CORRELATIONS BETWEEN BRIGHTNESS FIELDS AND MAGNETIC FIELDS ON THE SUN*

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ABSTRACT

In places on the solar surface where longitudinal magnetic fields are detectable using Leighton's photographic technique, spectroheliograms taken in the cores of many Fraunhofer lines show a *bright photospheric network* similar to, but with finer structure than, the familiar chromospheric network visible on Ca^+ K_{232} spectroheliograms. This paper describes preliminary results of a study of the relation between the photospheric network and its associated magnetic fields.

1. Introduction

As Dr. Kiepenheuer mentioned in his introductory lecture yesterday, many optical phenomena seem to be *direct products* of magnetic fields. The Ca^+ K_{232} emission and Hα brightenings are repeatedly referred to as indicators of magnetic fields, and spectroheliograms in these lines are commonly used to guess where these fields may be located on the solar surface. Figure 1 illustrates the close spatial relationship between the longitudinal magnetic fields and the K_{232} emission.

We are not limited to chromospheric lines as indicators of magnetic fields, but can also use photospheric lines. We have known for some time (Beckers and Schröter, 1966; Sheeley, 1966b, 1967) that many photospheric lines are weakened in places on the solar surface where there are relatively strong magnetic fields. This is illustrated in Figure 2. As we shall demonstrate, spectroheliograms taken in the cores of these lines show a *bright photospheric network* similar to, but more delicate than, the familiar bright chromospheric network visible on spectroheliograms taken in the core of the Ca^+ K line and Hα. At the Kitt Peak National Observatory we are now using the newly installed spectroheliograph with the 82-cm solar image of the McMath Solar Telescope to study the relation between photospheric magnetic fields and the as-

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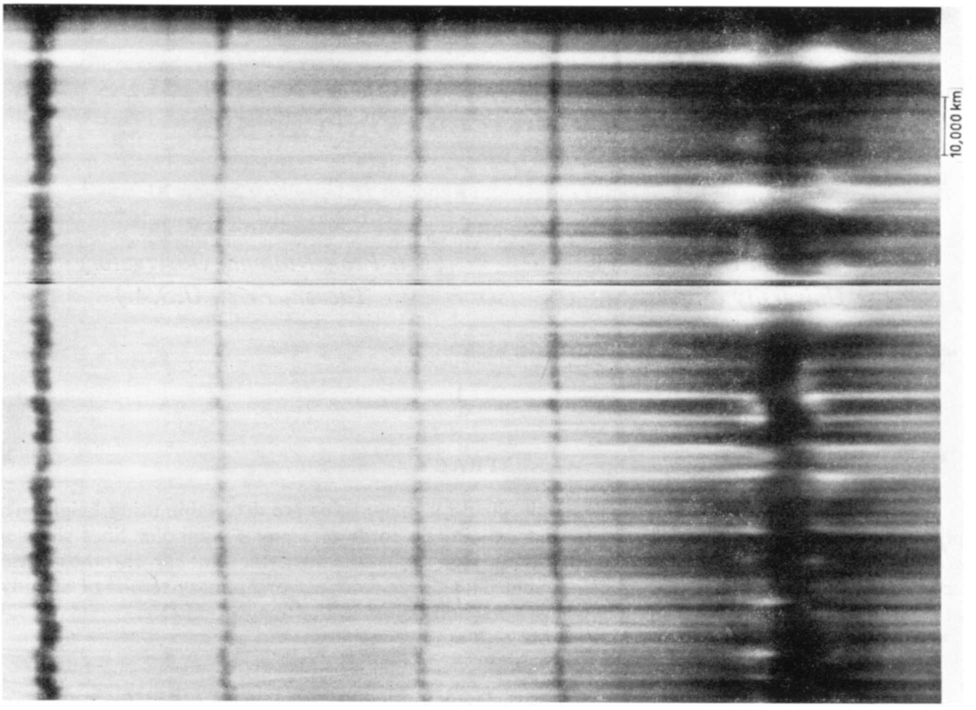

FIG. 1. *Spectrogram of a magnetic feature taken on June 19, 1966. The magnetic feature is indicated by the pair of dark lines caused by hairs across the entrance slit. Note that the* Ca^{+} *K line has bright* K_{232} *emission at this point.*

sociated weakenings in Fraunhofer lines in hopes of finding out what causes the line weakenings.

2. Preliminary Results

Figure 3 shows a spectroheliogram taken in the core of the λ 5131 line of Fe I together with a Zeeman photograph of the same region. The λ 5131 line is a 'degenerate' Zeeman triplet arising from transitions between states having the same Landé g-factors. The magnetic sensitivity is $\Delta\lambda/B = 3{\cdot}0 \times 10^{-5}$ Å/gauss. The slit widths were 25 μ corresponding to a band pass of 0·02 Å. The atmospheric seeing was excellent. The Zeeman photograph was made about $1\frac{1}{2}$ hours later during very poor seeing conditions, and is included here only for a rough comparison between the pronounced photospheric network visible in the λ 5131 spectroheliogram and the longitudinal magnetic fields. In addition to the bright network visible in the λ 5131 spectroheliogram there is a 'bright ring' visible in the penumbra of the large sunspot. Spectroheliograms in the core of the Zeeman-insensitive λ 5124 line do not show such 'bright

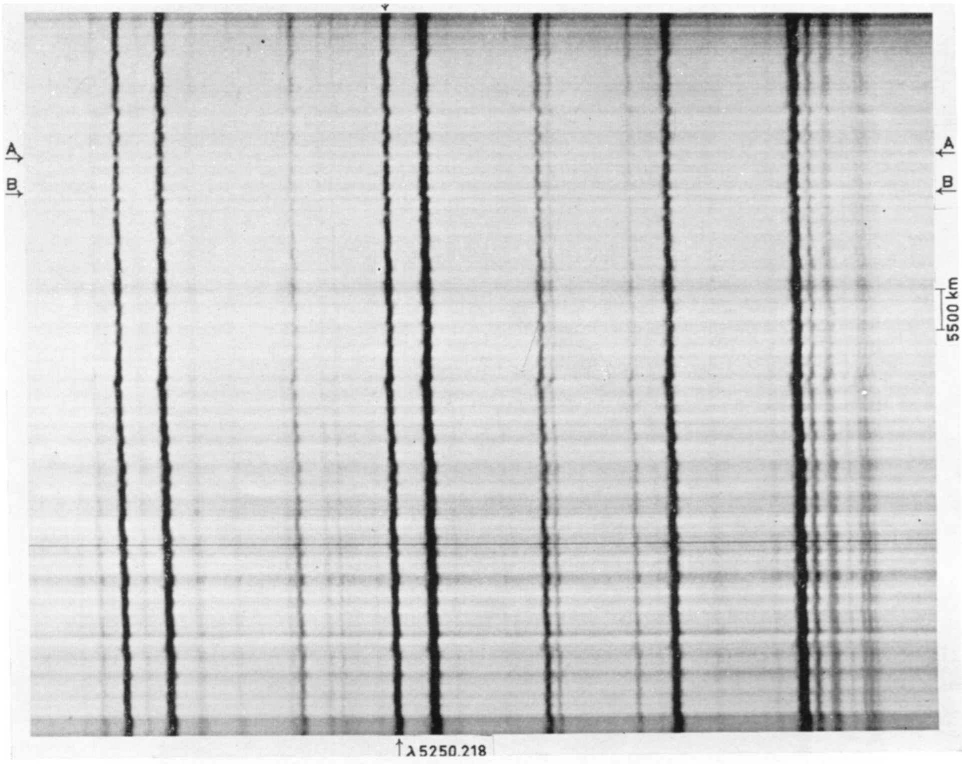

FIG. 2. *Spectrogram of the λ 5250 wavelength region taken on July 4, 1966. The arrow A indicates the position of a magnetic feature along the slit. The arrow B marks a position on the Sun both where the absorption lines have a characteristic arch-shaped appearance (the arch concave to the red) and where the continuum is locally bright, probably corresponding to a very bright solar granule. Notice that several Fraunhofer lines appear weakened at A, whereas they do not at B. Notice also that the continuum at A is locally dark, suggesting that the magnetic field occurred in a dark lane in the granulation field.*

penumbral rings', as one would expect if these rings are produced by separation of the magnetic components of a Zeeman-sensitive line by a magnetic field.

Figure 4 shows a Zeeman-step scan made using the Ca I λ 6103 line with an entrance slit of 75 μ and exit slits each of 50 μ. The left and right columns show uncancelled Zeeman spectroheliograms, made from left-circularly and right-circularly polarized light respectively for a given sign of the quarter-wave plate ($\lambda/4$). The bottom figures are doubly cancelled Zeeman photographs made from some of the above pairs. The longitudinal magnetic fields shown in the Zeeman photograph correspond to a bright network visible in the spectroheliograms made at $\Delta\lambda = -0{\cdot}02$ Å, near the core of the line. Proceeding further into the wings of the line this bright network occurs alternately on spectroheliograms in the left or right column depending on the sign of the

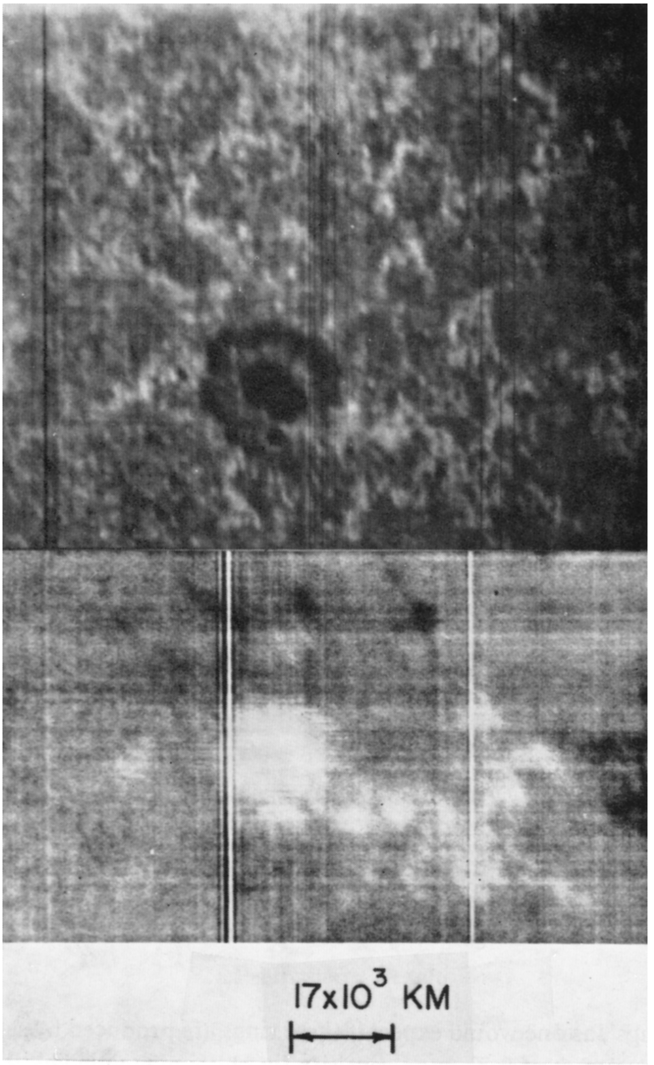

FIG. 3. *Upper picture: SHG taken in the core of λ 5131 on August 2, 1967. Lower picture: Z-photo of low quality obtained on August 2, 1967 about 1 hour after the λ 5131 SHG.*

quarter-wave plate. We interpret this as an indication that wherever a line-of-sight component of magnetic field can be detected outside sunspots using Leighton's technique with the λ 6103 line, a locally bright feature can also be detected in the same solar position on a spectroheliogram taken in the core of this line.

Figure 5 shows a pair of spectroheliograms made simultaneously through two exit slits. The upper figure is a λ 5124 spectroheliogram and the middle figure is a λ 5131

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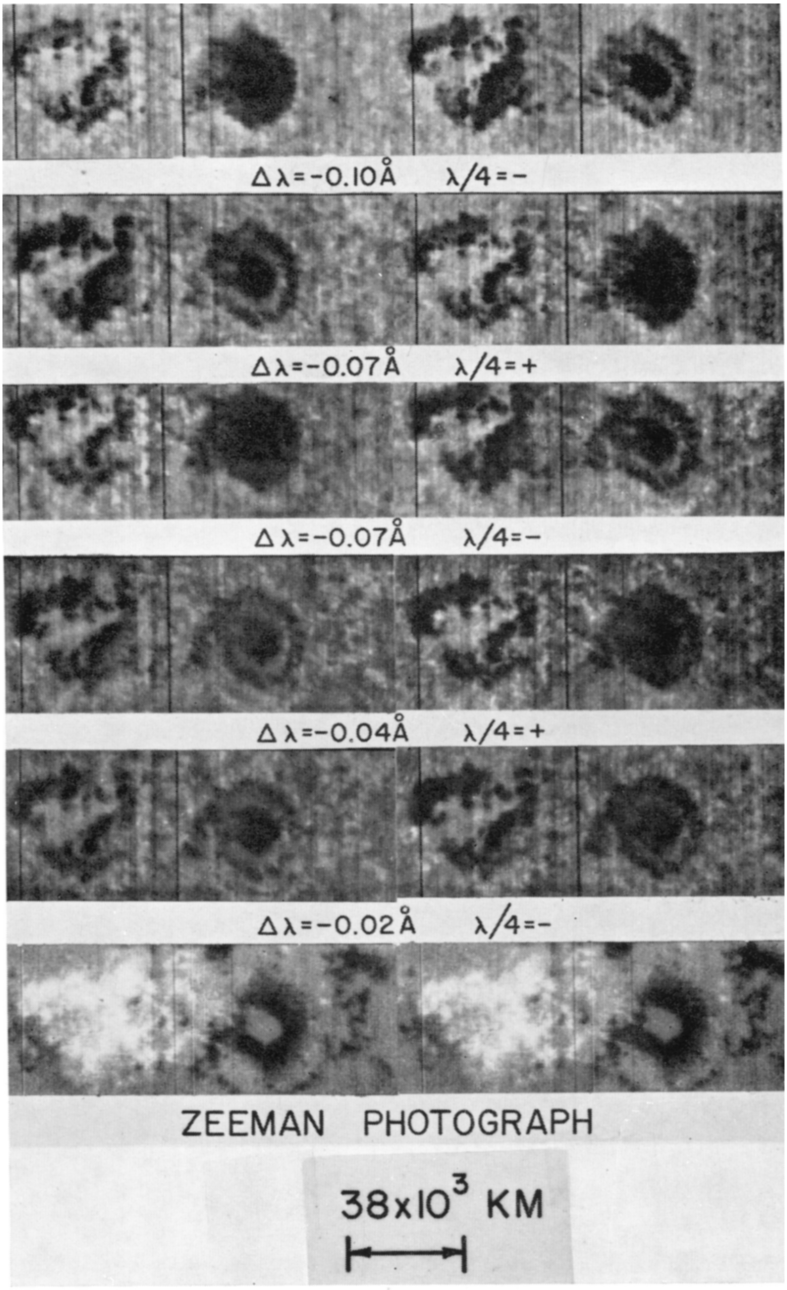

FIG. 4. *A sequence of uncancelled Zeeman spectroheliograms at different distances from the λ 6103 line core together with a doubly cancelled Z-photo for the same region (August 7, 1967).*

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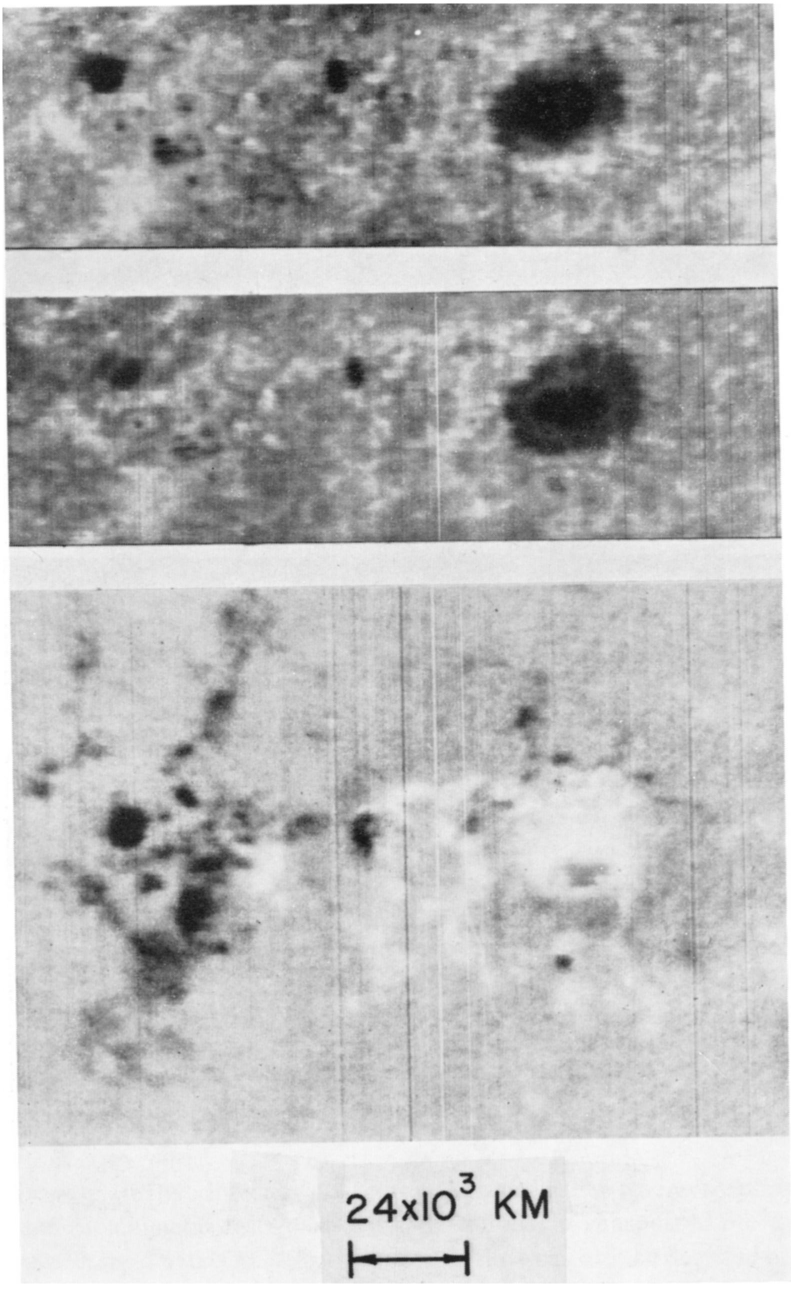

FIG. 5. *Upper picture: SHG taken in the core of the Zeeman-insensitive line λ 5124. Middle picture: SHG taken simultaneously in the core of the strongly Zeeman-sensitive line λ 5131. Bottom picture: Doubly cancelled Z-photo taken about 1 hour earlier on June 27, 1967.*

spectroheliogram. Also included is a Zeeman photograph of the same region. A bright network corresponding roughly to the longitudinal magnetic fields is apparent in both the λ 5124 and λ 5131 spectroheliograms despite the fact that the λ 5124 line is Zeeman-insensitive and the λ 5131 is strongly Zeeman-sensitive. However, the bright network is definitely more pronounced in the λ 5131 spectroheliogram than in the λ 5124 one. Also the bright penumbral ring is evident in the λ 5131 picture but not in the λ 5124 picture. Outside sunspots, the field strengths vary from about 70 gauss for the fainter features to about 500 gauss for the more intense ones.

Figure 6 shows two spectroheliograms made simultaneously in the core of the λ 5250·218 Fe I line but through polaroids that were at right angles to each other. Note that the appearance of the bright penumbral ring is different in the two spectroheliograms, but other features in the two pictures appear the same, as shown in the

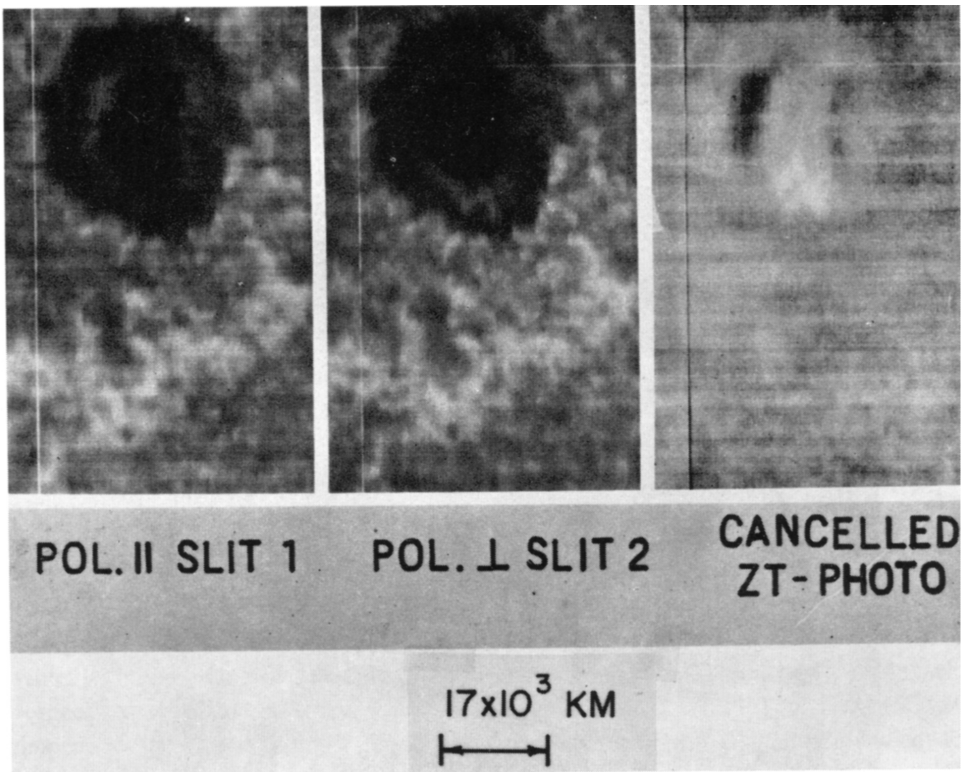

FIG. 6. *Left picture: SHG taken in the core of λ 5250 through a polaroid placed with its axis of polarization parallel to the exit slit. Middle picture; SHG taken in the core of λ 5250 simultaneously with that in the left picture but with a polaroid placed with its axis of polarization perpendicular to the exit slit. Right picture: Cancelled transverse Zeeman photograph produced by placing a unity gamma contact print of the left picture in contact with the middle picture (June 29, 1967).*

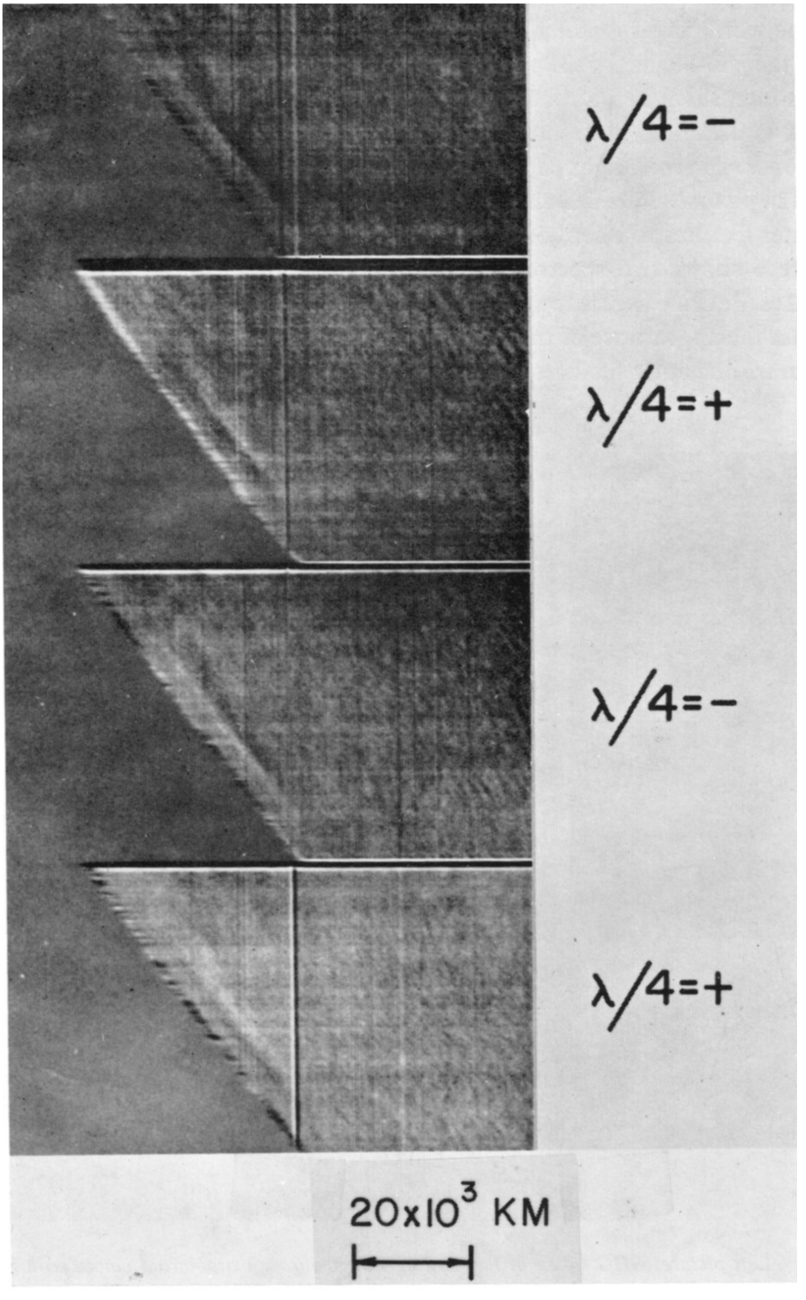

FIG. 7. *A sequence of doubly cancelled Zeeman photographs showing the magnetic field in a facula near the East limb of the Sun on July 20, 1967.*

cancelled picture on the right. We interpret this result as an indication both that the component of magnetic-field transverse to the line of sight is directed approximately along the radius of the sunspot and that if such a transverse field exists in the nearby plage its field strength is less than our detection threshold of approximately 300 gauss.

Figure 7 shows a sequence of Zeeman photographs in which the quarter-wave plate was alternately $+45°$ and $-45°$ from the entrance slit. An elongated feature appears very close to the Southeast solar limb corresponding to the location of a large facula observed on the white-light image. This feature is bipolar in the sense that in the upper picture the limbward side is lighter-than-average whereas the centerward side is darker-than-average. This polarization reverses with each reversal of the quarter-wave plate, as shown in the figure. Calibration and measurement of this Zeeman photograph revealed that the line-of-sight component of the field was in the 70–100 gauss range. The 'neutral line' occurs at 85° 32′ from disk center and the maximum field strengths occur at approximately 0° 26′ (centerward) and 0° 21′ (limbward) of this line. The range of angle over which the centerward side has detectable field is 1° 06′, whereas the range of angle over which the limbward side has detectable field is 0° 36′. These figures correspond to a feature which extends 13000 km centerward and 7300 km limbward, measured along the solar surface. The polarity of the side of the facula nearest the disk *center* is the same (negative) as the polarity of the *following* spots of this same Southern hemisphere. This bipolar effect has often been seen in large sunspots near the solar limb and has been interpreted as a manifestation of an inclination of the sunspot field from the vertical (Hale and Nicholson, 1938; Leighton, 1960). Often the sunspots observed have been the long-lived leading spots that are typical of the remnants of sunspot groups, and the polarities of the centerward sides of these bipolar features have the polarities that the spot assumes as it comes into view on the solar disk. In the case described here, there were no spots visible when the Zeeman photograph was obtained and none came subsequently into view. We interpret this then as a measure of an inclination from the vertical of the lines of force associated with faculae by enough to produce a tangential field of roughly 70–100 gauss. Since the components normal to the surface are generally in the range 200–500 gauss, we estimate a divergence of the lines of force with inclinations in the range 10–20° from the normal to the solar surface.

Figure 8 shows two pairs of uncancelled Zeeman photographs obtained in the violet wing of the Na D_1 (λ 5896) line. The first pair (upper row) has $\lambda/4 = +45°$ with respect to the entrance slit, and the second pair (lower row) has $\lambda/4 = -45°$ with respect to the slit. A doubly cancelled Zeeman photograph is included (twice) for comparison. These spectroheliograms were taken on May 3, 1967 during rather poor seeing, but in an active region where small flares and bombs were observed in a 1/4 Å bandpass Hα filter. The appearance of the region in the Hα filter looked considerably more like the doubly cancelled Zeeman picture than either of the uncancelled plates. There were filaments visible where the regions of opposite magnetic field are contigu-

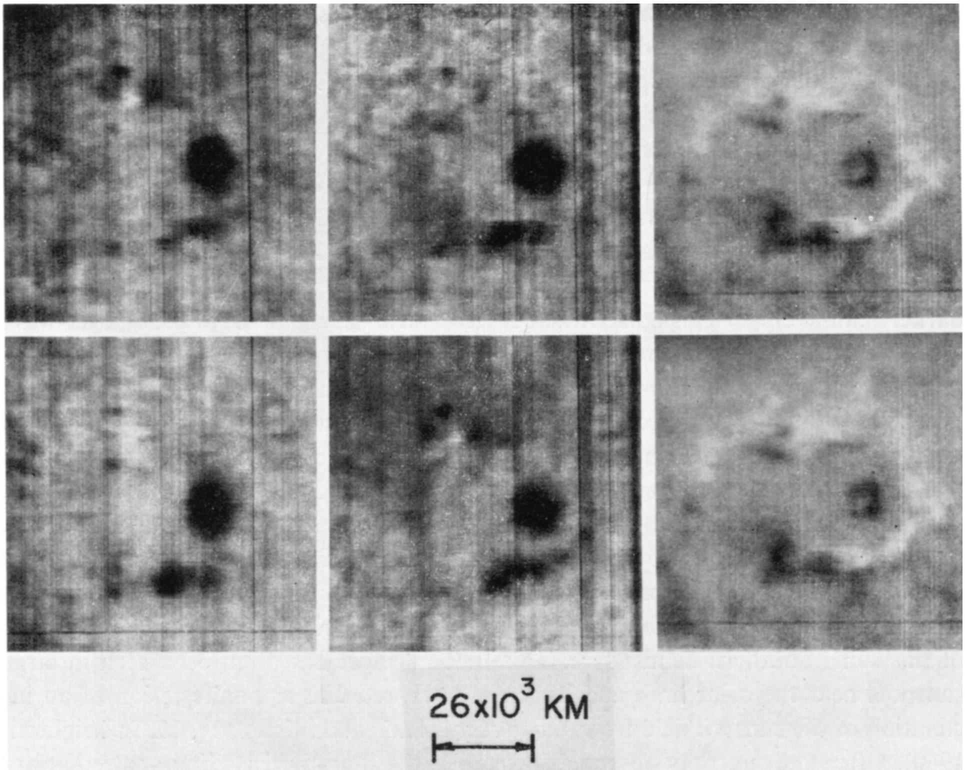

FIG. 8. *Upper left: SHG taken in the violet wing of Na D_1 with a quarter-wave plate in front of the entrance slit and a polaroid parallel to the exit slit. Upper center: SHG taken simultaneously with that of the upper left in the violet wing of Na D_1 with a quarter-wave plate in front of the entrance slit and a polaroid perpendicular to the exit slit. Lower left and center: Same as upper left and center, except the axis of the quarter-wave plate was changed from $+45°$ to the entrance slit to $-45°$ to the entrance slit. Right column: Doubly cancelled Z-photos made from the four other pictures (poor seeing on May 3, 1967).*

ous. We see a bright feature in the left picture of the first pair (upper row) and the right picture of the second pair (lower row). This bright feature is also visible as a 'black' magnetic field in the doubly cancelled Zeeman photograph. We think that this Na D_1 brightening corresponds to a flare or bright bomb, and thus suppose that such features occur *in* regions of longitudinal magnetic field that are contiguous to regions having longitudinal magnetic field of opposite sign, but not *between* regions having fields of opposite sign.

Another example of such bright features in Na D_1 is given in Figure 9, which compares a spectroheliogram in the core of Na D_1 with a spectroheliogram taken in the Ca^+ K line on the same day.

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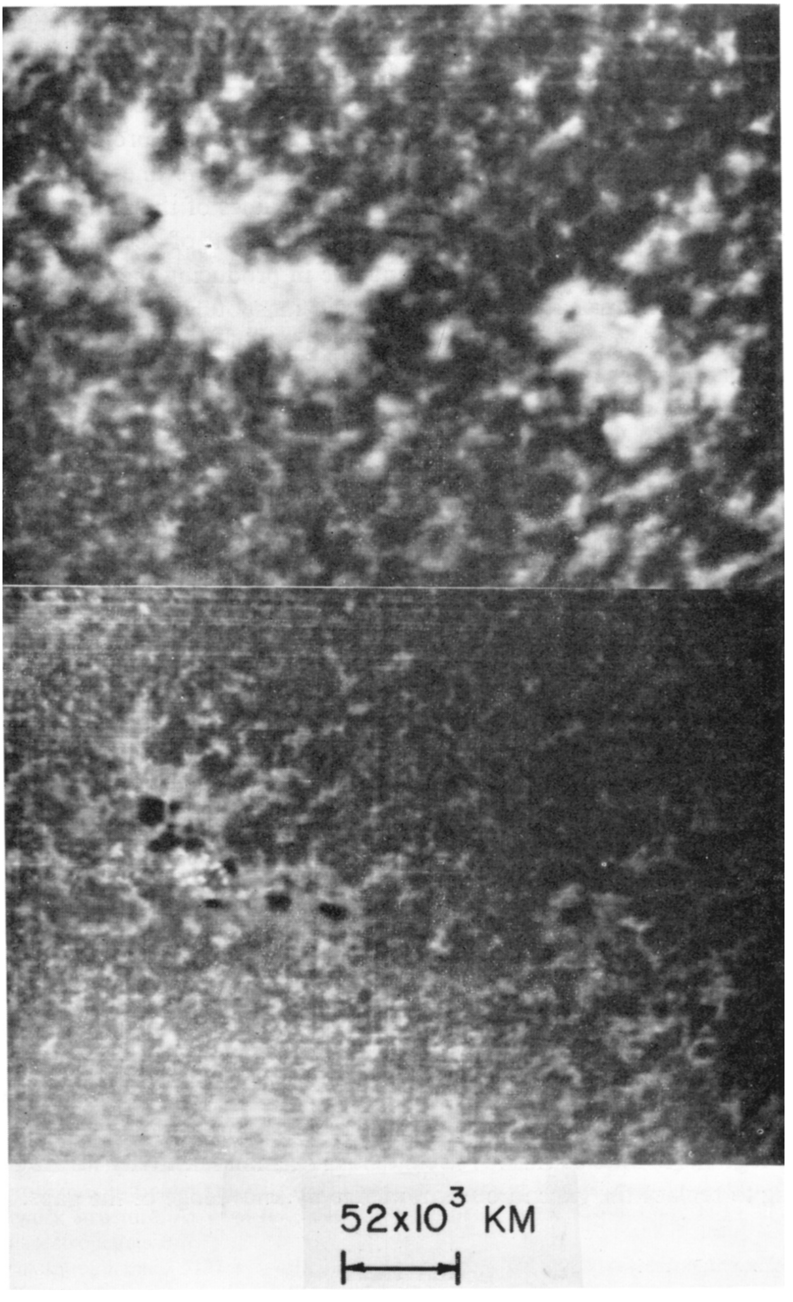

FIG. 9. *Upper: SHG taken in the core of the K line on January 30, 1967. Lower: SHG taken near the core of the Na* D_1 *(λ 5896) line the same day.*

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3. Summary

We summarize our preliminary results as follows:

(1) Although the photospheric network is visible on spectroheliograms in both Zeeman-sensitive and Zeeman-insensitive lines, it seems more pronounced on spectroheliograms taken in the cores of highly Zeeman-sensitive lines than on spectroheliograms taken in the cores of Zeeman-insensitive lines of the same strength. This suggests that the direct separation of magnetic components of Zeeman-sensitive lines by the magnetic field may play a significant role in producing the photospheric network. This is certainly true for the strong fields in sunspot penumbras where spectroheliograms in the cores of highly Zeeman-sensitive lines show 'bright penumbral rings' surrounding sunspot umbras while spectroheliograms in the cores of Zeeman-insensitive lines do not show such 'rings'.

(2) An attempt was made to see if the magnetic fields associated with the network deviate appreciably from the normal to the solar surface, first by photographically measuring the line-of-sight component near the solar limb, and second by photographically measuring the component transverse to the line of sight near the disk center. The measurements are consistent with a divergence of the lines of force from the network with inclinations of roughly 15° from the normal to the solar surface.

(3) Many bombs and flares that occur in Hα seem visible as corresponding brightenings on uncancelled Zeeman spectroheliograms made with the Na D_1 (λ 5896) line, and produce detectable line-of-sight components of magnetic field on the cancelled Zeeman spectroheliograms.

4. Conclusion

We have begun to extend our study of the line weakenings or gaps associated with magnetic fields from the one-dimensional aspect provided by spectrograms to the two-dimensional view provided by spectroheliograms. We can easily find regions on the solar surface where the Fraunhofer lines are weakened, but we still do not know what causes these weakenings. Our preliminary observations suggest that they are produced by a combination of line formation under the physical conditions accompanying magnetic fields and the direct separation of Zeeman components by these fields, the dominant mechanism depending on the strength of the line. By taking spectroheliograms in lines of various strength and Zeeman sensitivity we are presently attempting to replace the gaps in our knowledge by knowledge of the gaps.

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DISCUSSION

Bappu: Could you elaborate on the techniques used, image size, dispersion, method of Zeeman shift detection, etc.?

Sheeley: The Kitt Peak spectroheliograph is similar to the one at Mount Wilson except that there are two exit slits with a prism-type beamsplitter just ahead of them at Kitt Peak, whereas at Mount Wilson there is a beamsplitter just ahead of the entrance slit and only one exit slit. The Kitt Peak solar image is 82 cm and the dispersion used was about 0.8 Å/mm. The techniques used were essentially those used by Leighton at Mount Wilson.

Severny: In my opinion the described effect of the increase of intensity in the core of metallic lines associated with strong magnetic field is essentially the same as that investigated by Dr. Tsap of Crimean Observatory. Tsap found well-expressed correlation between the strength of magnetic force ($H_\parallel$ as well as $H_\perp$) and the contrast $\Delta J/J$ in the core of the line in the sense that $\Delta J/J$ increases with increasing H. (See *Publ. Crim. astrophys. Obs.*, **35** (1966), 161.)

Sheeley: If I were asked how the fluctuations in line intensity might depend on magnetic field I would suggest that for sufficiently small fields the relation would be

$$\frac{\Delta J}{J} \sim 2B_\parallel^2 + B_\perp^2,$$

and since we might expect $B_\parallel$ to be roughly 3 times $B_\perp$, the longitudinal component, $B_\parallel$, would be expected to have the dominant effect. This relation comes from an expression of the form $(1 + \cos^2\gamma)$ $(\Delta\lambda)^2$, and does not include possible effects of line saturation.

Krat: I should like to remind that at first time after the beginning of regular magnetographic observations many 'invisible' spots with the field strength about of several hundred gauss were discovered. But an exact comparison of the results of magnetic-field scanning with direct photographs of the active regions with good resolution showed that always these 'invisible' spots coincide with very small sunspots which were not noticed at the process of scanning. The direct photographs of the Sun at high resolution obtained by Dr. Schwarzschild and his colleagues show many small spots in the vicinity of the greater ones. Such small spots cannot be seen on the photographs or spectrograms taken at lower resolution. As preliminary results I may mention that on the photographs taken by the first Soviet stratospheric station show spotlike objects of great contrast being not greater as 0.″4 in size. The resolution on Dr. Sheeley's photographs does not enable us to make definite statement that the magnetic fields observed by him in the intergranular space do not belong to small sunspots.

Sheeley: I do not agree.

Kiepenheuer (Question to Dr. Krat): Are your small structures of 0.″4 diameter really spots, or are they just dark structures?

Krat: (did not answer this question).

G. W. Simon: In one of the slides you showed an intensity-network pattern which you said originated in the photosphere, although the structure appeared to resemble closely the well-known chromospheric network structure. At what height in the atmosphere is the line formed which you used to obtain this spectroheliogram?

Sheeley: Although the λ 5131 network occurs in roughly the same places on the solar surface where the K_{232} network occurs, the λ 5131 network has a more delicate or finer appearance than the K_{232} network. Although we do not really know where the λ 5131 line is formed, presumably it is well below the height at which the core of the K line is formed, and we interpret the finer structure of the λ 5131 network as a further indication of this.