Figure 4b) indicates a very high correlation. The very bright region (A) is associated with a vertical magnetic field of nearly 500 G and most of the smaller bright regions, only 1 or 2 s in diameter, have vertical magnetic fields of 100 to 300 G, (C) and (D) for example.

Figure 5 is another set of contour maps showing (a) the continuum, (b) the spectroheliogram at line center, and (c) the vertical magnetic field of a small pore having a central field exceeding one kilogauss. The narrow lane of low vertical field in the top-center of the magnetic field map is apparently real – it is also present in a vertical magnetic field map (not shown) constructed from film exposed $\frac{1}{2}$ h earlier.

In contrast to the very high correlations between vertical magnetic fields and bright regions in Figure 4, we see that the location cospatial with the highest field [(E) in Figure 5b] occurs 2 to 3 arc s from the bright patches in the spectroheliogram. The correlation does not improve when other positions in the spectral line are examined. This, then, is a pore that is clearly visible in the continuum but in a spectroheliogram does not show up as a bright region over its entire area.

The last set of contour maps (Figure 6) is of an interesting region containing some small pores. The continuum map (a) shows pores at F and G. The line center spectroheliogram (b) indicates that one of the pores correlates with a bright region and the other with a dark one. It also shows an additional bright feature (H) to the left and below the two pores. The vertical magnetic field map (c) is qualitatively correlated with the spectroheliogram in that the vertical magnetic fields and bright regions in

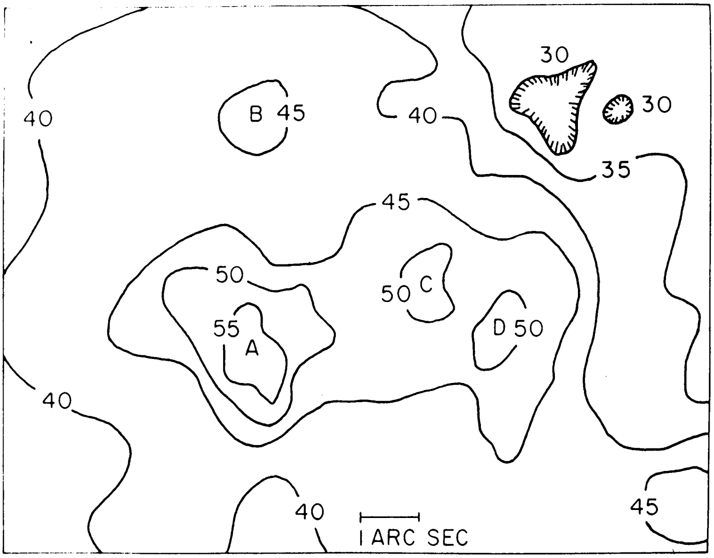

Fig. 4a.

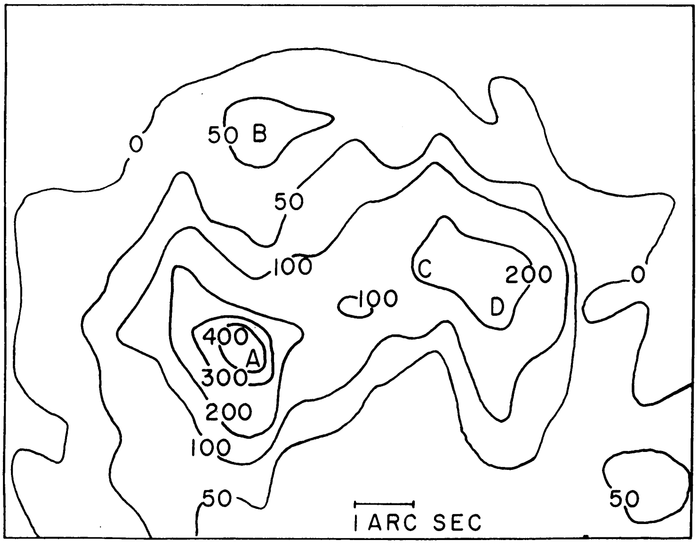

Fig. 4b.

Figs. 4a–b. Contour maps of a gap region. (a) Spectroheliogram at line center Fe I (λ5250.2). (b) Longitudinal magnetic field.

the spectroheliogram are roughly cospatial. However the vertical magnetic field map is distinctly different from the continuum map; that is, the pore (F), clearly visible in the continuum, has no vertical magnetic field. The linearly polarized spectra from this pore differ from spectra in neighboring regions. Thus, even though the data are not completely reduced, we suspect the presence of a significant horizontal field.

B. SPECTRA

Shown in Figure 7 are 4 traces of the $\lambda 5250.2$ spectrum in a pair of orthogonal linear

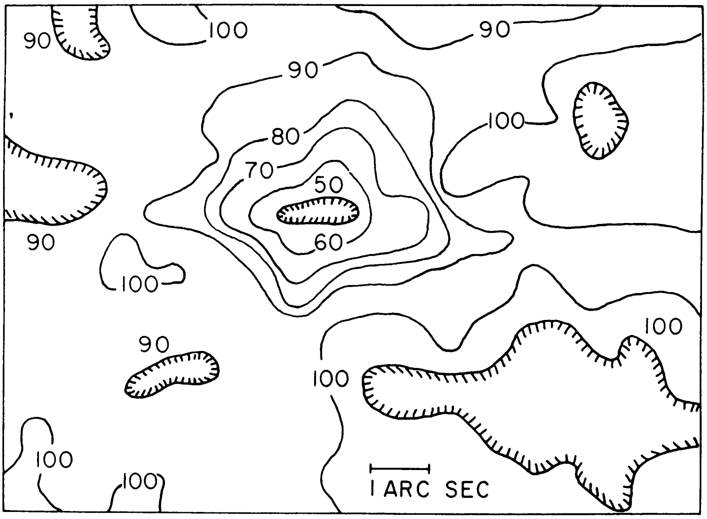

Fig. 5a.

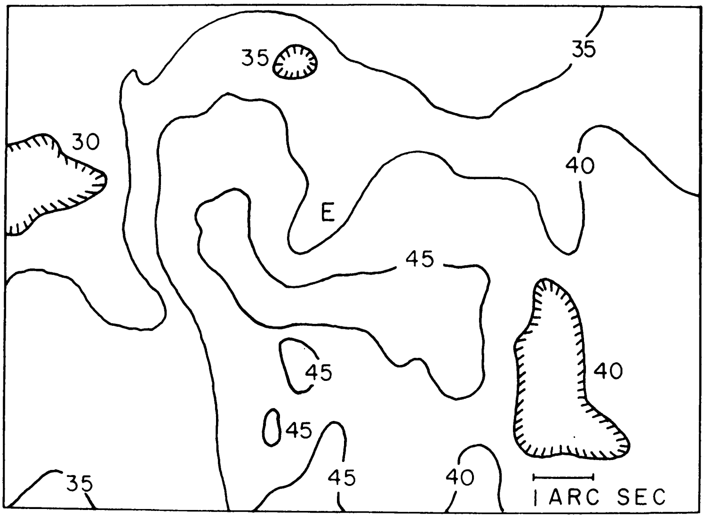

Fig. 5b.

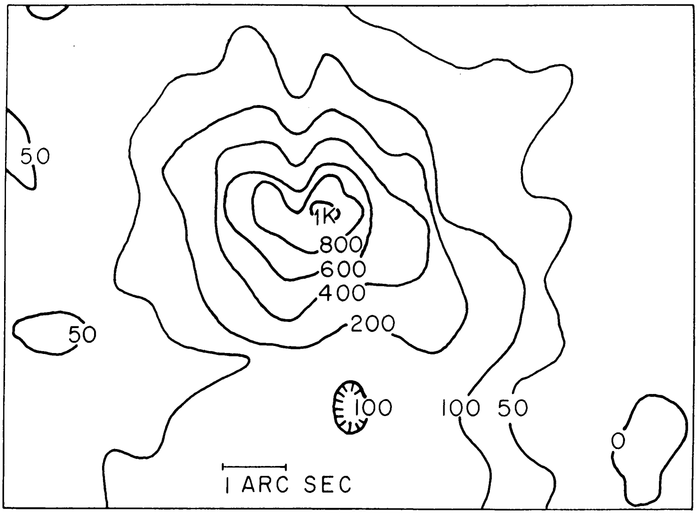

Fig. 5c.

Figs. 5a–c. Contour maps of pore region I. (a) Continuum. (b) Spectroheliogram at line center. (c) Longitudinal magnetic field.

polarizations. The spectra are from points on the Sun spaced one arc second apart along a line that starts just inside the umbra of an ordinary round sunspot and ends just outside, in the penumbra. From these tracings we infer that the transverse component of the magnetic field rotates about 90° in 2 arc s, that the field strength is on the order of 2000 G, and that the change of direction occurs precisely at the umbra-penumbra boundary. Inside the umbra the transverse component of the field is in the east-west direction. Inspection of the circularly polarized spectra indicates that the vertical component of the field does not do anything unusual in this region.

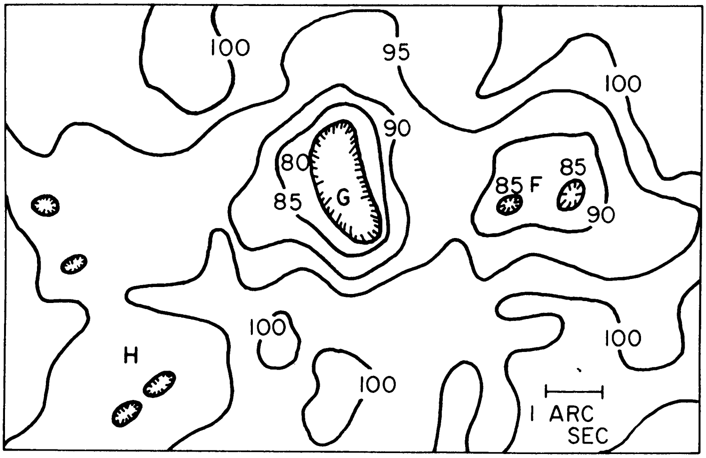

Fig. 6a.

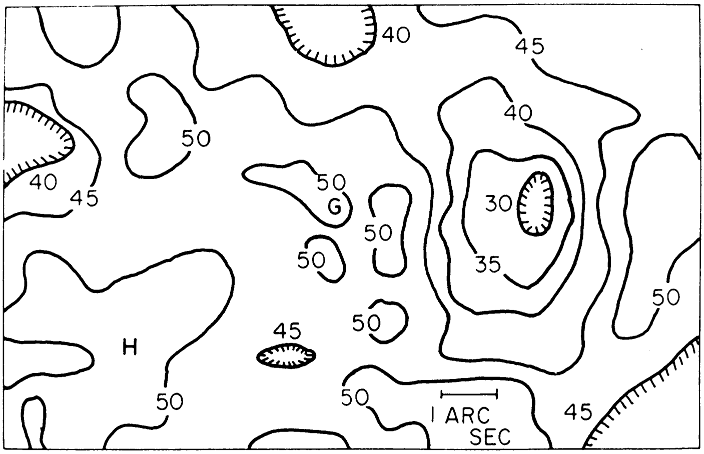

Fig. 6b.

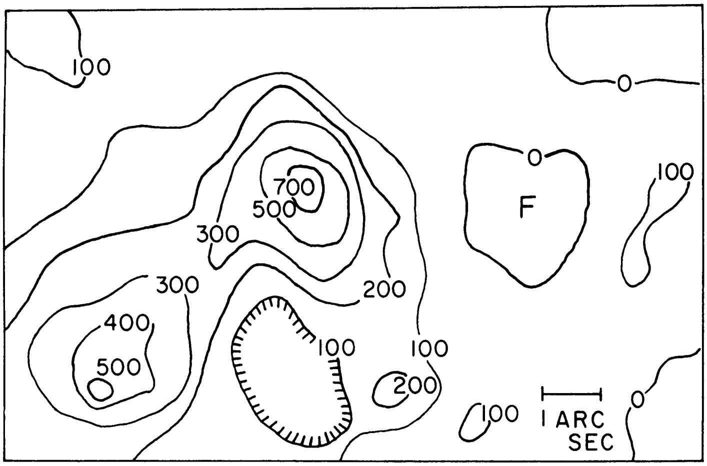

Fig. 6c.

Figs. 6a–c. Contour maps of pore region II. (a) Continuum. (b) Spectroheliogram at line center. (c) Longitudinal magnetic field.

In fact, comparison of circularly polarized spectra for this high transverse gradient sunspot and those of similar round spots having no unusual transverse fields shows them to be almost identical.

We cannot now state whether the sharp gradient in the transverse field develops with time or if the spot originates with this characteristic. However, the feature is not uncommon. We have observed it in a number of similar ordinary round sunspots.

High gradients in the transverse field are by no means limited to regular round sunspots. We mentioned the ordinary spots first only to draw attention to the fact that high gradients and high currents can and do exist in what might be considered

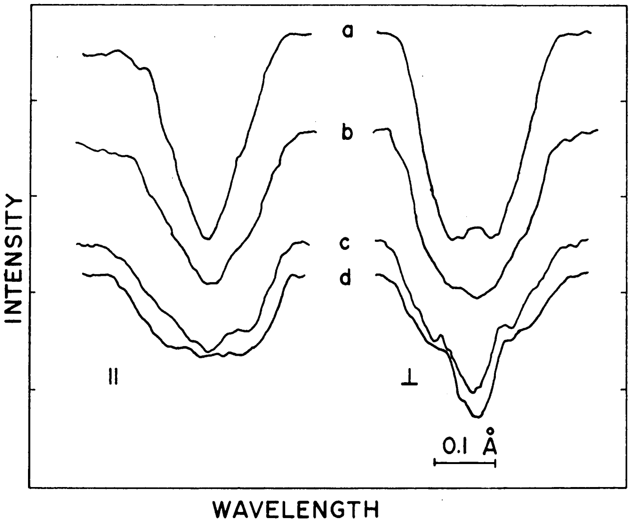

Fig. 7. The traces are of Fe I λ 5250.2 in orthogonal polarizations. Points *a*, *b*, *c* and *d* lie along a radius of the sunspot. Traces for *a* are from a point 1 arc s inside the penumbra; for *b*, from a point on the umbra-penumbra boundary; *c* and *d*, from points 1 and 2 arc s, repectively, inside the umbra.

uncomplicated field regions. Shown in Figure 8 is a series of spectra in pairs of orthogonal linear polarizations taken of a complex sunspot having several umbra. Note that a transverse field of 2500 G rotates by 90° in an arc second or less.

Figure 9 shows spectrograms of the same complex sunspot in circular polarization. From these spectra we infer that a 2900 G field reverses direction in one-half arc second or less; that is, there exists a gradient in the magnetic field on the order of 12 kG per arc second. This high gradient region occurs along a line 8 arc s long. The field is vertical and upward on one side of the line and vertical and downward on the other. Note also that the magnitude of the field increases toward the line of discontinuity; that is, the field is 2900 G at the reversal but 2500 G only a few arc seconds away. Further examination of the transverse field shows it to rotate by about 45° cospatially with the reversal. This discontinuity persisted for at least a week during which time the length of the line increased. No flares were observed in this high vertical gradient region.

6. Summary of Results

A. CONTOUR MAPS

(1) The gradient of the vertical magnetic field in regions of pores and gaps is often at least as great as 500 G/arc s for pores and 250 G/arc s for gaps.

(2) Regions with moderate magnetic fields (less than 700 G) that are not in the immediate neighborhood of large magnetic fields are brighter than average in the center of λ 5250. The magnetic field regions in the magnetogram and the bright regions in the spectroheliogram are coincident within our one-half arc second resolution.

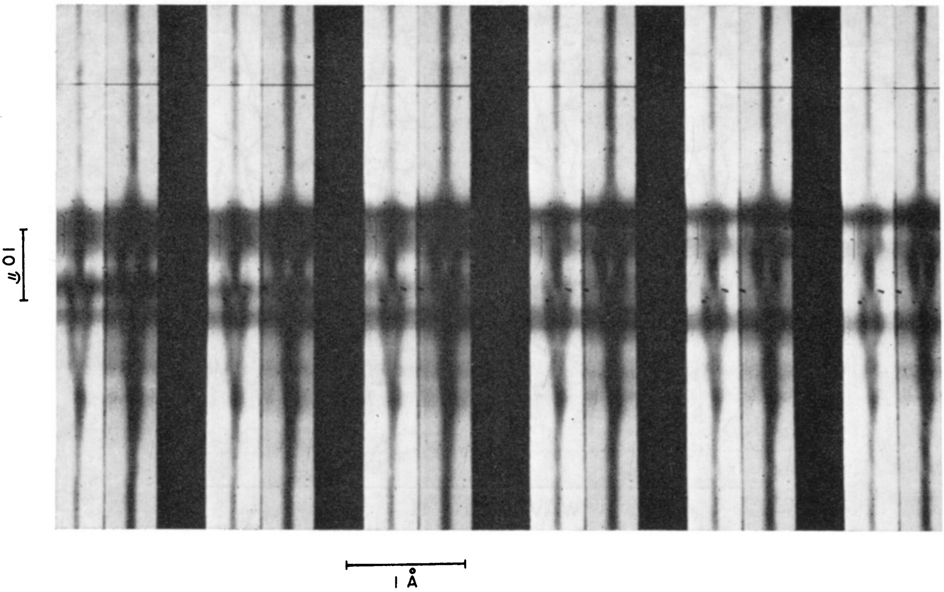

Fig. 8. Six pairs of spectra from the region around λ5250.2. One member of each pair was taken in right circularly polarized light, the other in left circularly polarized light. Each pair of spectra is displaced from the next by a distance corresponding to one-half arc second on the Sun. The displacements are in the R.A. direction.

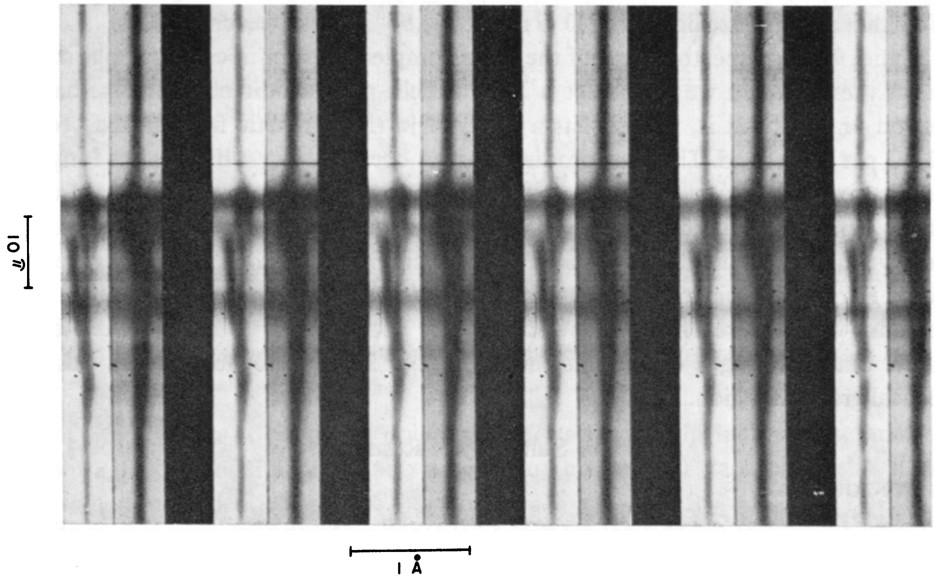

Fig. 9. Six pairs of spectra from the region around λ5250.2. One member of each pair was taken in a linear polarization parallel to the slit, the other in the orthogonal direction. Each pair of spectra is displaced from the next by a distance corresponding to one-half arc second on the solar disk. The displacements are in the R.A. direction. The variation in intensity between members of a pair is due to different spectrograph efficiencies for the two polarizations.

(3) Regions with magnetic fields greater than 700 G are darker than average in the continuum. [The converse is not necessarily true, as shown in (4) below.] The high magnetic field region in the magnetogram and the dark region in the continuum map are coincident within our one-half arc second resolution.

(4) Regions that are darker than average in the continuum and of an appropriate size to be a pore sometimes have no vertical magnetic field.

B. SPECTRA

(1) The transverse field in apparently normal round sunspots may change direction by approximately 90° in 1 to 2 arc s, with the reversal occurring at the umbra-penumbra boundary.

(2) The transverse field in complex spots may change direction by 90° in one half arc second or less.

(3) In complex spots large vertical magnetic fields may change direction by 180° in one half arc second or less. This implies a gradient of 12 kG/arc s.

Acknowledgements

The work described here was based on data taken with the McMath Solar Telescope of the Kitt Peak National Observatory. We are extremely grateful for the help and encouragement given to us by the staff of the Solar Division there. Without the considerable aid of Keith Pierce we could not have obtained data of such quality.

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Discussion

Jakimiec: I would like to emphasize that the observed large gradient of the magnetic field strength does not necessarily imply the presence of a strong current at the place. Large gradients of the field strength may exist also in the regions where the magnetic field is already nearly potential.

Meyer: It would be interesting to compare the magnetic field gradients that you observe with the distances that one would expect theoretically if one considers the diffusive penetration by finite conductivity of opposing fields. For a quasistationary diffusive equilibrium at the border of regions of opposite field direction one has to require that the plasma being swept up by the diffusive cancellation of opposite fields has time to settle vertically. For electrical conductivities suggested by Schröter and Kopecký for sunspots, one determines typical widths for the transition region between opposite strong fields of less than 100 km.

Michard: Since you told us that this line of abrupt inversion of $H_{\parallel}$ was stable in time, it is not surprising that no flares were associated with it. Changes in the magnetic patterns on an hour-to-hour scale are necessary for flare productivity.