Mg I 12 μm diagnostics of sunspot penumbrae

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Abstract

We give three examples of diagnostic applications of the Mg I 12 μm lines to sunspot penumbrae. We find: (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 dB/dz 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. Detailed line profile modeling delivers additional information on field geometry; we synthesize 12.32 μm line profiles to re-interprete observations by Hewagama *et al.* (1993). This work is described by Bruls *et al.* (1993).

2. Diagnostic applications

Excess σ-component widths. Observed penumbral Mg I 12 μm profiles (almost perfect Zeeman triplets with $g = 1$) have excess σ-component widths compared with the π component. The FWHM of the π component is about 14 mK, whereas the width (22 mK on average) and shape of the σ components vary strongly across penumbrae. 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 from a radiative-equilibrium model atmosphere with $T_{\rm eff} = 5000$ K, which is characteristic of solar penumbrae. The left part shows that vertical field gradients in excess of 2 G km^{-1}, which

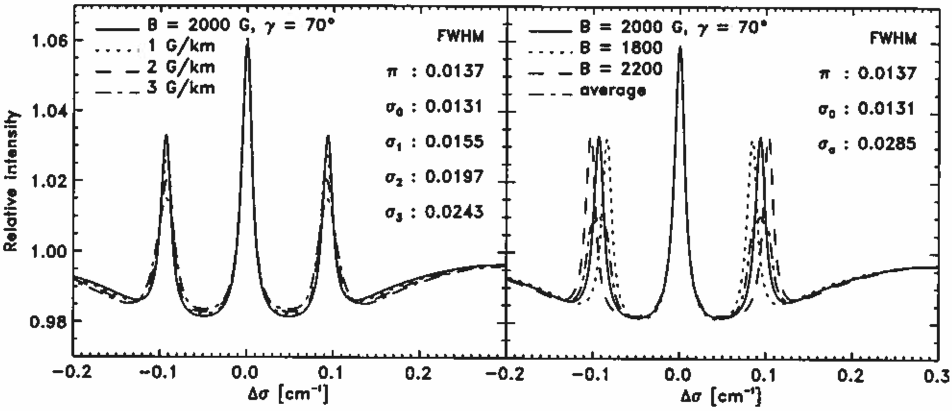

Figure 1: Stokes I profiles for inclined magnetic fields ($\gamma = 70°$) differing in gradient (left) and strength (right). The halfwidths of the peaks are specified in cm^{-1}. *Left:* 12.32 μm profiles for uniform magnetic field (solid) and for fields with vertical gradients dB/dz of 1, 2 and 3 G km^{-1}, each with $B = 2000$ G at the line formation height. *Right:* 12.32 μm profiles for uniform fields at the three specified strengths, averaged together with equal weights in the "average" profile, with width σ_a.

presents an upper limit to the actual field gradients in most of the penumbra, are required to produce the observed σ-peak widths. This result excludes vertical field gradients as the main excess broadening agent, except for the innermost parts of penumbrae. The right part of Fig. 1 shows that a horizontal distribution of field strengths of 400 G width produces sufficiently wide σ peaks. The smooth observed radial variation dB/dr in the penumbra already suffices to produce the required 300–400 G wide distribution of B over the field of view, indicating that this large-scale field structuring is an important σ-peak broadening agent. Small-scale inhomogeneities of order $\Delta B = \pm 200$ G would already produce too much additional broadening.

Vertical gradients. The only direct method of measuring vertical field gradients in penumbrae is to employ two lines with different formation heights. We have obtained the difference ΔB between magnetic field strengths derived from Mg I 12.32 μm and Fe I 630.25 nm using data of Hewagama *et al.* (1993). We employed three radiative equilibrium models of different T_{eff}, which bracket the temperature range of penumbral fibrils, to compute the Stokes Q σ-peak formation height difference Δz between these lines. This estimate is valid for nearly horizontal fields. The resulting gradients $\Delta B/\Delta z$ for the intermediate model (Fig. 2) may be considered as characteristic for actual penumbral field gradients. They agree with earlier observational determinations, but they exceed the values from theoretical sunspot modeling and the estimates based on potential-field extrapolations

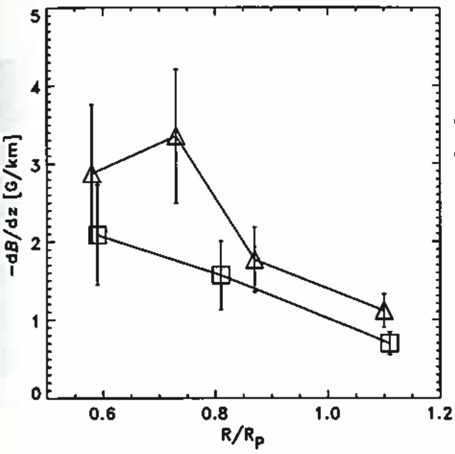

Figure 2: Magnetic field gradients at different distances R/R_P from sunspot center. Locations on different sides of the sunspot are marked by triangles and squares. The error bars are computed assuming ± 0.25 dex uncertainty in the continuum optical depth of the line formation height

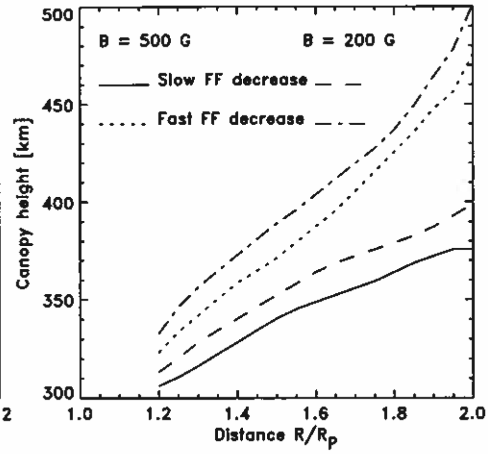

Figure 3: Superpenumbral canopy height as function of distance R/R_P from spot center, for outward filling factor decrease of 50% (slow) and 90% (fast) per unit R/R_P outside the penumbral radius R_P. Magnetic field strengths of 200 and 500 G are used.

or on the $\nabla \cdot \mathbf{B} = 0$ requirement. We believe that the trend to larger gradients closer to the umbra in Fig. 2 is real; it exceeds the uncertainties, which are primarily due to the temperature variation with R/R_P. The asymmetry between the two sides of the spot may be due to the azimuthal averaging of the Fe I 630.25 nm data and/or due to intrinsic sunspot asymmetry.

Canopy base heights. Finally we determined the base height h_c of the magnetic canopies that overlie the photosphere around sunspots. The magnetic field vector continues the trend of the outer penumbra in "superpenumbral" canopies. We derive an estimate of h_c from the data of Hewagama *et al.* (1993) using quiet-Sun models with 200 and 500 G horizontal fields, characterizing the vicinity of a penumbra. Figure 3 shows the resulting $h_c(R/R_P)$-relations. They are nearly independent of the assumed field strength, and they correspond well with canopy base heights derived from the 1.5 μm Fe I lines (Solanki *et al.*, 1992).

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