Mg I 12 μm diagnostics of sunspots

J. H. M. J. BRULS[1], S. K. SOLANKI[1], R. J. RUTTEN[2] AND M. CARLSSON[3]

[1] *Institut für Astronomie, ETH-Zentrum, CH-8092 Zürich, Switzerland*
[2] *Sterrekundig Instituut, Postbus 80 000, NL-3508 TA Utrecht, The Netherlands*
[3] *Institute of Theoretical Astrophysics, P.O. Box 1029, Blindern, N-0315 Oslo, Norway*

Abstract

We give three examples of diagnostic applications of the Mg I 12 μm lines. We find that (1) – The observed excess broadening of the σ-component peaks compared with the π component in penumbrae is well explained by the smooth radial variation of the magnetic field strength. (2) – The vertical field gradients $\partial B/\partial z$ in penumbrae range from 0.7 to 3 G km^{-1}. (3) – The base heights of superpenumbral magnetic canopies lie between 300 and 500 km above continuum optical depth $\tau_{500} = 1$ across an area of penumbral width outside penumbrae.

1. Introduction

The Mg I 12 μm lines appear in the solar spectrum as narrow emission peaks superposed on shallow, wide absorption troughs. Their diagnostic potential lies in the complete Zeeman splitting of their emission peaks down to 200 G fields. However detailed modeling can derive additional information from the profiles of these lines. We synthesize 12.32 μm line profiles to re-interprete observations by Hewagama *et al.* (1993), focusing on three points:

- The excess width of the σ-peaks in the observed penumbral Mg I 12 μm profiles compared with that of the π-component.
- The vertical magnetic field gradient in penumbrae.
- The height of the base of superpenumbral magnetic canopies.

The results and methodology are described in detail by Bruls *et al.* (1993).

2. Diagnostic applications

Observed penumbral Mg I 12 μm profiles (almost perfect Zeeman triplets with $g = 1$) have *excess σ-component widths over the π-component.* The FWHM of the π component is about 14 mK, whereas the width (on average 22 mK) and shape of the σ components vary strongly from one location in the penumbra to another. Hewagama *et al.* (1993) present correlations which slightly favor a magnetic origin of the excess broadening rather than velocities. Figure 1 displays 12.32 μm line profiles computed for different magnetic field strengths in a radiative equilibrium

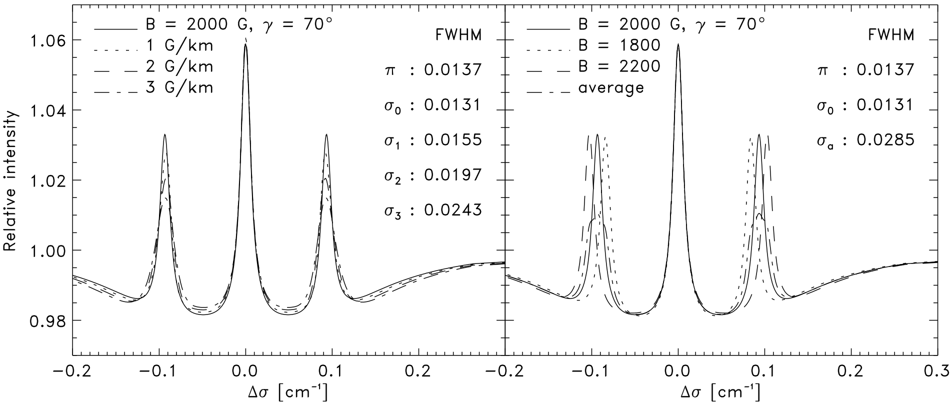

Figure 1: Stokes I profiles for inclined magnetic fields ($\gamma = 70°$) with different strengths or gradients. The halfwidths of the peaks are specified in cm^{-1}. *Left:* $12.32\,\mu$m profiles for uniform magnetic field (solid) and for fields with vertical gradients $\partial B/\partial z$ of 1, 2 and $3\,\mathrm{G\,km}^{-1}$ with $B = 2000\,\mathrm{G}$ fixed at the line formation height. *Right:* $12.32\,\mu$m profiles for uniform fields at the three specified strengths, averaged together with equal weights in the "average" profile, with width σ_{a}.

model atmosphere characteristic of solar penumbrae ($T_{\mathrm{eff}} = 5000\,\mathrm{K}$). The left part shows that vertical field gradients in excess of $2\,\mathrm{G\,km}^{-1}$, which presents an upper limit to the actual field gradients in most of the penumbra, would be needed to produce the observed σ-peak widths. This excludes vertical field gradients as the main excess broadening agent, except in the innermost penumbra. The right part of Fig. 1 shows that a horizontal distribution of field strengths of 400 G width produces sufficiently wide σ-peaks. The measured smooth large-scale radial variation, $\partial B/\partial r$, in the penumbra suffices to produce the required 300–400 G wide distribution of B over the field of view for these observations, indicating that large-scale field structuring is an important σ-peak broadening agent. Small-scale inhomogeneities of order $\Delta B = \pm 200\,\mathrm{G}$ would already produce too much additional broadening.

The only direct method of measuring *vertical field gradients in penumbrae* is to employ data taken in two lines with different formation heights. We obtain $\partial B/\partial z$ from magnetic field strengths derived from Mg I $12.32\,\mu$m and Fe I 630.25 nm. The difference between the field strengths obtained from the two lines, ΔB, is straightforward to obtain from the data of Hewagama *et al.* (1993). We have employed three radiative equilibrium models of different T_{eff}, bracketing the temperature range of dark and bright penumbral fibrils, to compute the Stokes Q σ-peak formation height difference Δz (from line depression contribution functions) between both lines, which is the appropriate parameter in case of nearly horizontal fields. The magnetic field gradients are given by $\Delta B/\Delta z$. The gradients for the T5000 model (Fig. 2) are intermediate between the hotter and cooler models so they may be considered as characteristic for actual penumbral field gradients. They agree with earlier values for the vertical field gradients in umbrae and penumbrae that were obtained in similar fashion, but exceed the values from theoretical sunspot modeling and estimates based on potential-field extrapolations or the $\nabla \cdot \mathbf{B} = 0$ requirement. We believe that the systematic trend to larger gradients closer to the umbra is real; it exceeds the uncertainties in the gradients, which are primarily

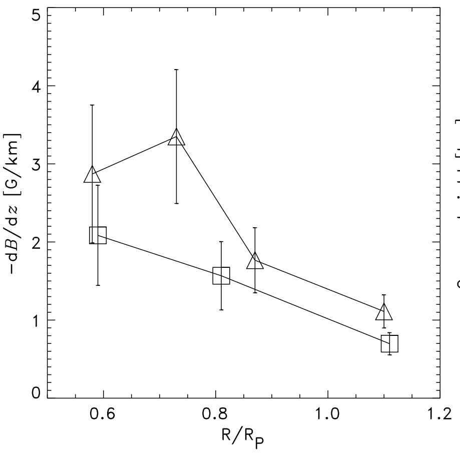

Figure 2: Magnetic field gradients at different distances R/R_P from sunspot center. Points on different sides of the sunspot are marked by triangles and squares. The error bars are computed assuming ± 0.25 dex uncertainty in the continuum optical depth of the line formation height

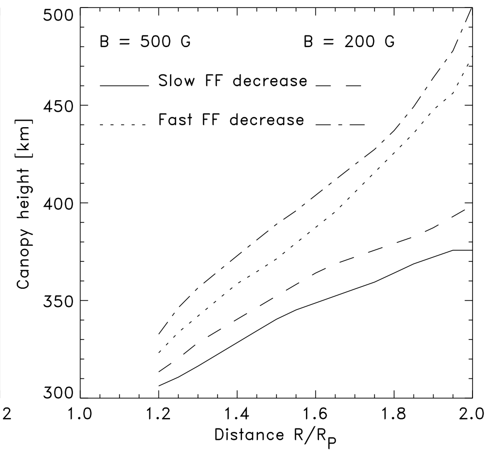

Figure 3: Superpenumbral canopy height as function of distance R/R_P from spot center, for outward filling factor decrease of 50% (slow) and 90% (fast) per unit R/R_P outside the penumbral radius R_P. Magnetic field strengths of 200 and 500 G are used.

due to uncertainties in the temperature behavior with R/R_P. The asymmetry between the two sides of the spot may in part be due to the azimuthal averaging of the Fe I 630.25 nm data (cf. Hewagama *et al.*, 1993), but may also be due to true sunspot asymmetry.

Finally we determined *the base height* h_c *of the magnetic canopies* that overlie the non-magnetic photosphere around sunspots and in which the magnetic field vector continues the trend of the outer penumbra. We derive an estimate of h_c from the data of Hewagama *et al.* (1993) using a quiet-Sun like model with 200 or 500 G horizontal fields, typical of the vicinity of a penumbra. Figure 3 shows the $h_c(R/R_P)$-relations, which are nearly independent of the assumed field strength. The results correspond well with the canopy base heights derived from the 1.5 μm Fe I lines. The fact that the field is almost horizontal and that a considerably larger magnetic signal is seen in the 12 μm lines (formed in the upper photosphere) that at 1.5 μm (arising from the lower photosphere) strongly supports the canopy interpretation.

References

Bruls J. H. M. J., Solanki S. K., Rutten R. J., Carlsson M. (1993). *A&A*, submitted

Hewagama T., Deming D., Jennings D. E., Osherovich V., Wiedemann G., Zipoy D., Mickey D. L., Garcia H. (1993). *ApJS*, **86**, 313