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HIGH RESOLUTION MAGNETIC FIELD MEASUREMENTS IN THE SUNSPOT PHOTOSPHERE

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ABSTRACT We analysed calibrated Stokes V magnetograms and simultaneously measured Stokes I spectra of high spatial and spectral resolution taken in a medium sized sunspot. We found a clear (anti-) correlation between the brightness variation of penumbral structures and the longitudinal component ($B^*\cos\gamma$) of the magnetic field. No azimuthal variation of the amount of the magnetic field strength (B) was observed across dark and bright structures. There the field is more vertical in bright filaments compared to dark ones.

INTRODUCTION

Sunspots are the oldest known features of solar activity and a lot of models has been developed to explain the observed size and intensity and their relation to the magnetic and velocity field structure. Today we know a great variety of fine structures like umbral dots, penumbral filaments with the non-steady outflow (Evershed flow) and the inward motion of bright points (grains), and irregular wave motions and oszillations. In recent years the explaination of fine structures and their dynamics rose to great importance for the understanding of the physics of sunspots.

At present there are three partly contending theoretical penumbral models which could explain the structure of magnetic field and Evershed motion: the convective roll model (Danielson 1961), the model of floating filaments (Spruit 1981 and Schmidt et al. 1986) and the model of elevated dark filaments (Moore 1981, Thomas 1981). No clear discrimination between these models was found by observation of penumbral fine structures. The main reason consists in difficulties to obtain high resolution magnetic field measurements which are very sensitive to telescopic and atmospheric influences so that they require a very difficult and complex data analysis and interpretation. In recent years a lot of effort has been made to obtain such observations and some interesting results concerning the relation between inhomogeneities of circular polarization and penumbral brightness fluctuations was found by Lites and Skumanich 1990, Lites et al. 1990, Degenhardt and Wiehr 1991, Title et al. 1992, and Keller et al. 1992.

In this paper we present some results of the analysis of simultaneously taken two-dimensional Stokes-V-filtergrams and Stokes-I-spectra of high spatial and spectral resolution. The problem we adress here is the correlation between the brightness of penumbral filaments and the observed circular polarization.

OBSERVATIONS

The observations were made at the Vacuum Tower Telescope on Tenerife on June 19, 1991. The target was a simple medium-sized spot in AR 6681 located at 25° outside disc centre.

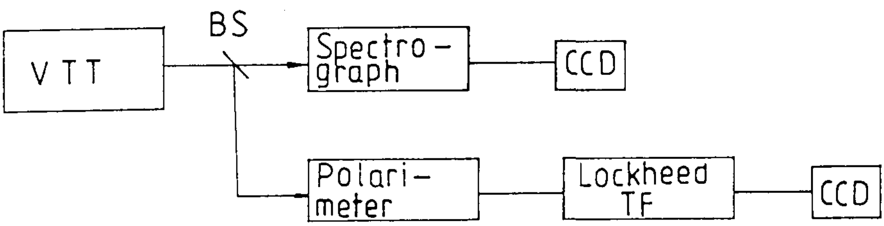

Fig. 1. Basic design of the observational instrumentation.

The basic design of the instrumentation is shown in Figure 1. Following we list the main parameters :

VTT	: 70 cm Vacuum Tower Telescope(Tenerife)
BS	: beam splitter
Polarimeter	: achromatic quarter-wave plate followed by a polarizing beam splitter (two crossed calcites)

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Lockheed TF	: tunable filter, FMWH=72mÅ, Fe I line 6302,5 Å Filtergrams were taken at ± (0, 30, 60, 90, 120, 150, 180, 210) mÅ distance from the centre of the Fe line
CCD (filter)	: 1024*1024 pixel, 2*2 summing mode, spatial resolution 0.25 arcsec, field of view 45*128 arcsec
spectrograph	: Fe I line 6302,5 Å Ti I line 6303,8 Å spatial scanning over 15 positions (area of 4.5*90 arcsec)
CCD (spectr.)	:1024*1024 pixel, 2*2 summing mode, spatial resolution 0.19 arcsec, spectral resolution 4 m Å

We observed during good seeing conditions and the best data sets achieved a spatial resolution of about 0.4 arcsec.

DATA ANALYSIS

Spectra

Magnetic field strengths were derived by fitting synthetic I profiles to the measured ones. Larger fields (>1800G) were determined directly by measuring the Zeeman splitting of the components of the Fe line. The simulation of the I profiles is based on different models to describe the temperature-height distribution (umbra: Kollatschny et al. 1980, penumbra: Ding and Fang 1989, photosphere: Vernazza et al. 1977 and Holweger and Müller 1974) and assuming constant values for all atomic parameters and the micro- and macroscopic velocity distributions.

Filtergrams

The polarimeter produces two parallel output images with a polarization oriented at 45° with respect to the grating grooves thus avoiding a brightness difference of the two oppositely polarized images. The beams correspond to Stokes I+V and I-V. Their simultaneity avoids a generation of artifical polarisation signals due to varying seeing. The optical paths are different for the I+V and I-V images in the polarimeter and camera so that small distortions have to taken into consideration. Such residual distortions were corrected by a cross correlation technique using additionally observed unpolarized continuum images.

We measured the Müller matrix of the whole instrument with a total polarizer and a quarter-wave plate in front of the first coelostat mirror. The I- and V-related elements of the matrix were used to correct the filtergrams for instrumental polarization. The corrected Stokes V/I filtergrams were transformed into magnetograms using calibrational functions calculated by the

Potsdam computer code (Staude and Hofmann 1988). The calibrational functions include separate empirical model atmospheres for the umbra and the photosphere.

RESULTS

In Figure 2 we show limb-side(bottom) parts of the sunspot observed and the adjointing photosphere. The upper panel displays Stokes I while the bottom

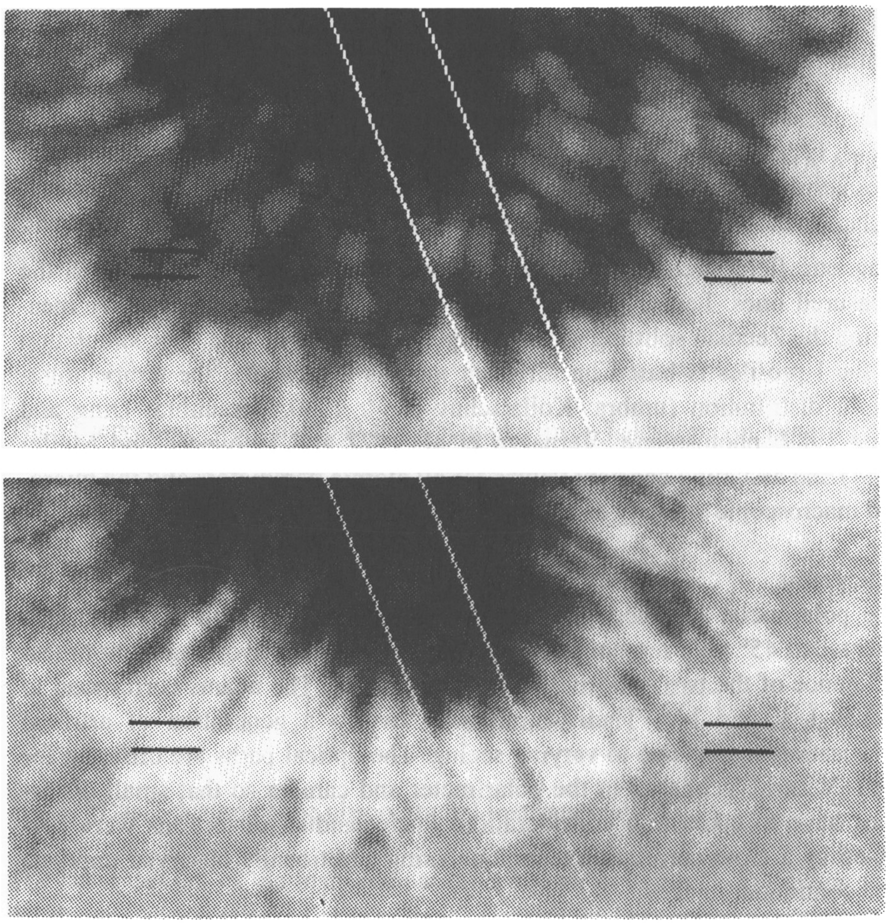

Fig. 2. Part of the spot. Upper panel: Stokes I, bottom panel: longitudinal magnetic field. The bright lines mark the scan raster of the spectrograph slit. The black horizontal lines mark the end segments of the traces for the profiles of Figure 3.

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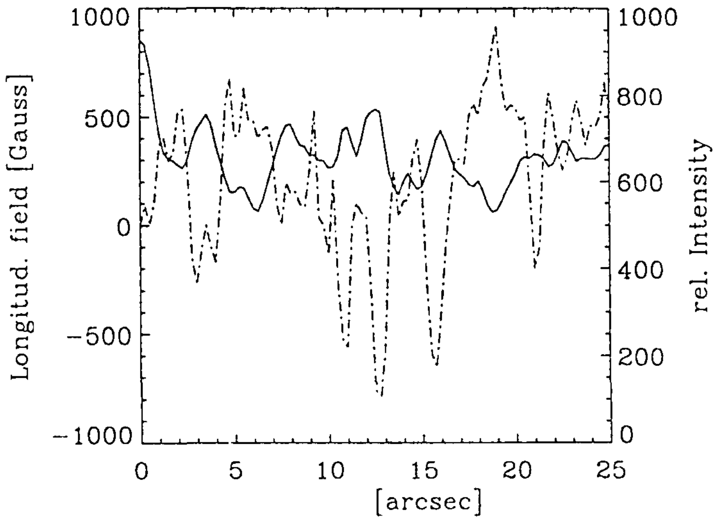
one displays the corresponding longitudinal magnetogram (B*cosγ) derived from the filtergrams taken at 120 mÅ outside line center. The dark areas indicate low(negative) intensities(field strengths) and vice versa. The small-scale filamentary structures seen in the magnetogram, too, demonstrate the high spatial resolution. At the outer, limb-side penumbral region the field reverses sign due to projection effects. The radial location of the field reversals changes on the scale of the magnetic fibrils.



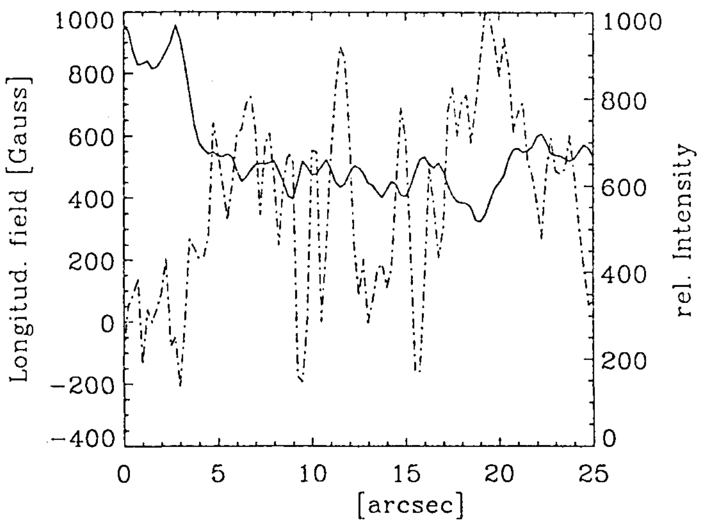


Fig. 3. Profiles of intensity(solid) and longitudinal magnetic field(dash-dotted) through penumbra, taken at increasing distance from spot center (cf. Figure 2).

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Figure 3 displays profiles of intensity and longitudinal field component along the black indicatet traces in Figure 2. We note a clear anti-correlation between the magnetic and intensity signal. The sunspot is of negative (southern) polarity, so that the bright structures are related to more negative (i.e. stronger) longitudinal field and vice versa. The profiles were taken just at that location were the field reversal is observed. With increasing distance from spot centre the field reversal occurs first in the dark elements (upper profiles). There the bright features still show umbral polarity (we regard the central part of the profiles where we are looking parallel to the filaments). More outward (bottom profiles) the field reversal has taken place almost everywhere. This behaviour reflects different inclination angles of the magnetic field in dark and bright structures.

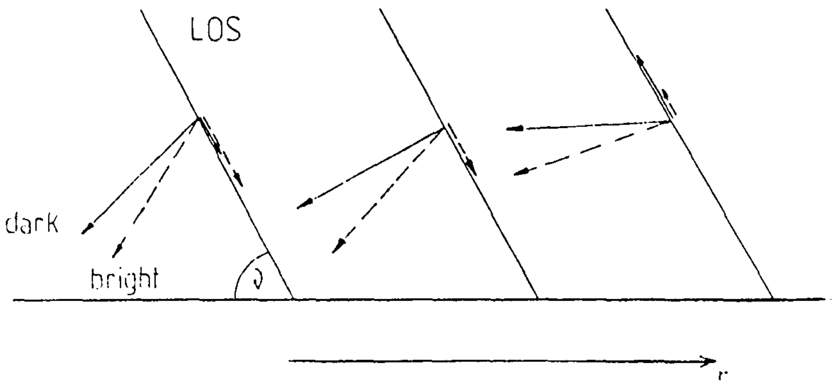

Fig. 4. Schematic sketch of field geometry, demonstrating the effect of different inclination of the magnetic field in bright and dark penumbral structures. r = distance from spot centre, LOS = line of sight, ϑ = angle between the LOS and the surface.

Figure 4 shows some schematic sketches to demonstrate this result. Before the field reversals occur (left sketch) the more horizontal field of the dark filaments leads to a smaller longitudinal component than the more vertical field in bright structures. Because of a steady drop in inclination angle of the magnetic field toward the outer penumbra the field reversal firstly occurs in the dark filaments (middle sketch). More outward, after the field reversal in the stronger inclined bright features the longitudinal field is now stronger in the dark structures (right sketch and bottom of Figure 3).
The raster of the spectra (cf. Figure 2) covers that part of the penumbra where the field reversal was observed in the magnetograms and shown in Figure 3. Figure 5 displays the magnetic field strengths (B) derived from the spectra and the cospatial magnetographic measured line of sight components

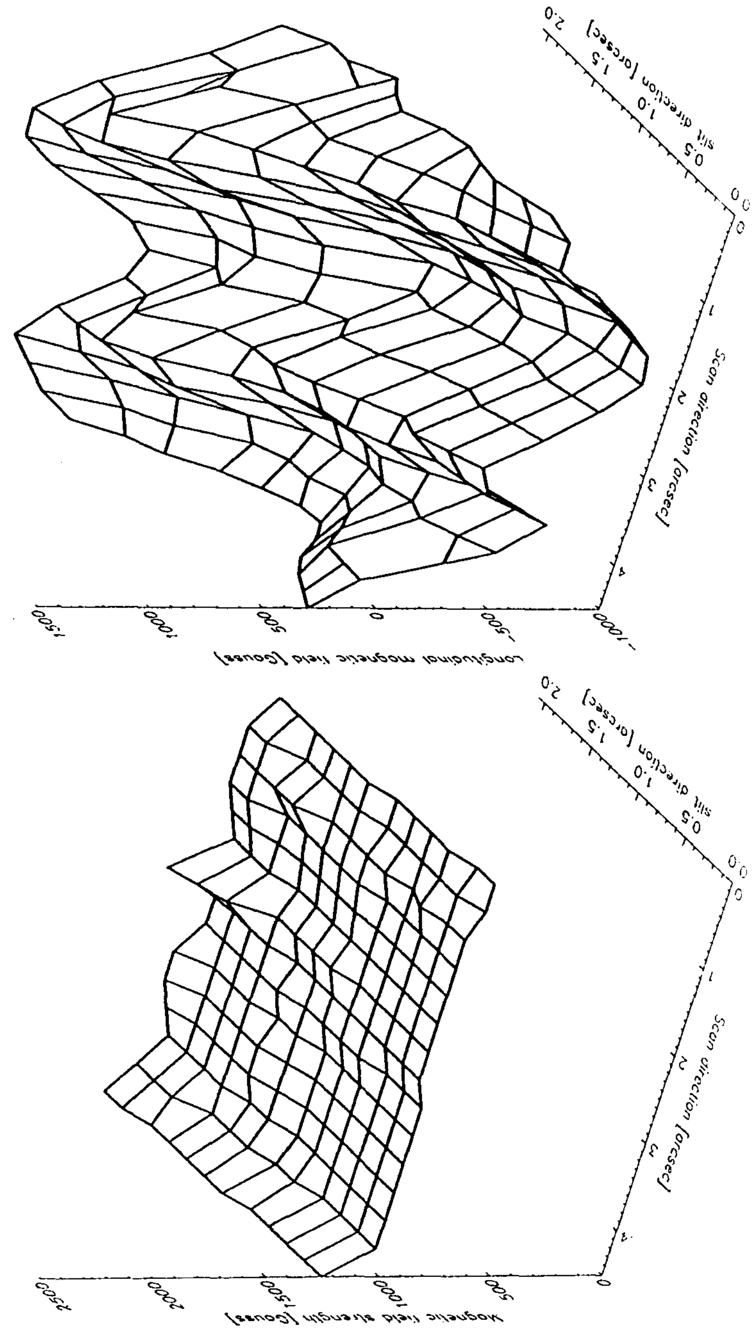

Fig. 5. Magnetic field strength (left) and longitudinal field (B*cosγ) in the penumbral region where field reversals take place. View is toward the umbra.

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(B*cosγ) in this region. The comparison demonstrates that the azimuthal variation of the field inclination is indeed the reason for the fluctuations of the magnetogram values.

SUMMARY AND CONCLUSIONS

We have presented some results of a high spatial as well as high spectral resolution polarimetry campaign at the Vacuum Tower Telescope on Tenerife in June 1991. We analysed Stokes I spectra and calibrated longitudinal field magnetograms. Main results are:
(i) the clear correlation between the longitudinal component of the magnetic field and the brightness variation of penumbral structures
(ii) no azimuthal variation of the magnetic field strength across dark and bright structures
(iii) a more vertical field in brighter penumbral filaments compared to darker ones.
Such a spatially varying field inclination has been supposed by different authors (Beckers and Schröter 1969, Lites et al. 1990, Degenhardt and Wiehr 1991, Keller et al. 1992, and Title et al. 1992) as one of different possible explainations, as indirect result of a more integral analysis, or without a clear correlation to the brightness fluctuation, respectively. The high spatial and spectral resolution of our simultaneous measured spectra and filtergrams enables us directly to prove a well defined relationship between the brightness of penumbral structure and their field inclination on the scale of penumbral fibrils. This picture of a spatially varying magnetic field inclination favours the model of floating filaments.

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