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Magnetic Field Strength and Filling Factor Sensitivity of the Mg I 12 μm Infrared Lines in Solar Plage

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Abstract. We discuss the sensitivity of the Mg I 12.32 μm line to magnetic field strengths and flux-tube filling factors in solar active region plage. This line's moderate sensitivity to the range of temperatures expected for plages adds to its value as a magnetic field diagnostic of the upper photosphere of plages. Its line shape and Zeeman splitting are highly sensitive to both the magnetic flux tube filling factor and the magnetic field strength within the tubes. This significantly complicates the analysis of observed profiles, but also provides a handle on the sub-spatial-resolution distribution of flux-tube field strengths and filling factors.

1. Introduction

The Mg I 12 μm lines, although quite weak features in the infrared spectrum, are formed in the upper photosphere. In principle, they enable the measurement of magnetic field strengths as low as 200 G directly from their Zeeman splitting. Their large Zeeman sensitivity and favorable formation height have made the Mg I 12 μm lines a major diagnostic of magnetic fields in the upper photosphere. They have been used to observationally study sunspot penumbrae, and solar plage and magnetic network fields. Bruls et al. (1993) studied the potential of the 12 μm lines as sunspot penumbrae magnetic fields diagnostics, and in the present paper we briefly discuss the possibilities to use these lines to determine the magnetic field in the upper photospheric layers of solar plage. A more detailed analysis is presented by Bruls and Solanki (1993b).

Solar plage and network regions are thought to consist of individual small magnetic flux tubes, surrounded by field-free material. The flux tubes fill only a fraction of the surface area at photospheric heights, but pressure equilibrium requirements force the tubes to fan out with height and merge into a magnetic canopy. The Mg I 12 μm line formation occurs at the heights where the tubes fan out and merge, so that the line profile shapes are very sensitively influenced by the detailed magnetic field structure.

The observed complex shapes of the 12 μm line profiles (e.g. Zirin and Popp 1989) belie the general belief that the profiles of fully Zeeman split lines are straightforward to interpret. Detailed modeling is the only means to interpreting and understanding the observed profiles.

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2. Computational aspects

The basic Mg I atomic data for this plage flux-tube investigation are from the non-LTE Mg I 12 μm line formation analysis by Carlsson et al. (1992), who produce the observed quiet-Sun Mg I 12 μm line profiles without ad hoc assumptions.

The sensitivity of the 12.32 μm line to temperature variations within the range thought acceptable for solar plage and network is remarkably low, so that in this paper we omit the temperature-sensitivity investigation. We use a (two-component) atmospheric model that consists of a vertical, axially-symmetric magnetic flux tube embedded in a non-magnetic atmosphere, which is represented by the quiet-Sun model of Maltby et al. (1986). The plage flux-tube model PC2, taken from Bruls and Solanki (1993a), has a chromospheric temperature rise similar to that of the above quiet-Sun model attached at continuum optical depth $\tau_{500} \approx 10^{-3.5}$.

The radial expansion of the flux tubes with height, i.e. the increase of the magnetic filling factor with height and the associated proportional decrease of the magnetic field strength (flux conservation), is computed by means of the "thin-tube" approximation. Field strengths B_0 of 0, 500, 1000, 1400, 1500, 1600 and 1680 G at the $z = 0$ level (corresponding to $\tau_{500} = 1$ in the quiet Sun model) and magnetic filling factors f_0 of 1, 2, 4, 8, 16, and 32% at that height are used. The flux tube is allowed to expand up to the height z_{m} at which the cross-sectional area becomes $1/f_0$ times as large as its area at $z = 0$, and it is assumed to merge with its nearest neighbors. The field strength becomes constant B_{m} there.

The statistical equilibrium and radiative transfer equations are solved in 1-D fashion for 10 representative vertical rays through each flux-tube model at different distances from the flux-tube axis. Relying on the field-free approximation, the statistical equilibrium and radiative transfer equations are solved neglecting the magnetic field, using version 2.0 of Carlsson's (1986) radiative transfer code MULTI, and the resulting line source functions and opacities are used as input for the Diagonal Element Lambda Operator (DELO) Stokes profile synthesis code (Murphy and Rees 1990) to compute Zeeman-split Stokes I and V profiles for each ray, accounting for the pertinent magnetic field stratification.

3. Filling factors

A sequence of flux-tube models with magnetic filling factors f_0 ranging from 1 to 32% (and $B_0 = 1600$ G) illustrates that the Mg I 12.32 μm line profile depends strongly on this parameter, not only in the Stokes V amplitude, but also in the shape of the Stokes I and V profiles. Here we discuss the results.

The left part of Fig. 1 shows the Stokes I and V profiles for all rays through the model with $f_0 = 16\%$. At large distance from the flux-tube axis, only the Stokes V profiles show the presence of (rather weak) magnetic fields above the flux-tube merging height, which are sampled by the long chromospheric tail of the line contribution function. Towards the tube axis the line formation gradually moves into the magnetic zone completely, and the magnetic field first broadens the Stokes I profiles and eventually shows two distinct emission σ-

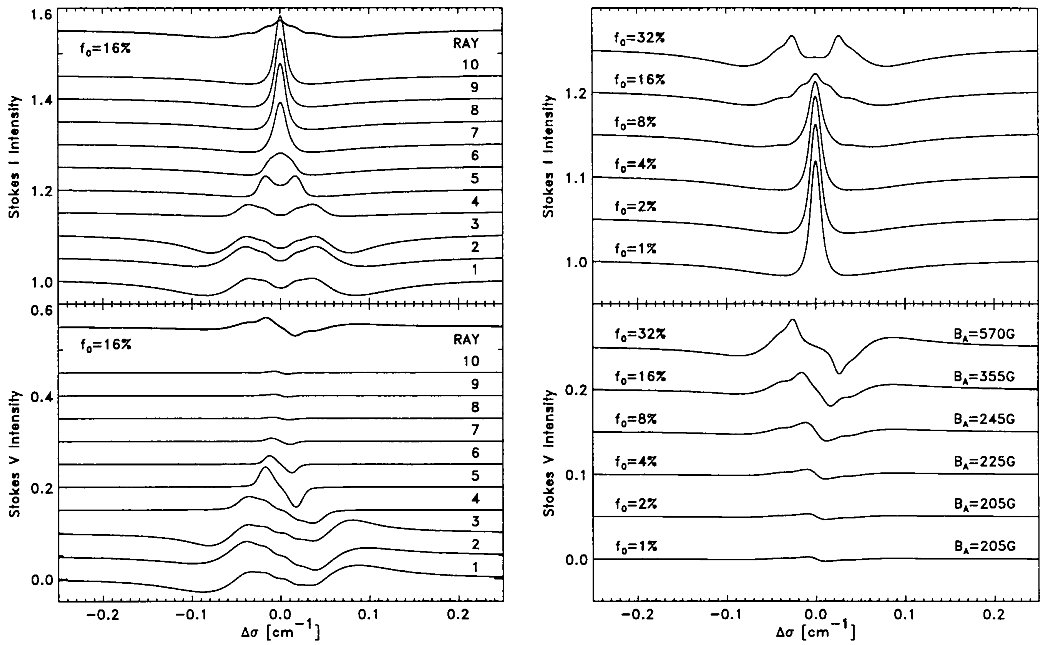

Figure 1. *Left:* Mg I 12.32 μm Stokes I (top) and V (bottom) profiles for the 10 vertical rays through the PC2 model with filling factor $f_0 = 16\%$ and $B_0 = 1600$ G. The curves are numbered 1 to 10 from the flux-tube axis to the outermost ray. The uppermost curve is the average line profile. *Right:* Average Mg I 12.32 μm Stokes I (top) and V (bottom) profiles for model PC2 with different filling factors f_0 (indicated at the left). The apparent magnetic field strengths $B_{\rm A}$ corresponding to the Stokes V splitting are indicated at the right. All Stokes I and V intensities are normalized to the respective Stokes I continuum intensities, and then shifted upward in steps of 0.05.

peaks. Still closer to the flux-tube axis (rays 1–4), the large vertical field strength gradients that exist deeper in the atmosphere dominate the profile shape and produce significant broadening of the σ-peaks. In the average Stokes I and V profiles (top curves in right panels of Fig. 1) all parts of the flux-tube model are represented.

At other values of f_0 the average Stokes I and V profiles show similar behavior. At lower f_0 (roughly $f_0 < 8\%$) little or no magnetic signature is directly visible in Stokes I and only a marginal signal is seen in Stokes V. With increasing f_0 the unpolarized quiet-Sun contribution to the line-center emission peak in Stokes I becomes weaker, and the emission σ-peaks become visible; first only as a very small intensity enhancement near the deepest points in the Stokes I profile and at $f_0 = 32\%$ as two separated wide peaks. The Stokes V amplitude of the emission σ-peaks increases approximately linearly with f_0.

The wide, low part of the σ-peaks results from the strong photospheric fields with large gradients, and the narrow part closer to line center arises in the nearly constant magnetic field close to the merging height. $B_{\rm m}$ increases linearly with f_0, so that the splitting of the narrow σ-peaks in Stokes I also increases with f_0. The apparent magnetic field strength $B_{\rm A}$, derived from the Stokes V

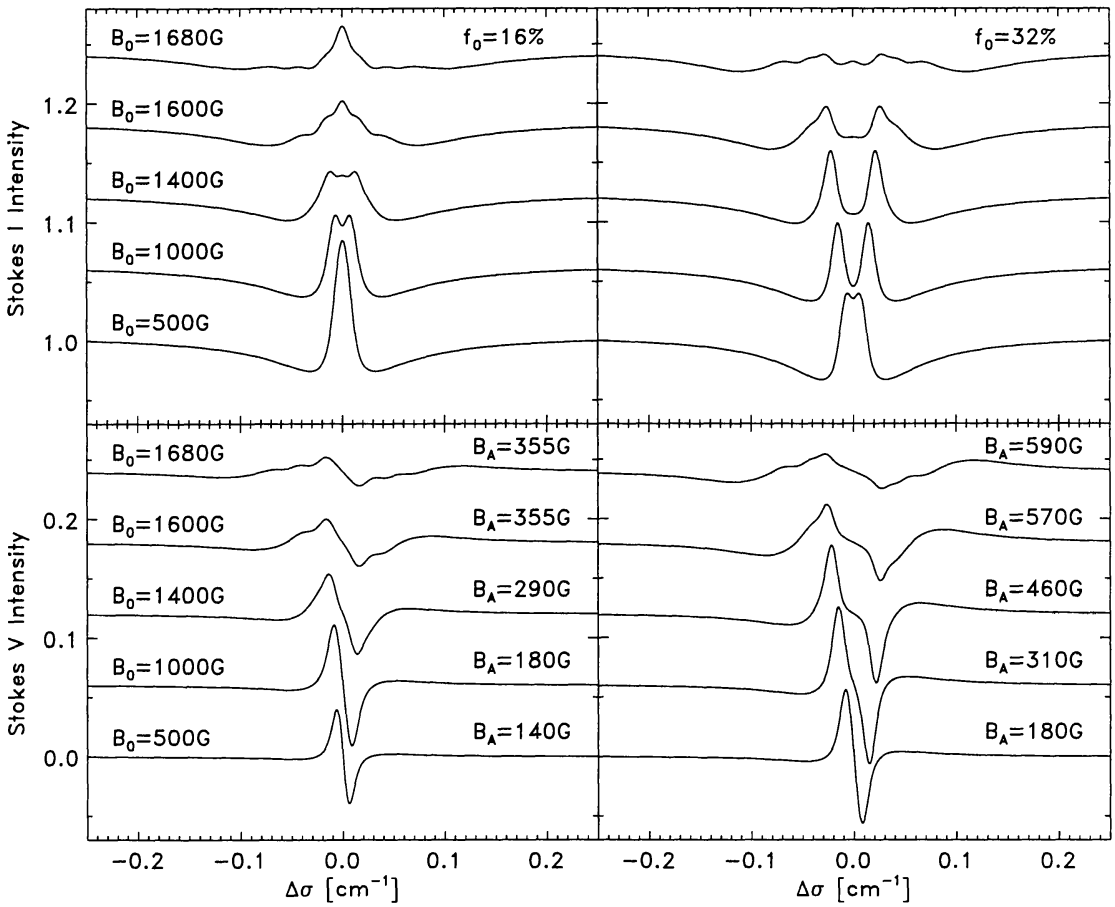

Figure 2. Average Mg I 12.32 μm Stokes I (top) and V (bottom) profiles for model PC2 with different magnetic field strengths and with filling factors of 16% (left) and 32% (right). In the lower panels the apparent magnetic field strength B_A that follows from the Stokes V splitting is indicated. All intensities have been normalized to the continuum intensity, and then shifted upward in steps of 0.06.

splitting, corresponds to the field strength at the median formation height of the emission peaks. B_A represents an upper limit to $B_m = f_0 B_0$: at low f_0 the line is formed well below the canopy, while at larger f_0 values B_A represents the field strength just below the height where it becomes constant. In addition, for small f_0 the Stokes V splitting is incomplete, so that B_A is an overestimate of the actual field strength. For $f_0 \gtrsim 5\%$ there is a measurable dependence of B_A on f_0, and for $f_0 \gtrsim 16\%$ B_A changes almost as rapidly as B_m.

One important finding is that the shape of the Mg I 12.32 μm line profile depends strongly on the distribution of the magnetic features within the spatial resolution element. For example, a profile calculated with $f_0 = 16\%$ is easily distinguishable from a sum of profiles computed for $f_0 = 0$ and 32%. This property is so far unique to the 12.32 μm lines.

4. Magnetic field strengths

We display in Fig. 2 the dependence of the Mg I 12.32 μm line profile on B_0. The magnetic filling factor f_0 is 16% at the left and 32% at the right. B_A increases with B_0, but the exact dependence is relatively complex. At small B_0, B_A tends to become independent of B_0 since the line then enters the weak-field regime and is no longer fully split. At larger B_0 the B_A value can change either more or less rapidly than B_0, depending on a number of factors. For instance, if z_m is much higher than the formation height of the line, it is $B(\tau_{int}) = 1$ rather than B_0 which determines B_A (τ_{int} is the continuum optical depth in the tube at 500 nm). $B(\tau_{int}) = 1$ increases much more rapidly than B_0 for $B_0 \gtrsim 1400$ G, so that B_A is then also expected to change more rapidly than B_0. On the other hand, for large filling factors, $f_0 \gtrsim 30\%$, B_A is determined chiefly by $B_m = f_0 B_0$.

In addition, the Stokes V amplitude of the absorption trough, which is of mid-photospheric origin and has the opposite sign to the emission σ-peaks of Stokes V, increases linearly with B_0, and its splitting remains constant (B_0 is still in the weak-field regime for such wide features). The amplitudes of the emission peaks actually decrease with B_0 (see below), so that in Stokes V the amplitude of the absorption trough increases relative to the emission peak with increasing B_0. The interference of the σ-components with the absorption trough at large B_0 tends to move the σ-peaks closer together, thus lowering B_A.

The shapes of the individual σ-components also depend strongly on B_0. The vertical field strength gradient is coupled to B_0 and increases with it. This produces considerably broader, lower, and more asymmetric σ-components at $B_0 \gtrsim 1400$ G than at low B_0. To a smaller extent the interference with the absorption trough also distorts the emission peaks in both Stokes I and V. The canceling effect and profile distortion is especially pronounced at $B_0 = 1680$ G: if such profiles were to be observed, the broad, low amplitude σ-emission peaks would drown almost completely in the noise unless the data were of exceptional quality.

At large B_0 each σ-component tends to be roughly triangular in shape, with a steep inner flank and a more gradual decrease in the outer part. For large f_0 and B_0 the inner "cutoff" corresponds to B_m, for small f_0 or B_0, to the non-magnetic width of the emission profile (weak-field limit). The wide outer flanks are a product of the large vertical field strength gradient in the flux tube below the merging height. Consequently, B measured from the center of gravity of the V σ-components increases more rapidly with B_0 than B_A does. On the one hand, the interference between emission peaks and absorption trough poses severe problems to straightforward flux-tube magnetic field determinations from σ-peak separations in observed 12.32 μm line profiles. On the other hand it offers a handle on fB deeper in the photosphere, even if it is a complicated one that requires detailed modeling. Stokes Q and U profiles, which have absorption trough signals proportional to B^2, could partially solve the problem posed by emission peak/absorption trough interference.

The synthetic 12.32 μm profiles formed in the range of magnetic features covered here, show splitting corresponding to 200–600 G, which agrees well with the measured splitting of 200–700 G. Unfortunately, only Stokes I was observed, which limits the accuracy of the observed splitting, in particular for weaker fields. For example, a field with $B_0 = 500$ G, $f_0 = 16\%$, does not obviously distort Stokes I. However, the presence of such fields has been reported from Fe I 1.56 μm line measurements. Even Stokes V does not allow such fields to be identified uniquely. Note that in Fig. 2 the 12.32 μm V and I profiles for $B_0 = 500$ G and $f_0 = 32\%$ are practically indistinguishable from the V and I profiles for $B_0 = 1000$ G and $f_0 = 16\%$. Thus for the measurement of fields that are weak in the photosphere the Fe I 1.56 μm line is superior to the 12 μm lines.

5. Discussion and conclusion

We have studied the behavior of the 12.32 μm line under conditions characteristic of solar plage. The low temperature sensitivity of the 12.32 μm line adds to its potential as a magnetic field diagnostic.

The large Zeeman separation of the emission σ-peaks in principle enables accurate upper photosphere magnetic field measurements down to a few hundred Gauss. In practice we find that the splitting of the synthetic line profiles resulting from flux-tube models, which consistently include the main features of the magnetic field, depends not only on the magnetic field strength, but also on the filling factor (via the merging height). On the one hand this complicates the analysis of the Mg I 12 μm emission lines observed in plages, which consequently need to be analyzed using detailed models. On the other hand, this very property means that they can provide some information on the inhomogeneity of the distribution of flux tubes within the resolution element. They also provide observational evidence for the merging height of flux tubes in strong plages.

The large and complex dependence of line shape and splitting on the intrinsic field strength and filling factor of small-scale magnetic features also means that the typical difference in B_0 and f_0 present between different plages and different positions within a plage, completely dominates any dependence of the splitting on the limb distance. Thus it is not surprising that no such dependence has been found by Zirin and Popp (1989).

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