1.5 μm OBSERVATIONS AND THE DEPTH OF SUNSPOT PENUMBRAE

S. K. SOLANKI and I. RÜEDI
Institute of Astronomy, ETH-Zentrum, CH-8092 Zürich, Switzerland
W. LIVINGSTON
National Solar Observatory, NOAO, P. O. Box 26732, Tucson, AZ 85726, U.S.A.*
and
H. U. SCHMIDT
Max-Planck-Institute of Astrophysics, Garching, Germany

Abstract. The magnetic structure of a simple, relatively symmetric sunspot is determined using the extremely Zeeman sensitive Landé $g = 3$ line of Fe I at 1.5648 μm. From the measured strength and inclination of the magnetic field we estimate the fraction of the total magnetic flux of the sunspot passing through the solar surface in the penumbra. It is found that on average approximately 1/2–2/3 of the total magnetic flux of the spot emerges in the penumbra. Sunspot penumbrae are therefore deep, *i.e.*, the $\tau = 1$ level does not correspond to the lower magnetic boundary of the spot in its penumbra.

Key words: infrared: stars – Sun: magnetic fields – sunspots

1. Introduction

Sunspots are the solar magnetic features most easily accessible to direct observations and have invited considerable attention. Nevertheless, much of their physics remains unresolved, including a number of global aspects of their magnetic fields. Here we mainly address the question: Are sunspot penumbrae deep or shallow?

In a *shallow penumbra* the current sheet bounding the sunspot roughly corresponds to the $\tau = 1$ surface in the penumbra, *i.e.*, no (or very few) field lines cross the solar surface in the penumbra. In such a model the total magnetic flux of the sunspot emerging from the solar interior passes through the umbra. On the other hand, a significant number of field lines do cross the solar surface within a *deep penumbra*. We obtain a rough (indirect) measure of the "depth" of a penumbra by determining the total magnetic flux in the umbra, Φ_u, and comparing it with the magnetic flux in the penumbra, Φ_p. If $\Phi_p \ll \Phi_u$, then the umbra is shallow; if $\Phi_p \gtrsim \Phi_u$, it is deep. To determine the flux we need the magnetic field strength, B, and inclination angle to the vertical, γ', measured as a function of radial distance, r, from the center of the sunspot.

2. Observations and Analysis

The observed sunspot was close to solar disk center ($\theta = 10°$). Figure 1 shows a drawing of the umbral and penumbral boundaries of the spot with the approximate positions of the entrance apertures to the spectrograph overlaid. In all, 71 spectra of Fe I 1.5648 μm in Stokes I and V were obtained. Field strength, B, and magnetic

* Operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

D. M. Rabin et al. (eds.), Infrared Solar Physics, 471–475.

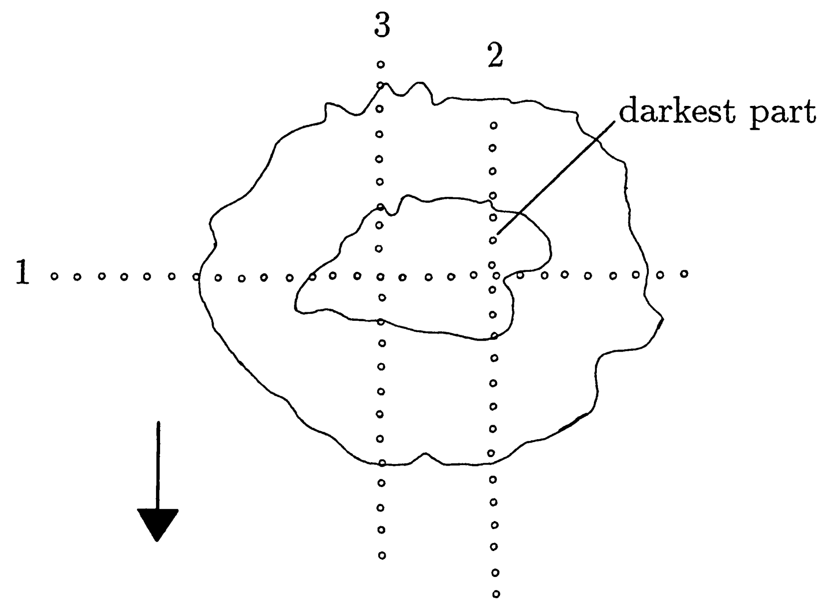

Fig. 1. Contours of the umbral and penumbral boundary of the sunspot. The small circles represent the positions at which spectra were obtained. The three scans through the sunspot are numbered near their starting positions. The arrow points toward the center of the solar disk.

inclination angle, γ, relative to the line of sight are determined by fitting the observed Stokes I and V profiles with numerically calculated synthetic profiles using an inversion code. Details of the code and the analysis are given by Solanki *et al.* (1992).

3. Field Strength and Inclination Angle

We combine the measurements of the three slices through the sunspot by plotting field strength and inclination angle *vs.* radial distance, r, from the geometrical center of the sunspot. The field strength, B, is plotted in Figure 2 as a function of r/r_p, where r_p is the radius of the sunspot. We wish to stress two points in Figure 2.

a. Most of the scatter around the mean curve is intrinsic to the sunspot. To illustrate this we have represented the data points along each half of each slice by a different symbol. In some directions (*e.g.*, dots) the field drops off more slowly with r/r_p than in others (*e.g.*, open circles).

b. The field strength at the outer penumbral boundary is accurate to approximately 50 G, so that the scatter there is also mainly solar in origin. Note also that the field strength values at $r/r_p > 1$ have been determined from the splitting of the V profiles (determined from the profile fits) and therefore represent the true field strengths in the superpenumbra.

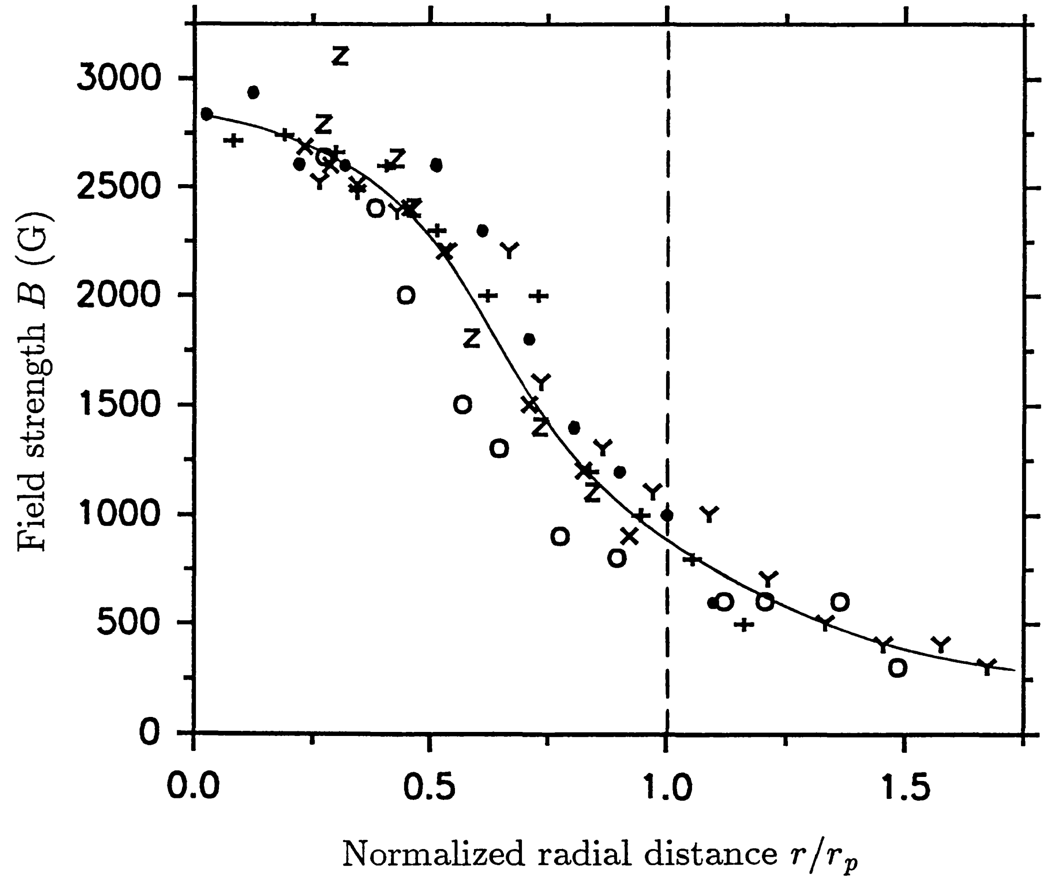

Fig. 2. Magnetic field strength, B, *vs.* r/r_p. Here r is the radial distance from the geometrical center of the sunspot and r_p is the outer penumbral radius r_p in the relevant direction (*cf.* Fig. 1). The symbols refer to different halves of the 3 sunspot slices shown in Figure 1.

In Figure 3 we plot the inclination angle, γ', of the field lines to the vertical. At the outer penumbral boundary we find $\gamma'(r/r_p = 1) = 82 \pm 4°$. The γ' values lying above the dashed line are more accurately determined than those lying below it.

4. Depth of the Penumbra

In addition to the B and γ' values plotted in Figure 3, we have used $B(r)$ and $\gamma'(r)$ values published by Beckers and Schröter (1969), Wittman (1974), Kawakami (1983), and Lites and Skumanich (1990) to determine $\Phi(r)$, the magnetic flux emerging within radius r. For simplicity we use azimuthally averaged curves of $B(r)$ and $\gamma'(r)$, such as the solid curves plotted in Figures 2 and 3. For details on how $\Phi(r)$ is determined see Solanki and Schmidt (1992).

Values of $\Phi(r)$ (normalized to $\Phi_{\max} = 1$), derived from the data in the literature and the 1.5 μm observations described above, are plotted *vs.* r/r_p in Figure 4.

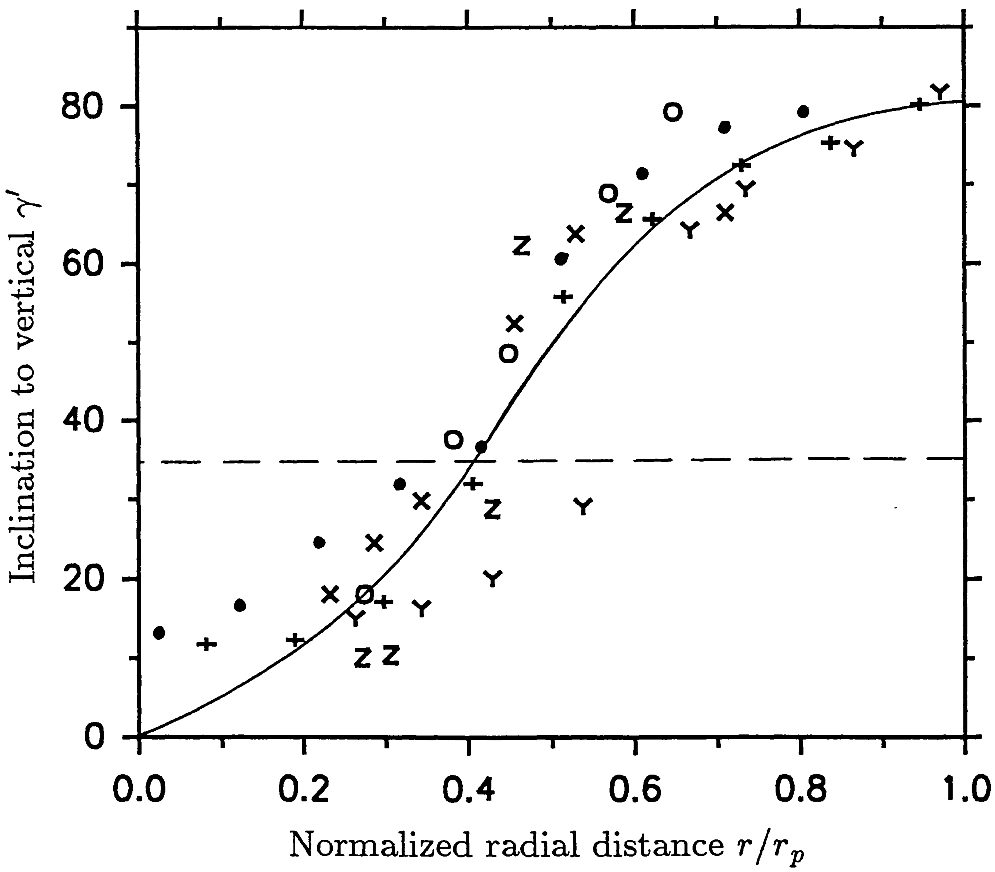

Fig. 3. Angle of inclination, γ', to the solar surface normal *vs.* r/r_p. Points below the horizontal dashed line are of lower accuracy than the rest.

For a shallow penumbra we expect the curves to be flat for $r/r_p \gtrsim 0.4$–0.5 (the umbral radius is approximately 0.4–0.45 of r_p). This is obviously not the case. Quantitatively, we find that, on average, 1/2–2/3 of the total magnetic flux of the spot emerges in the penumbra.

5. Conclusions

From an analysis of the radial dependence of the field strengths and inclination angles in nine sunspots (including one for which the field strength has been determined with great accuracy using the 1.5648 μm, $g = 3$ line) we conclude that a significant fraction (approximately 1/2–2/3) of the magnetic flux of a sunspot emerges in the penumbra – *i.e.*, sunspot penumbrae are deep. This is in agreement with most magnetohydrostatic models of the sunspot magnetic field (*e.g.*, Schlüter and Temesvary 1958, Deinzer 1965, Yun 1971, Pizzo 1986, and Jahn 1989). Models of a shallow penumbra (*e.g.*, Schmidt *et al.* 1986, *cf.* Nordlund and Stein 1989) and observations suggesting a penumbral canopy (*e.g.*, Giovanelli 1982) are not compatible with our analysis.

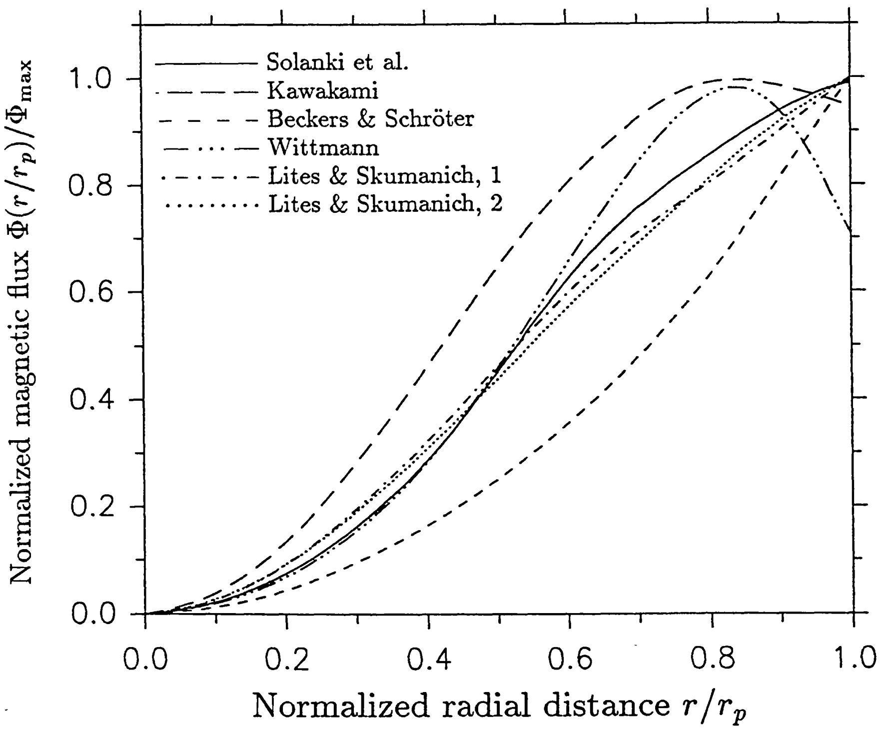

Fig. 4. Magnetic flux Φ emerging within radial distance r of the sunspot center, normalized to a maximum value of unity, Φ/Φ_{max}, *vs.* r/r_p.

References

Beckers, J. M., Schröter, E. H.: 1969, *Solar Phys.* **10**, 384.

Deinzer, W.: 1965, *Astrophys. J.* **141**, 548.

Giovanelli, R. G.: 1982, *Solar Phys.* **80**, 21.

Jahn, K.: 1989, *Astron. Astrophys.* **222**, 264.

Kawakami, H.: 1983, *Pub. Astron. Soc. Japan* **35**, 459.

Lites, B. W., Skumanich, A.: 1990, *Astrophys. J.* **348**, 747.

Nordlund, Å, Stein, R. F.: 1989, in R. J. Rutten and G. Severino (eds.), *Solar and Stellar Granulation*, Kluwer Academic Publishers, Dordrecht, p. 453.

Pizzo, V. J.: 1986, *Astrophys. J.* **302**, 785.

Schlüter, A., Temesvary, S.: 1958, in B. Lehnert (ed.), 'Electrodynamic Phenomena in Cosmical Physics', *IAU Symp.* **6**, 263.

Schmidt, H. U., Spruit, H. C., Weiss, N. O.: 1986, *Astron. Astrophys.* **158**, 351.

Solanki, S. K., Schmidt, H. U.: 1992, *Astron. Astrophys.*, submitted.

Solanki, Rüedi, I., Livingston, W. 1992, *Astron. Astrophys.* **263**, 312.

Wittmann, A. D.: 1974, *Solar Phys.* **36**, 29.

Yun, H. S.: 1971, *Solar Phys.* **16**, 398.