# THE INTENSITY, VELOCITY, AND MAGNETIC STRUCTURE IN AND AROUND A SUNSPOT*

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ABSTRACT

An observational study of the fine structure in a sunspot region led to the following results: (a) The photosphere around a sunspot is covered with the so-called Magnetic Knots. These features have a diameter of 800 km and a magnetic field of up to 1400 gauss. Although they coincide with dark, intergranular spaces, they are distinctly different from pores. We estimate some 300 to surround the sunspot. The magnetic field of the smallest pores were found to be 1500 gauss. (b) For the Umbral Dots we find a lifetime of 25 min. Their colour, as derived from simultaneous observations at 4700 Å and 6400 Å, was found to be identical to that of the photosphere. Assuming their brightness to be photospheric we derive a diameter of 160 km.

## 1. Observations

With the setup shown in Figure 1 we observed a number of large, fairly symmetrical sunspots during their passage across the solar disc in order to make a detailed study of the intensity, velocity, and magnetic field structure in and around a sunspot. We used simultaneously the 40-cm coronagraph and the 30-cm coelostat telescopes of the Sacramento Peak Observatory. The observations obtained at the West bench consist of high dispersion, simultaneous spectra (7 mm/Å) of the Fe lines $\lambda$ 5576 ($g=0$) and $\lambda$ 6173 ($g=2{\cdot}5$) exposed 10 sec at a rate of 15 sec. The Zeeman-line spectra were obtained through a $\lambda/4$ plate and a Wollaston prism. Slit-jaw photographs exposed simultaneously with the spectra allow a very precise determination of the slit position with respect to the sunspot fine structures. We placed the slit in many different positions across the spot covering also extensively the region around the spot.

The coelostat telescope fed the East bench camera which – through the use of a dichroic mirror – allows the simultaneous photography of two spot images in either red and blue continuum radiation ($\lambda$ 6400 Å and $\lambda$ 4700 Å resp.) or in H$\alpha$ and blue light. The East bench observations made at a 5-sec rate cover sometimes 1 to $1\frac{1}{2}$ hours of intermittent good seeing. From these we are able to study both motions and changes of the spot fine structures. By comparison with the slit-jaw pictures we are moreover able to relate the fine structures visible in the spectra with details in the white-light images.

* Presented by J. M. Beckers.

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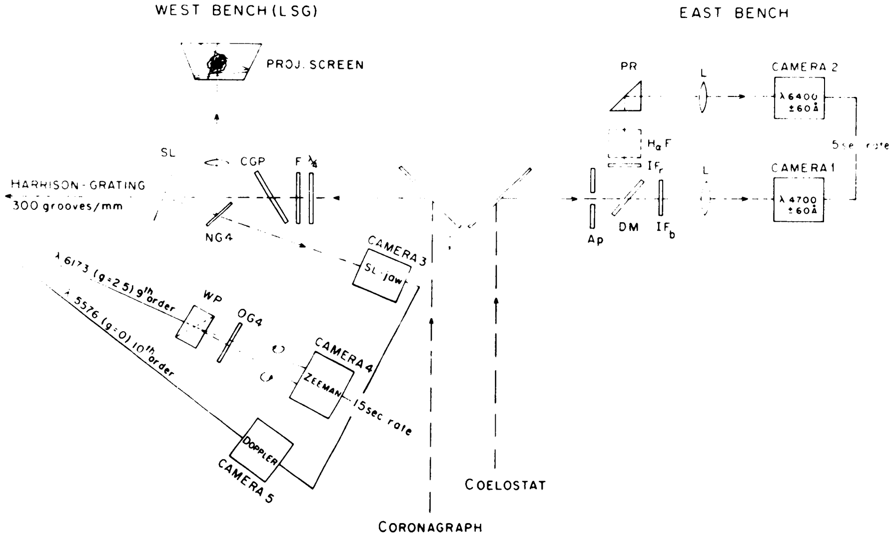


FIG. 1. *Diagram of the observational setup. – West bench: 40-cm coronograph with solar image 25 cm; LSG = Littrow spectrograph; F and OG 4 = colour filters; CGP = glass plate to correct for instrumental polarisation; SL = slit with reflecting jaws; NG 4 = neutral density filter; first surface is used to form an image of the solar region for visual monitoring; WP = Wollaston prism to separate the two opposite circular polarised spectra. – East bench: 30-cm coelostat with final solar image 25 cm; Ap = aperture defining the solar region to photograph; DM = dichroic mirror;* $IF_b$ *and* $IF_r$ *= blue and red interference filters; Hα F = Hα-Lyot filter with 0·5 Å bandwidth.*

A test of the performance of our photographic method for the magnetic field determination was made by investigation of the magnetic field in the quiescent photosphere. This showed the noise for our method to be 5 gauss r.m.s. for an effective scanning aperture of $(0{\cdot}8 \text{ sec of arc})^2$. A recording time of 10 sec is needed for 600 of these resolution elements. Comparison with the noise characteristics of the Babcock magnetograph shows the noise of the photographic method to be less by about 1 order of magnitude. It takes about 30 times less time to compile a magnetic and velocity map for an active region with the photographic method.

The spectra of the undisturbed photosphere give after correction for noise an r.m.s. magnetic field of 7·5 gauss. This r.m.s. magnetic field is mainly due to a number of isolated regions a few seconds of arc in diameter in which the magnetic field is of order of 50 gauss. We find no significant correlations between the magnetic field and either continuum brightness or velocity.

Figure 2 shows a high-resolution photograph of the sunspot which we selected for our study.

## 2. Magnetic Knots

In the vicinity of spots we detected many isolated points (< 1500 km) with strong

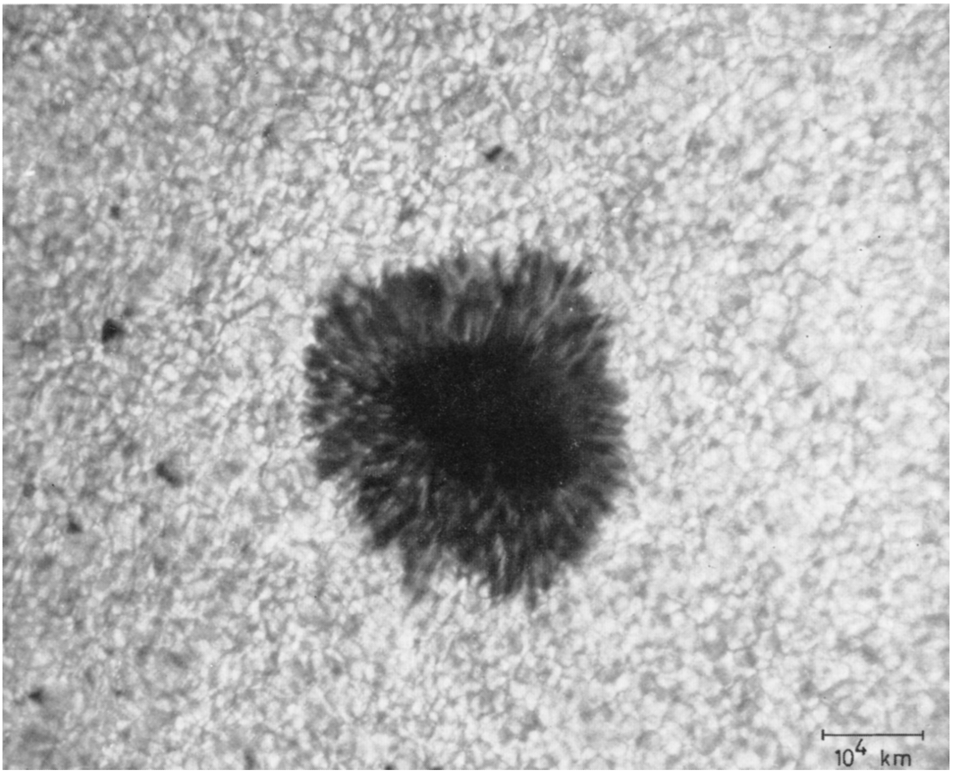


FIG. 2. *White-light photograph of the sunspot selected for the study: July 25th 1966, exposure time 15 milliseconds on Kodak High Contrast Copy emulsion, $\lambda = 4700 \pm 60$ Å.*

magnetic fields (see Figure 3). These 'magnetic knots' coincide with normal dark intergranular spaces and are clearly distinct from pores. They show a striking decrease in line depth; the equivalent width remaining unchanged.

An interpretation of the line profile measured in the magnetic knots in terms of the Stepanov-Unno theory (see Mattig, 1966) results in magnetic fields of about 1300 gauss. The inclination of the field with respect to the line of sight amounts to $\gamma \sim 75°$ when no correction is applied for light not originating in these magnetic knots. However, the inclination angle depends strongly on such a correction. Since the spatial resolution of our spectra is probably less than the actual size of the magnetic knots we expect the amount of this 'non-magnetic light' to be high. A vertical field ($\gamma = 0°$) in all magnetic knots is obtained for $\sim 60\%$ of the observed light to be blurred into the magnetic knots. This gives 800 km for the true diameter of the magnetic knots and 1400 gauss for the field.

The magnetic knots described here are probably identical to the so-called 'invisible sunspots' observed by Hale and Nicholson (1938), to the 'gaps' with apparent field

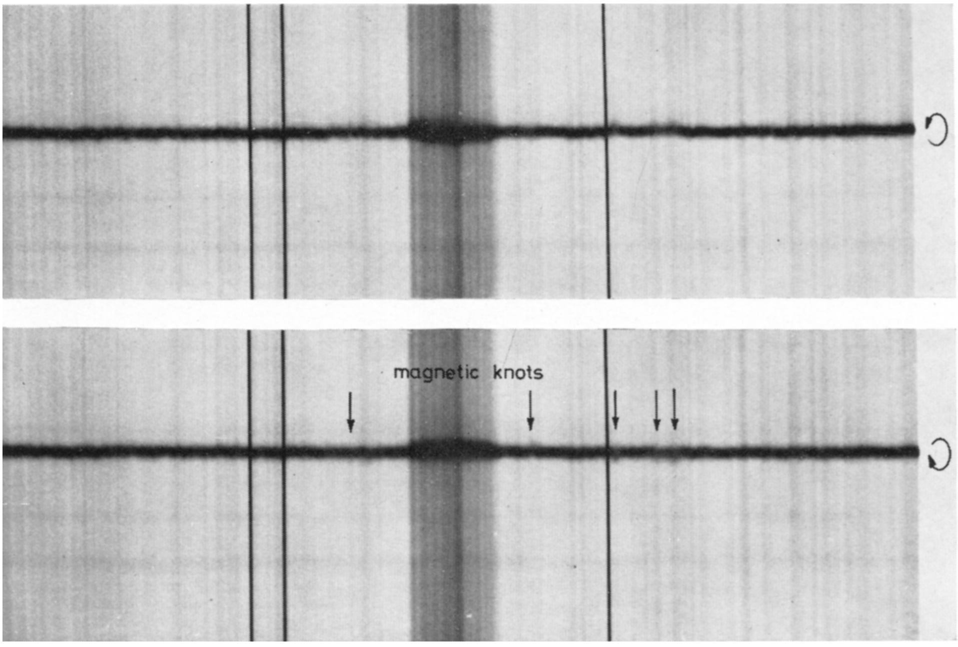


FIG. 3. *Clockwise and anticlockwise circular polarised spectra around the Fe line λ 6173 (Landé-factor 2.5 with the slit intersecting the penumbra. The arrows indicate a number of magnetic knots. Note: magnetic field produces a line shift of opposite direction, whereas Doppler effect gives a line shift of the same direction in both spectra.*

strength of 350 gauss observed by Sheeley (1967) and the 1000 gauss non-spot regions recently discussed by Steshenko (1967). We find the magnetic knots to have mainly a red shift in the non-magnetic line indicating a downward motion, and to be located in the Hα-plage regions. The non-magnetic line shows generally no weakening, confirming again that the change of the Zeeman line is of magnetic origin. The polarity of the knots varies at random, it can be both equal or opposite the spot polarity. We do not know yet the knot lifetime. We estimate our spot to be surrounded by 300 knots.

For some pores surrounding the spot we found a field strength of about 1500 gauss, so that about 1400 gauss appears to be the critical value for pore and spot formation.

## 3. Umbral Dots

We obtained some very good time sequences of umbral structures simultaneously at λ 6400 Å and λ 4700 Å covering $1\frac{1}{2}$ hours in time at a rate of one photograph per 5 sec. On these photographs (see Figure 4) the umbra shows isolated bright points (< 600 km). These umbral dots (called so by Danielson, 1964) form a pattern very

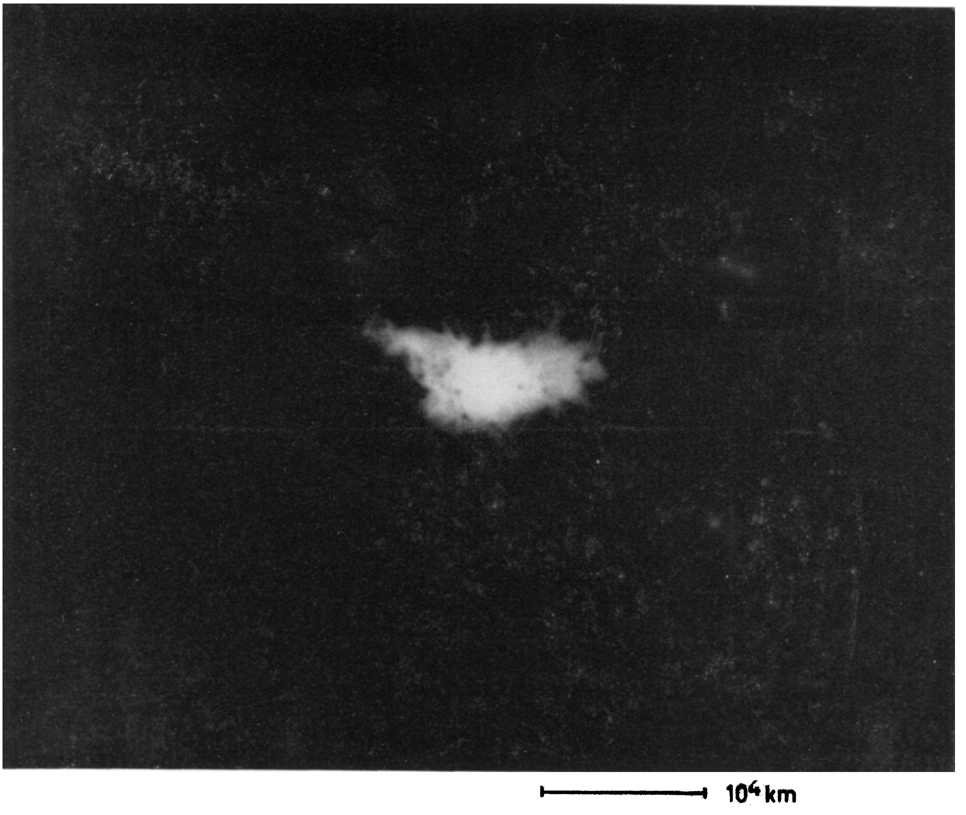


FIG. 4. *Photograph of umbral dots at 4700 Å; July 20th 1966; exposure time 50 milliseconds on Kodak HCC-emulsion. Average observed diameter of the dots: 500 km.*

different from the photospheric granulation; we therefore disagree with the term 'umbral granulation' as used by Bray and Loughhead (1964).

In the particular spot under study the umbral dots were all located in the outer parts of the umbra. It is not sure yet if this is the case for all spots of this type. We did observe a number of sunspot umbrae in which the umbral dots are suppressed in parts of the umbra. This area of the umbra was generally the darkest.

We have determined a lifetime of 25 min for the structures from a good time sequence $1\frac{1}{2}$ hours long. After 25 min no dots can be recognized except for statistical coincidences. This is a factor 2 smaller than that found by Bray and Loughhead (1964) for their umbral granulation. But it falls within the limits of 4 and 50 min given by Danielson (1964). We found the visibility curves of the individual dots to be asymmetrical in the sense that they show a faster increase to maximum brightness than the decrease thereafter.

For 10 umbral dots we measured an average diameter (halfwidth of the intensity peak) of 500 km, which is an upper limit for the true diameter of the features. The contrast with the umbral background is 44% at 4700 Å and 26% at 6400 Å, so that umbral dots are bluer than the umbra. The excess intensity expressed in terms of the photosphere is resp. 7·8% and 7·9%, meaning that the umbral dots have the same colour as the photosphere. In order to make the dot intensity equal to the photosphere intensity one would need a true diameter of 160 km. There is no way to separate the dot intensity of its diameter; we can give only limits. The true diameter lies between 160 km and 500 km, if one takes the photospheric brightness as the upper limit for the true dot intensity. No lower brightness limit can be given because we observed a number of dots with very low contrast.

We do not exclude the possibility that at least some of the umbral dots are of photospheric intensity and therefore 160 km in diameter since the blurring on our photographs could be as much as 500 km. In fact the white colour of the brighter dots is very suggestive for this possibility.

## 4. Magnetic- and Velocity-Field Measurements in a Sunspot

From each of the 9 days at which we observed the spot in Figure 2 we selected from ~600 spectra the best 15–17 spectra, covering the entire spot area and the surrounding photosphere. After a lengthy investigation we found that there was no satisfactory short cut for the reduction of the magnetic spectra without losing a significant amount of information. We therefore undertook a detailed photometric reduction of the line profile of $\lambda$ 6173 in each circular polarisation at each point along the slit (every 600 km on the Sun). This reduction is not yet completed.

Figure 5 shows a flow diagram of our reduction procedure.

First the line center is determined by the elimination of the Doppler shift. The Doppler shift is obtained by shifting a mirror image of the one spectrum over the other spectrum, until the maximum correlation between the two spectra is obtained. The difference curve (the intensity difference between spectrum 1 and spectrum 2) is then fitted by least squares with the difference of two functions $f$. These functions have the same shape as the photospheric profile but are displaced by an amount $\Delta$ (separation of the $\sigma$-components). The quantity $\Delta$ is approximately equal to the Zeeman splitting of the line. The amplitude $A$ of the function is determined by the field angle $\gamma$ (the relative strength of both $\sigma$-components). We used the Stepanov-Unno theory for line formation in magnetic field to calibrate the $\Delta$ and $A$ in terms of $H$ and $\gamma$ by fitting the difference of theoretical line profiles of $\lambda$ 6173 in the same way.

With the $H$-value found from the difference curve the profiles of the individual spectra are analysed. By least squares we find the amplitudes of the two $\sigma$- and the $\pi$-components. These in turn give a more precise value for the field direction.

Figure 6 gives the result of such a reduction for one of our spectra.

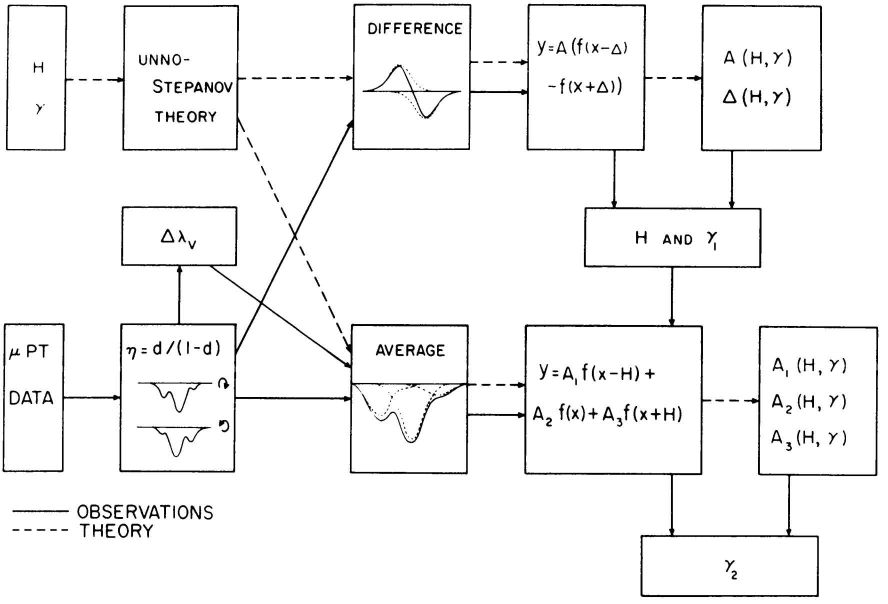


FIG. 5. *Flow diagram of the interpretation of the Zeeman-line profiles in terms of the Stepanov-Unno theory.*

It is our intention to make reductions like the one given in Figure 6 for all magnetic and velocity spectra we selected from this spot and which we have traced already. Our observational data are of sufficient quality to relate the magnetic and velocity field and its fluctuation to the penumbral intensity structures.

The detailed publications will be submitted to *Solar Physics*.

## Acknowledgements

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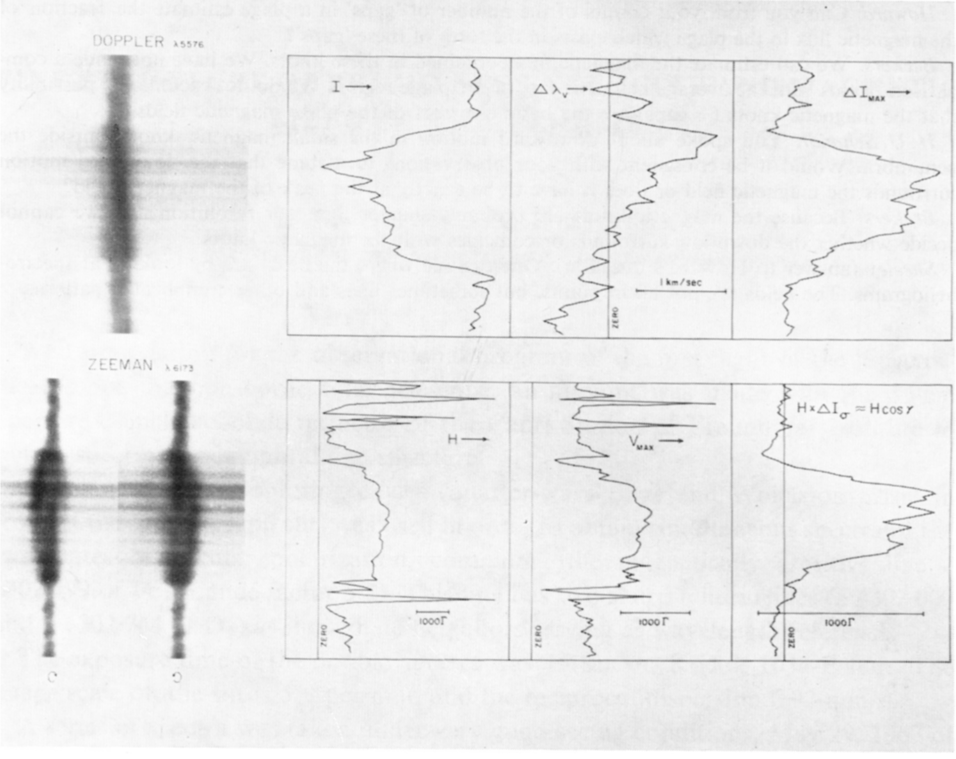


FIG. 6. *Reduction of a Zeeman and Doppler spectrum obtained on 25th July 1966 (spot near disc center). $I$ = continuum intensity across the slit; $\Delta\lambda_v$ = Doppler shifts across the slit (Evershed effect); $\Delta I_{\max}$ = the maximum amplitude of the difference curve (see Figure 5) across the slit ($\Delta I_{\max}$ is very close to $H \cos\gamma$): $H$ = magnetic field across the slit: for small Zeeman splitting or for transversal field the position of the σ-components becomes very unreliable. This results in the large noise of the H-values outside the penumbra. Note the local fluctuations of $I$, $\Delta\lambda_v$ and $H \cos\gamma$. At points where the last curve intersects the zero line ($H \times \Delta I_\sigma = 0$) we have transversal magnetic field. Looking for these points in spectra exposed at different disc positions of the spot, we obtain the field configuration free from any theoretical assumptions.*

## DISCUSSION

*Rösch:* About umbral dots (French: 'points maculaires'): I agree that they should not be called 'granules' because they differ in nature from the photospheric ones. As for the distribution of these dots, there are at least cases where the whole umbra is filled with bright dots with different average level of brightness in different parts of the umbra. Before deciding that no dots appear, one should be sure that the exposure time puts them in the high-contrast part of the emulsion-characteristic curve. And of course, the stray-light plays an important role.

*Beckers:* We have exposures of various densities of the umbra of the spot in discussion, some of these give the high-contrast part of the emulsion in the darkest part of the umbra. These do not show umbral dots in this part of the umbra. Scattered light would indeed diminish the contrast of the umbral dots, we took this into account.

*Howard:* Can you from your counts of the number of 'gaps' in a plage estimate the fraction of the magnetic flux in the plage which exists in the form of these 'gaps'?

*Beckers:* We can estimate the magnetic flux contained in these knots. We have not made a comparison of this with the average magnetic flux of the plage region. We do not exclude the possibility that the magnetic knots (= gaps) are the basic elements of the plage magnetic fields.

*H. U. Schmidt:* You spoke about downward motion in the small magnetic knots outside the penumbra. Would it be consistent with your observations to assume that the downward motion surrounds the magnetic field or does it have to be exactly at the peak of the magnetic field?

*Beckers:* Because the magnetic knots are probably smaller than our resolution disk we cannot decide whether the downflow surrounds or coincides with the magnetic knots.

*Sheeley* (answer to Howard's question): One can see where the fields are by looking at spectroheliograms. The fields are not all in points, but sometimes lines and other complicated patterns.