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Photospheric structure of an extended penumbra(*)

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Summary. — The photospheric structure of an extended penumbra belonging to a complex spot observed near disk center is investigated by means of the inversion of the full Stokes vector of two Fe I lines at 1.56 μm. An attempt is made to classify the observed Stokes V profiles in terms of their shapes. It turns out that about 28% of the profiles have abnormal shapes indicative of two different magnetic-field components within the resolution element. The spatial distribution of abnormal Stokes V profiles is studied. It is found that such profiles are evenly distributed in the penumbra, without any particular tendency to concentrate near the so-called neutral line. Anomalous profiles are not only seen in the outer penumbra and beyond, but also in the middle part of it. A Milne-Eddington–like inversion is carried out first, revealing a smooth picture of the spatial distribution of magnetic-field vector and velocities along the line of sight. In particular, dark spines with stronger and more vertical magnetic fields are seen to coexist with nearly horizontal magnetic fields throughout the penumbra. A full inversion allowing for gradients of the atmospheric parameters along the line of sight indicates the existence of cool magnetic tubes returning back to the solar surface (inclination angles greater than 90°) and carrying the largest material flows.

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1. – Introduction

High spatial resolution observations invariably reveal the filamentary structure of sunspot penumbrae. Recent theoretical models incorporate this structuring in terms of penumbral flux tubes. Schlichenmaier *et al.* [1] have shown that the interchange convection model is able to account for many observed features of the penumbra, including bright points moving inwards and channeling very large outflows. Using a completely

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different approach, Montesinos and Thomas [2] have worked out the siphon flow model to explain the existence of Evershed flows.

The nature of penumbral fibrils is important for understanding many processes including mass motions and convective energy transport in sunspots. Unfortunately, our knowledge of the real structure of penumbrae is still limited. New observations can help distinguish among the different scenarios proposed. Solanki and Montavon [3] suggested that the penumbral magnetic field is structured into horizontal flux tubes embedded in a more vertical background field. Recent observational work appear to confirm the validity of this model, while providing additional detail [4-8].

The aim of the present work is to determine whether the *whole* penumbra can be described in terms of uncombed fields and, if so, investigate the properties of the various penumbral components. There is an urgent need to resolve this problem, as previous investigations did not attempt to infer the structure of the penumbra as a whole. To this end, we carry out inversions of polarization line profiles in the near infrared in order to distinguish different magnetic components and probe deep atmospheric layers.

2. – Observations and analysis technique

NOAA 9097 active region was observed at disk center ($\mu = 0.99$) on July 25, 2000 with the German VTT at Observatorio del Teide (Tenerife, Spain). The Tenerife Infrared Polarimeter and the IAC/KIS correlation tracker were used for measuring the four Stokes parameters of the two Fe I lines at 1.56 μm. A spatial map of the active region was obtained by scanning the spectrograph slit. Integration time was 5.4 s, the pixel size being 0.4×0.4 arcsec. The spatial resolution of the observations is about 1 arcsec. Details of the experimental set-up and reduction of the data can be found in Bellot Rubio *et al.* [9]. An image of the active region obtained by integrating the Stokes I profiles over wavelength is presented in fig. 1. The penumbra enclosed by the rectangular box in the lower right part of the figure is the region selected for analysis.

Investigating the structure of the penumbra requires determination of the full thermodynamical state of the plasma. This implies the inference of atmospheric parameters along the line of sight (LOS). A reliable method to obtain such information is the inversion of the full Stokes vector, whereby synthetic profiles are fitted to observed ones. In this investigation we use the SIR (Stokes Inversion based on Response functions) code developed by Ruiz Cobo and del Toro Iniesta [10].

3. – Milne-Eddington–like inversion

We have subject the observations to a one-component inversion in which the initial temperature is modified linearly and the other free model parameters (magnetic-field vector, line-of-sight velocity, micro- and macroturbulent velocity) are assumed to be constant with depth in the photosphere. This analysis is for exploratory purposes only, as no discontinuities along the line of sight can be inferred from the inversion. The results are presented in fig. 2, where continuum intensity, inclination angle, field strength and LOS velocity maps are shown. A glance at fig. 2 reveals the fine structure of the extended penumbra, especially in inclination angle. As expected, magnetic fields in the umbrae present in the region are strong (about 2000–2500 G) and rather vertical (inclinations of less than 20°). The magnetic field is seen to weaken and incline as one moves toward the outer penumbra. Near the visible penumbral boundary (marked with black contour lines in the spatial maps), the magnetic-field vector is almost horizontal, but no inclinations

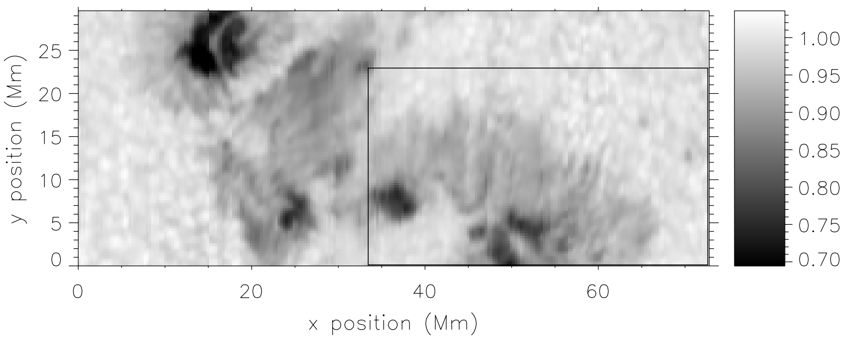

Fig. 1. – NOAA 9097 group observed on July 25, 2000. Image orientation is heliographic with north at the top and east to the left. The rectangular box delimites the extended penumbra analyzed in this work.

greater than 90° are detected with this simplified analysis. The penumbra extends well beyond its visible boundary with weaker fields of about 500 G. Although this has been known for some time, the rather large excursion of the penumbra beyond the visible boundaries we find here is certainly surprising in view of the deep layers where it occurs.

Spines of stronger and more vertical magnetic field are seen all over the penumbra, as reported by Degenhardt and Wiehr [11] and Title *et al.* [12]. In addition, downflows of up to 1 km s^{-1} are detected everywhere in the outer penumbra and beyond.

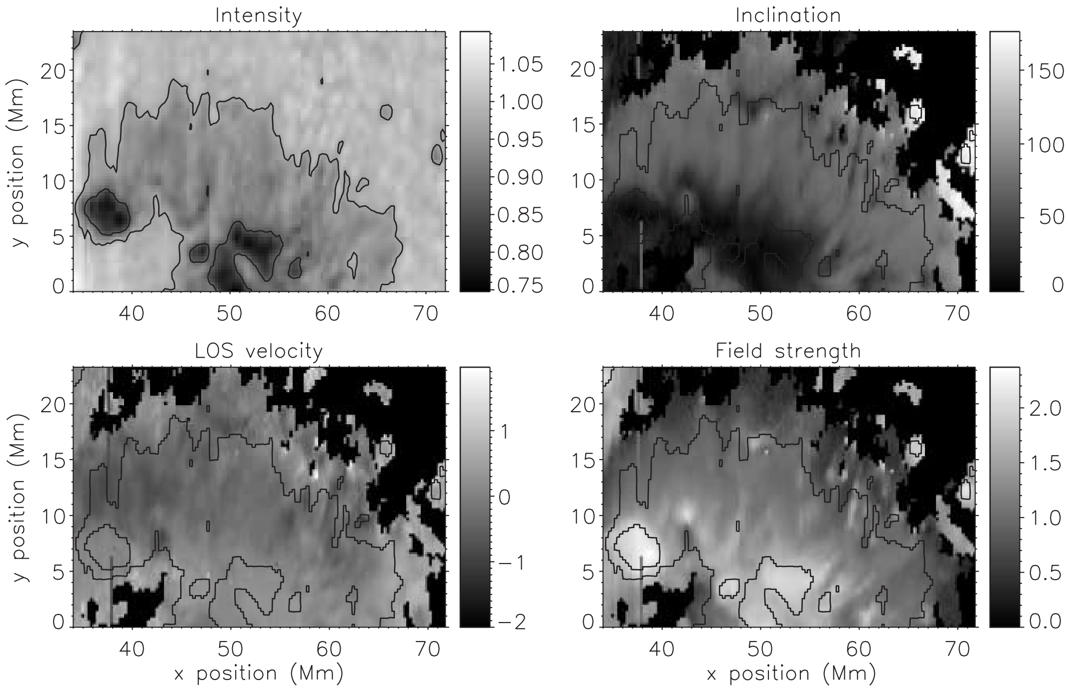

Fig. 2. – Results of a SIR inversion with constant magnetic-field vector and material velocity along the LOS. The continuum image of the penumbra is given in the upper left panel. Spatial maps of inclination angle, LOS velocity and field strength are displayed in the remaining panels.

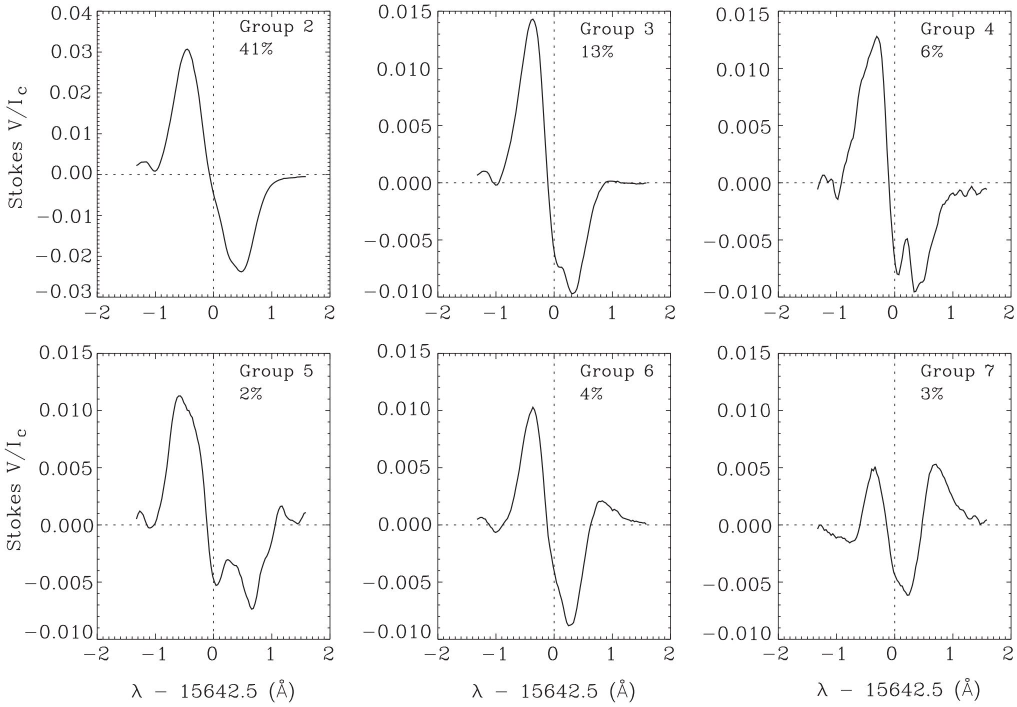

Fig. 3. – Example of profiles belonging to the different groups mentioned in the text. The percentage of occurrences is indicated in the top right corner of the figures.

4. – Stokes V profiles

A significant fraction of the observed V profiles have anomalous shapes indicative of large flows along almost horizontal field lines. We have classified them into 7 categories characterized by increasing anomalies. Typical profiles belonging to these groups are displayed in fig. 3, except for the first group which contains more or less normal profiles. Group 2 embodies profiles having a positive area asymmetry produced by a broad red lobe. Group 3 profiles are characterized by a small bump appearing in the Stokes V red lobe, which becomes more pronounced in groups 4 and 5. Profiles belonging to groups 6 and 7 have Q-like shapes with three lobes. In group 7, the redmost lobe has the same amplitude as the blue one.

The shape of these profiles can be explained in terms of the superposition of two different signals (of the same or opposite polarity), one of which is displaced with respect to the other in varying amounts. The exact values of the magnetic-field strength, inclination angle, and LOS velocity determine the final shape of the emergent profiles, giving rise to the seven groups mentioned above.

A very important point is that Q-like Stokes V profiles are mainly seen in the outer penumbral boundary and beyond (see fig. 4). They are not restricted to a neutral line region, which rules out projection effects as the origin of their anomalous shapes. The same conclusion was reached in [8].

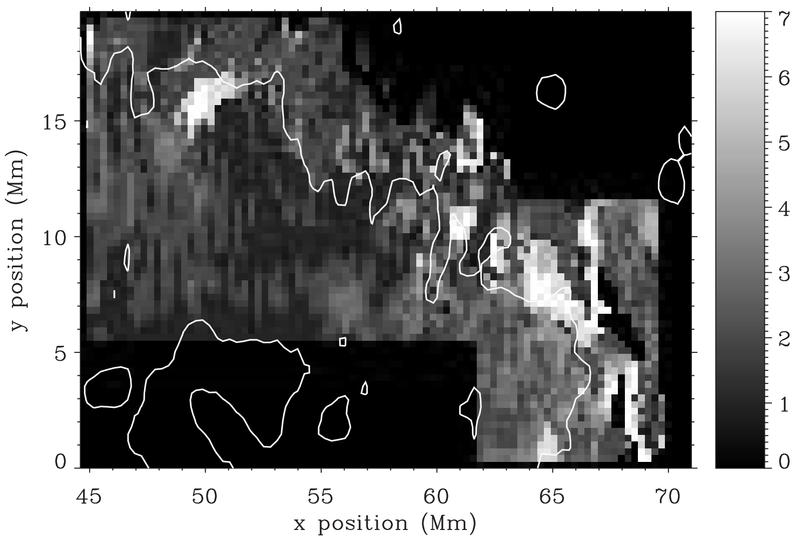

Fig. 4. – Spatial distribution of anomalous Stokes V profiles.

5. – Full inversion

Profile shapes hint at the existence of horizontal tubes. Therefore, discontinuous stratifications along the LOS can be expected. If individual tubes are crossed by the LOS, jumps of the physical quantities will be seen, preferentially in inclination angle and velocity. Taking these considerations into account, we have carried out a full inversion of the observed Stokes vector based on a one-component model atmosphere plus stray light. Depending on the filling factor and spatial resolution, two individual components might be needed. However, given the limited amount of information on high layers provided by our lines, the use of a single atmospheric model is reasonable. The free parameters of the model are the stratification of temperature, magnetic-field vector, and LOS velocity (represented by five nodes each), and appropriate values for the micro- and macroturbulence (assumed to be constant with depth). Note that much more flexibility is allowed in this inversion compared to the previous one.

Figure 5 shows the observed and best-fit profiles for a particular point located right on the visible boundary of the penumbra, along with the atmospheric stratifications inferred from the inversion. The quality of the fit is remarkable. In particular, the anomalous shapes of the Stokes V profiles are reproduced almost perfectly. The resulting model atmosphere is characterized by bumps in magnetic-field strength, inclination angle and LOS velocity at $\log \tau_5 \sim -0.8$. Hence, cool flux tubes coming back to the solar surface and harboring large velocities are indicated. For many other spatial points in the penumbra, the inversion code returns very similar model atmospheres. We therefore conclude that *one-component models with discontinuities along the LOS are able to provide a fit to the spectra emerging from all over the penumbra.*

The physical interpretation of these model atmospheres is that the LOS crosses a penumbral flux tube located at an optical depth $\log \tau_5 \sim -1$ which is embedded in a background magnetic environment. The penumbral tubes inferred from the inversion are characterized by different field strengths and larger inclination angles (in the example

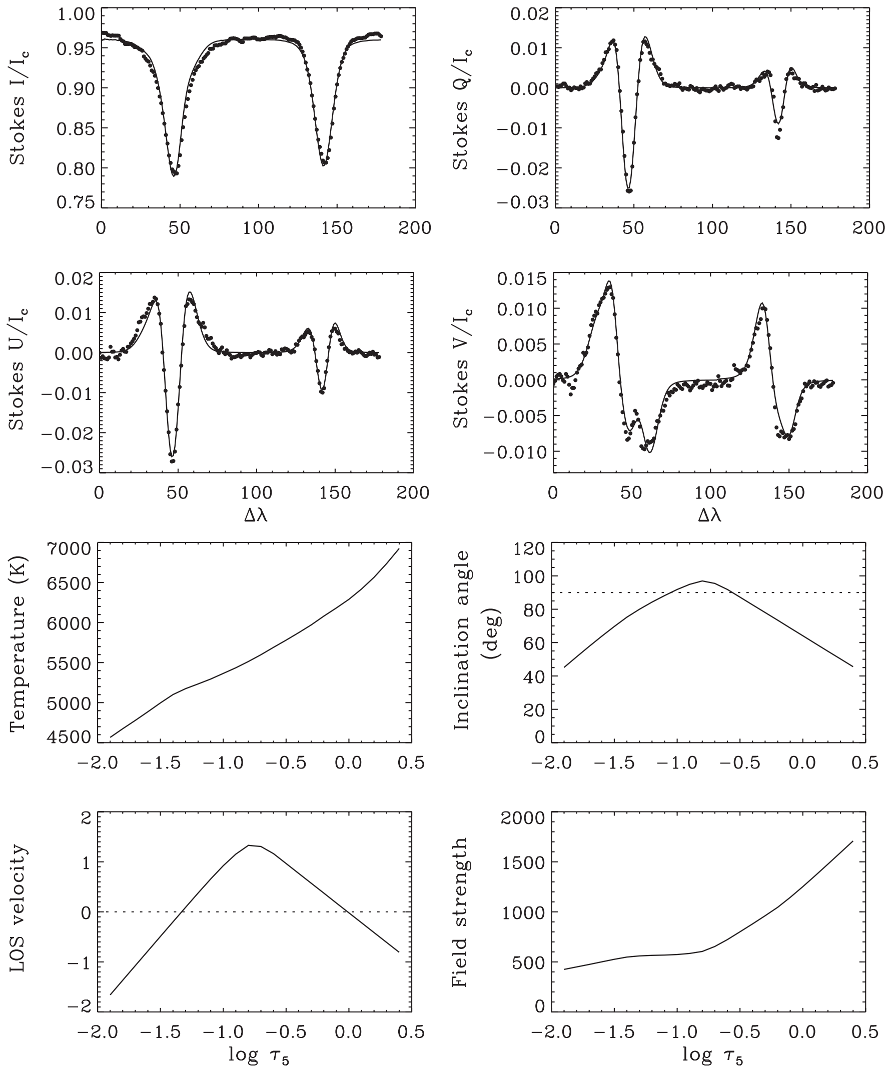

Fig. 5. – Top: observed (dots) and best-fit (solid lines) profiles emerging from a spatial point located right on the visible penumbral boundary. Wavelengths refor to the position of the minimum of the average Stokes I profile in the surrounding nonmagnetized regions. Bottom: parameters of the atmosphere determined from the inversion as a function of continuum optical depth τ_5 (temperature, inclination angle, LOS velocity and field strength, respectively). Positive velocities indicate downflows.

of fig. 5, the field lines actually return to the solar surface where $\gamma > 90°$). Downflows (positive LOS velocities) of up to 1.5 km s^{-1} are found inside the tubes, while the background medium is more at rest (the upflows seen in fig. 5 occur in the upper and lower parts of the atmosphere, where no reliable inferences can be made). Penumbral tubes turn out to be cooler than the surroundings at equal *optical* depth, but due to their much higher opacity we expect them to be hotter than the background atmosphere at equal geometrical heights.

6. – Conclusions

We have analyzed the full Stokes vector of two infrared Fe I lines emerging from a very extended penumbra. About 30% of the observed Stokes V profiles present abnormal shapes, indicating that two different magnetic components coexist almost everywhere in the penumbra. This is confirmed by inversion of the data. According to our results, horizontal tubes are embedded in a more vertical background field. Such tubes are usually cooler than the surroundings (at equal optical depth), possess weaker field strengths, carry most of the Evershed flow, and sometimes are seen to return back to the solar surface with inclination angles larger than 90°.

The analysis of polarization line profiles has allowed us to characterize the structure of the penumbra in deep photospheric layers. We have found that a simple one-component model with discontinuities along the LOS is capable of reproducing the Stokes profiles observed in the different parts of the penumbra. The fact that the same simple model provides a coherent picture of the whole penumbra, with smooth pixel-to-pixel variations, is very satisfying and certainly testifies to the consistency of the results.

The next step in determining the properties of penumbral flux tubes will be to extend the height coverage by including new spectral lines formed higher in the photosphere. In addition, a more appropriate model will be used to take account of the fact that two independent atmospheres coexist within the same resolution element. We envisage a two-component model in which the tube is constructed by adding a Gaussian perturbation to the background atmosphere. Free parameters of the model would be the amplitude of the perturbation for the various physical quantities, the position and width of the Gaussian, and the occupation fraction of both atmospheric components.

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