SESSION 1

STRUCTURE OF ACTIVE REGIONS

https://doi.org/10.1017/S0252921100028670 Published online by Cambridge University Press

The Magnetic and Velocity Fields of Solar Active Regions
ASP Conference Series, Vol. 46, 1993
Harold Zirin, Guoxiang Ai, and Haimin Wang (eds.)

SMALL-SCALE STRUCTURES IN ACTIVE REGIONS

CHRISTOPH U. KELLER
Institute of Astronomy, ETH-Zentrum, CH-8092 Zürich, Switzerland

ABSTRACT Within the last few years significant progress has been made in our understanding of the small-scale structures in active regions. Here I present some of the newest findings obtained by using speckle interferometric techniques. There exist continuum bright points with a contrast of about 30% that are cospatial with strong magnetic fields. The observations are consistent with the assumption that some facular and network bright points are the white-light signature of magnetic fluxtubes with a diameter of about 200 km. Magnetic elements larger than about 300 km are mainly darker than the average quiet sun. Their properties are similar to what has been called magnetic knots or invisible sunspots. In highly magnetic areas there is no clear relationship between continuum intensity and magnetogram signal at the smallest spatial scales. The magnetic field of pores extends beyond the dark umbra. There radially elongated structures may appear that are similar to penumbral filaments in sunspots.

INTRODUCTION

The magnetic flux outside of spots and pores is predominantly concentrated into tiny *magnetic elements* (Harvey and Livingston 1969) with 1–2 kG (Frazier and Stenflo 1972, Stenflo 1973). Recent very sensitive observations in the infrared directly confirm this result (Rabin 1992, Rüedi et al., 1992). The internal structure of magnetic elements has been explored by moderate spatial resolution Fourier Transform Spectrometer (FTS) data (see Stenflo 1989 and Solanki 1990 for recent reviews) while high spatial resolution filtergram movies revealed their relationship to intensity structures (Title et al., 1990, 1992). A few high resolution magnetograms have been recorded under excellent seeing conditions (e.g., Ramsey et al., 1977). These observations and estimates from indirect observations suggested that magnetic elements must be very small. Seeing has prevented the direct resolution of these elements because magnetic field measurements require long integration times. It has often been claimed that facular and network bright points (henceforth called continuum bright points) are the white-light signatures of magnetic elements (e.g., Mehltretter 1974, Muller 1983, Auffret and Muller 1991). However, no direct evidence for this claim did exist because magnetic field observations at a spatial resolution similar to the best white-light images could not be recorded with conventional techniques.

Solar speckle polarimetry (Keller and von der Lühe 1992a,b) has greatly improved the spatial resolution of magnetic field measurements. This novel method

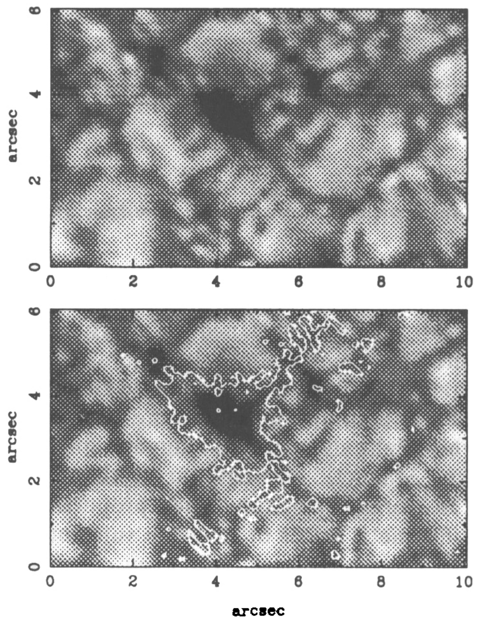

FIGURE I Both panels show the same small pore near disk center in the continuum. The contour lines of the Stokes V/I_c signal at 4% are overlaid on the lower panel. The magnetic field of the pore extends well beyond the dark umbra of the pore. The upper panel clearly shows penumbral filament like structures within the extended magnetic field

employs speckle interferometric techniques to deliver simultaneous, diffraction limited images of Stokes I, V, and the continuum intensity I_c. The technical details may be found in Keller and von der Lühe (1992b). The results shown in the following are based on observations recorded with the 50 cm Swedish Vacuum Solar Telescope at La Palma (Canary Islands), which has a diffraction limit of $0\farcs22$ at 5250 Å. The Zeiss tunable filter with a spectral resolution of 150 mÅ full width at half maximum (FWHM) was tuned to the blue wing of FeI 5250.2 Å. The continuum intensity is approximated by the light passed by an interference filter centered at 5200 Å with a FWHM of 82 Å. The noise in the reconstructed Stokes V/I_c images is about 1 %. First results have been reported by Keller (1992).

PORES

The difference between sunspots and pores is often defined by the absence of penumbrae in pores (Bray and Loughhead 1964). However, it has recently been suggested that the magnetic field of small pores extends beyond the dark umbra (Zirin and Wang 1992). All pores whose images have been reconstructed with solar speckle polarimetry show that the magnetic field covers an area larger than the umbra (see the lower panel of Figure I). In this surrounding magnetic field the pores often show radially elongated structures similar to penumbral filaments in sunspots (see the upper panel of Figure I). In the example shown in Figure I the length of these filaments is about $0\farcs5$ to $1''$, the separation between them is about $0\farcs3$ to $0\farcs5$, and the brightness of bright filaments is about 1.0–1.1 while that of the dark filaments is about 0.9–1.0 times the average quiet

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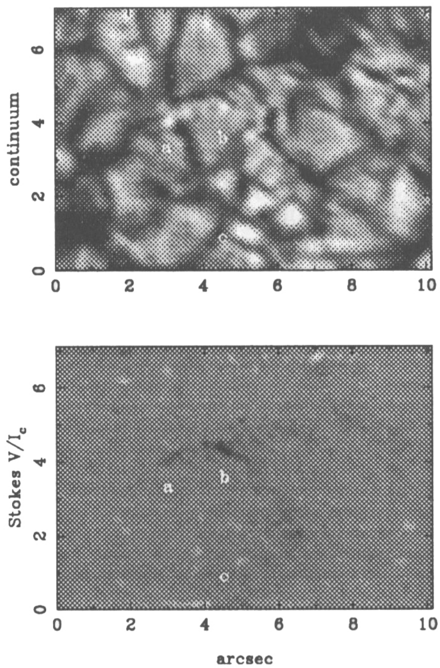

FIGURE II The continuum image (upper panel) and the magnetogram (lower panel) of solar magnetic elements in quiet granulation near a weak plage. In the magnetogram grey corresponds to zero signal while black and white correspond to opposite polarities. Above the points labeled "a" and "b" small magnetic elements can be seen that are associated with concentrated magnetic fields. To the right of "c" there are small, very bright granules that are not associated with a magnetogram signal

sun brightness. Some pores show penumbrae that are generally darker than the quiet sun.

MAGNETIC ELEMENTS

Figure II shows continuum bright points in the quiet granulation near a weak plage. The daisy-like granules surrounding point "a" are typical for network bright points (Muller et al., 1989). The continuum contrast (relative deviation from the average intensity) is 34%. Bright points also appear along granule borders (above "b" in Figure II). These points coincide with a concentrated magnetogram signal of up to 4%. Since these magnetic elements are probably not yet resolved the continuum contrast given above is only a lower limit. Near magnetic areas there sometimes exist small granules with a diameter of 400–600 km and a large continuum contrast of up to 40% that have no associated magnetogram signal (e.g., the granules to the right of "c" in Figure II).

A nearly resolved magnetic fluxtube in a plage can be seen in Figure III (element "d"). The maximum Stokes V/I_c signal there is 8% and the continuum contrast is 30%. An empirical plage fluxtube model with 2360 G at $\tau_{5000} = 1$ (Keller et al., 1990) exhibits a maximum Stokes V/I_c signal of 10% when the simulated Stokes V profile is convolved with the measured tunable filter profile. Therefore the magnetic field structure is almost spatially resolved. The FWHM is about 200 km in the magnetogram and the continuum image when taking into account the local background signal (see Figure IV). Although the magnetic

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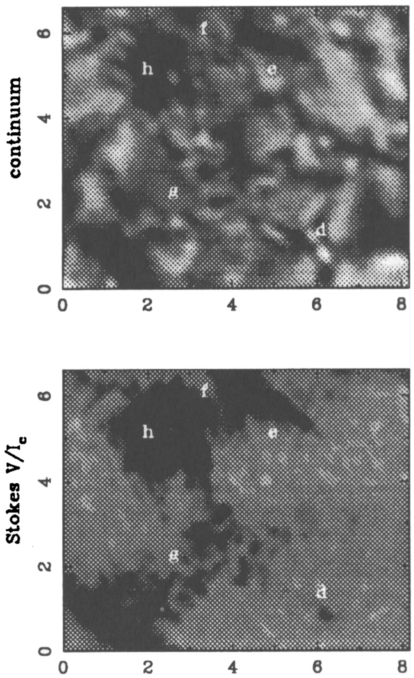

FIGURE III The same as Figure II in a pore region. The grey scale of the magnetogram is different from Figure II to account for the larger magnetogram signals here. Within the pores the signal to noise ratio is too small to give reliable results in the magnetograms. The bright point labeled "d" is an almost fully resolved fluxtube with a FWHM of about 200 km

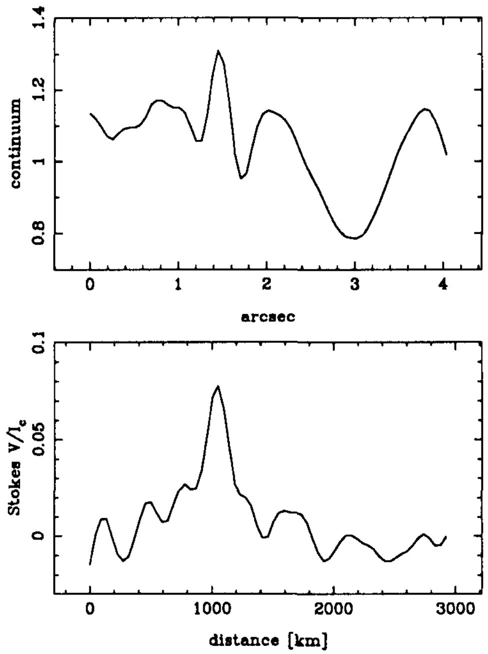

FIGURE IV A cut through the magnetic fluxtube "d" in Figure III. The upper panel shows the continuum brightness where 1.0 corresponds to the average brightness. The lower panel shows the Stokes V/I_c signal. Scales are given both in arcseconds and km. The strong magnetic signal is cospatial with the brightness enhancement.

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structure is nearly resolved, the continuum structure might still be well below the resolution limit and the true continuum contrast might be larger than 30%. The magnetic flux is about 6×10^{17} Mx. The lifetime of the concentrated state is probably shorter than 16 min. We do not know what happened to the magnetic flux since the magnetogram signal is hardly above the noise level 8 minutes before and after Figure III has been recorded.

There also exist non-bright magnetic elements. Point "e" is a large dark element whose brightness is about 0.7 times the quiet sun brightness. It probably is a magnetic knot (Beckers and Schröter 1968). Elements larger than about 300 km in at least one dimension seem to be darker than the average quiet sun. The highly magnetic areas around point "f" and to the right of "g" do not show a clear relationship between brightness and magnetogram signal (see also Title et al., 1992). The pore "h" has an umbral dot, which has average quiet sun brightness, and shows some penumbral structures on the left side.

It might well be that not all continuum bright points show a magnetogram signal. Figure V has been extracted from the penumbra movie of Frank et al. (1991). These images have not been reconstructed with speckle imaging, but they have been recorded during spectacular seeing conditions through the Zeiss filter in the FeI line at 5250.2 Å. A bright point without significant cospatial magnetogram signal can be seen in an area of 4 by 4 arcseconds during a period of 20 min. The penumbra of a major sunspot in the mature bipolar active region NOAA 6337 (heliocentric distance 24°) is just to the left of the field of view. The point is moving out of the active region. The sensitivity in the magnetograms is about 1×10^{16} Mx per $0''.2$ by $0''.2$ area element. The lifetime of the bright point is longer than 20 min and the horizontal velocity is about 1–1.5 km sec^{-1}. This fast moving point resembles the moving phase of network bright points described by Choudhuri et al. (1992).

DISCUSSION

Speckle polarimetry shows active region magnetic fields at a spatial resolution that can hardly be achieved with conventional techniques. The most important finding due to this new method is the direct resolution of magnetic fluxtubes (Keller 1992). It has been shown that there exist bright points with cospatial strong magnetic fields. The observed characteristics of these magnetic elements are compatible with values predicted by indirect observations (Solanki 1990) and theoretical models (Schüssler 1990) of fluxtubes. There is a distribution of sizes that extends from small bright to larger dark features (see also Spruit and Zwaan 1981, Knölker and Schüssler 1988, Title et al., 1992, Topka et al., 1992). The transition from bright to dark elements occurs at an extension of about 300 km in at least one dimension. Theoretical models estimated that the transition occurs at about 500 km (Knölker and Schüssler 1988). The properties of larger, dark elements are similar to magnetic knots (Beckers and Schröter 1968) and micropores (Zirin and Wang 1992). In strongly magnetic regions most flux is in the form of non-bright elements (Title et al., 1992, Topka et al., 1992). This has also been confirmed by a recent analysis of FTS data (Solanki and Brigljević 1992). In weakly magnetic regions most flux is probably in the form of bright points.

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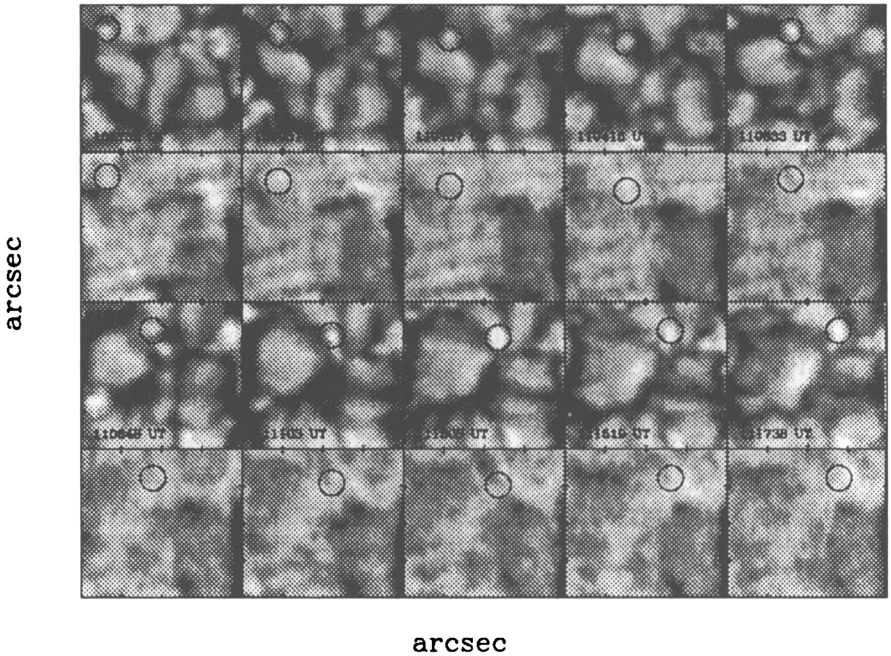

FIGURE V A time series of simultaneous Stokes I and V/I images of a 4″ by 4″ field just outside of a penumbra, which is to the left of the field of view. The time increases from the top left to the bottom right and the interval between consecutive images is two minutes. The first and the third rows show Stokes I while the second and the fourth rows show Stokes V/I. The first few magnetograms show signs of remaining fringes. The circle surrounds the position of a moving bright point. Although magnetic fields are found in many places no significant magnetogram signal can be detected that is cospatial with the bright point

From the data analyzed so far it seems that circular elements with diameters of 0.″4–0.″6 are relatively rare. This corresponds to a range of magnetic fluxes where theoretical arguments indicate that fluxtubes are not stable (Schüssler 1984, Bünte et al., 1992). Therefore observers should closely look at this scale for resolved elements with diameters of about 0.″5.

Magnetic fluxtubes might evolve significantly within 15 minutes, similar to the time scale associated with bright points (e.g., Dunn and Zirker 1973, Muller 1983). Evolution on this time scale has also been seen by Title et al. (1990), although their observations indicate that the magnetic flux appears and disappears on a much longer time scale.

The fast moving bright point without significant magnetogram signal is a puzzle. Its long lifetime, size, and brightness suggest that it is not just a bright granule fragment, but an entity that moves through the granulation. If

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it is associated with concentrated magnetic fields, the corresponding fluxtube must be strongly inclined, which would result in a very weak Stokes V/I signal. However, since the point is moving away from the bipolar region we do not know a particular reason for a strong inclination. We might expect this near the neutral line between the polarities, but the region shown in Figure V is far away from the neutral line. Nevertheless it is worthwhile mentioning that the point appears in a region of opposite polarities that are mixed on a small scale.

Pores do not show a significant morphological difference with respect to small sunspots. It has been shown that pores have magnetic fields extending beyond the dark umbra and penumbral filaments often appear there. The magnetic signal outside of the umbra cannot be explained by a lower spatial resolution in the simultaneous magnetograms or by the higher formation of the magnetogram signal with respect to the level of continuum formation. Since pores have less flux than sunspots the spreading of the field lines is not so fast and therefore the fields are more vertical. The existence of a penumbra around pores might give important hints for theoretical studies of penumbrae. In particular it renders superfluous a critical flux value for the formation of a penumbra (e.g. Schmidt et al., 1986). Finally I caution that statistical work in plages that include pores need to be performed very carefully. Removing the contribution of pores to statistical estimates by an intensity threshold may bias the result due to the extended magnetic fields of pores in non-dark form.

The results presented here are based on a limited number of examples. To obtain statistically relevant results much more data need to be collected and analyzed. Now that the diffraction limit of a 50 cm telescope can be reached even in narrow spectral bands that include polarimetric optics, the need for a large, polarization free telescope at a good site grows stronger and stronger: we urgently need LEST, the Large Earth-based Solar Telescope (Engvold and Andersen 1990) to obtain a sound understanding of the small-scale structures in active regions.

ACKNOWLEDGMENTS

I thank G. Ai and H. Zirin for inviting me to give this talk, G.B. Scharmer for his collaboration during the observations, J.H. Thomas and M. Bünte for helpful discussions on penumbrae around pores, and J.O. Stenflo for continuous support. This work is supported by the Swiss National Science Foundation.

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