

ring like structure. The downflow seen around the pore is an accelerated downflow and the acceleration is found to be stronger than that of the inter-granular downflows. These observational results very closely resemble the results obtained from the dynamical simulations of flux tube surrounded by granular flows. The size of the narrow downflow region is found to be around 0.5 arcsec or smaller.

It is also found from these observations that the fill-fraction plays an important role in obtaining the velocity inside pores. A pore with large fill-fraction (almost resolved) showed very little upflow whereas the pore with small fill-fraction (not-fully resolved) showed large downflows. We conclude from these observations that the downflow around the region contributes to the downflows seen in the unresolved pore.

The time variation of the velocity observed with very high-spatial resolution showed that the downflow region around the pore is stable and very little perturbed. We also find that the power for the velocity oscillation in the 5-minute periodicity at these downflow regions is small compared to the power found at the quiet region. The variation of the magnetic field parameters did not show any power at the 5-minute periodicity whereas the amplitude asymmetry in the V-profile showed power in 5-minute. The area asymmetry did not show any power confirming the earlier observations (Kupke, Labonte, & Mickey 2000).

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New Molecular Indicators of Sunspot Magnetic Fields: Infrared OH Lines

Svetlana V. Berdyugina

Astronomy Division, University of Oulu, Finland

Sami K. Solanki, Andreas Lagg

Max-Planck-Institut für Aeronomie, Katlenburg-Lindau, Germany

Abstract. Thanks to recent advances in theory we can now calculate molecular line profiles in the presence of magnetic fields with high accuracy, both in the Zeeman and Paschen-Back regimes (Berdyugina et al. 2000; Berdyugina & Solanki 2001). The agreement between the theory and observations is remarkable. For example, the mutually opposite polarities of different OH lines are reproduced without invoking any free parameters, except the magnetic field strength and sunspot temperature. Also, preliminary calculations suggest that introducing molecular lines into the inversion of sunspot spectra leads to significant improvements in the deduced magnetic field vector.

1. Introduction

The spectra of sunspots contain a rich collection of molecular lines (e.g. Wallace et al. 1998), which are good temperature and pressure indicators. Recently we performed an overview of the magnetic properties of molecular band systems observed in visible and near infrared spectra of sunspots and cool stars. We showed that many molecular lines are also good indicators of solar and stellar magnetic fields (Berdyugina et al. 2000; Berdyugina & Solanki 2002).

A particularly interesting case is presented by OH transitions in the infrared H-band. They belong to the Meinel system and are observed in sunspot spectra as two main band sequences extending up to 4.2 μm and starting at 1.4 μm and 3.1 μm , for the difference between the upper and lower vibrational state numbers $\Delta v = 2$ and $\Delta v = 1$, respectively (Wallace & Livingston 1993). Here we show that these lines represent powerful diagnostics for studies of sunspots. With our new perturbation calculations of the molecular Zeeman effect (Berdyugina & Solanki 2002) we resolve a long-lasting puzzle of reversal polarities in infrared OH lines. Also, carrying out inversions of OH lines along with atomic lines we are able to extend sunspot models, including the magnetic field, to layers, where atomic lines suffer from NLTE effects but molecules can still be treated in LTE.

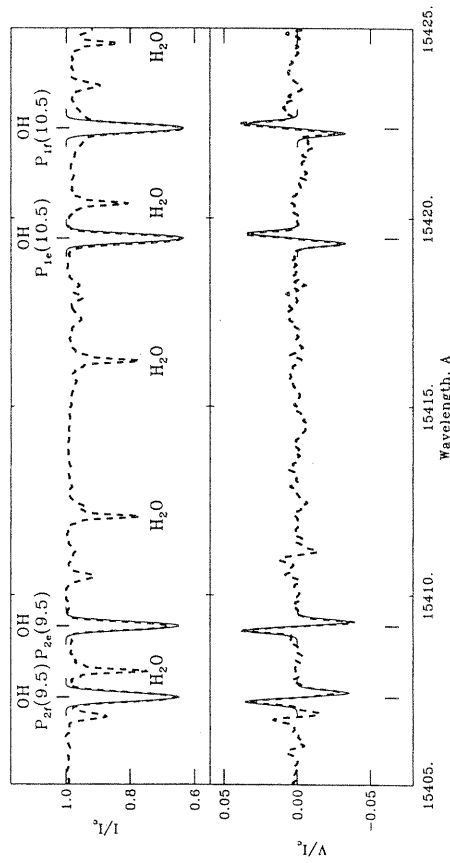


Figure 1. Stokes I and V spectra of the two pairs of OH lines pointed out by Harvey (1985). Dashed lines: spectra observed in a sunspot, solid lines: synthesized. The field strength is 2.5 kG, and the filling factor is 0.8. Note that the magnetic field in the spot is directed away from the observer and, thus, the reversed polarization is present in the left pair of lines. The weaker reversed-polarity V profiles, e.g. at 15407 Å, are also due to OH.

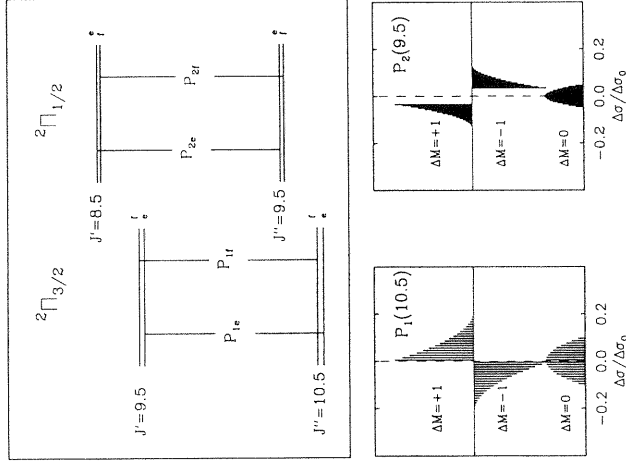


Figure 2. In the upper panel a schematic representation of the transitions underlying the two pairs of OH lines is shown, for one of which the puzzling reversed polarization was reported by Harvey (1985). The small Λ -type doubling intervals between levels denoted by e and f are exaggerated for clarity. The other two panels show the Zeeman patterns of the two pairs of OH lines. In spite of rather different Zeeman patterns, the two plotted lines have almost identical absolute values of the effective Landé factors: 0.11 and -0.12 for $P_1(10.5)$ and $P_2(9.5)$, respectively.

2. Long-lasting Puzzle

In the spectrum of a sunspot umbra Harvey (1985) discovered that Stokes V profiles of OH lines of the same band and of approximately the same strength exhibit opposite polarities. A portion of an FTS (Fourier Transform Spectrometer) spectrum of a sunspot umbra is plotted in Fig. 1, where 4 OH lines from the (2,0) band are marked. The complete data set is described and discussed by Rüedi et al. (1995). Note that the pair on the right has V profiles of opposite polarity compared with that on the left. The fact that two lines each have V profiles of the same polarity, the V profiles are antisymmetric and all lines are otherwise similar cannot be explained any other way than that they have equal but opposite effective Landé factors (Berdygina & Solanki 2002).

Using the theoretical Zeeman patterns calculated as described by Berdyugina & Solanki (2001), we carried out the forward spectral synthesis of Stokes parameters of OH transitions. The calculated splitting pattern is shown in Fig. 2, which reveals that reversed polarity is exhibited by the lines belonging to the P_2 sub-branch ($g_{\text{eff}} < 0$), while the P_1 transitions have normal polarity ($g_{\text{eff}} > 0$). We found also that the same occurs for the R_1 and R_2 transitions and such a behavior is typical for all OH lines from the Meinel system and pure rotational transitions in the ground state. Radiative transfer calculations were performed with an extended and improved version of the code STOPRO (Solanki et al. 1992; Frutiger et al. 2000), which solves the set of radiative transfer equations in the formulation given by Rees et al. (1989). This code has been updated to enable computations of lines of diatomic molecules in the presence of a magnetic field, i.e. calculate the wavelength shifts of the Zeeman components and their theoretical strengths as well as molecular number densities. As a model umbra we used a radiative equilibrium atmosphere tabulated by Kurucz (1993) having $T_{\text{eff}} = 3750\text{K}$ and $\log g = 4.5$, into which we introduced a height-independent magnetic field of an appropriate strength. The synthetic profiles are overplotted on the observed profiles in Fig. 1. The correspondence is gratifying.

3. Inversions of Stokes Profiles

The synthesis of Zeeman-split OH lines also helps to improve the diagnostic capability of atomic lines. In sunspots, strong OH lines from the (3,1) band are observed in the vicinity of the Zeeman sensitive Fe I 15648.5 Å line and are blended with Fe I 15652.9 Å. Together, these two Fe I lines are the premier infrared diagnostics of the solar magnetic field (e.g. Solanki et al. 1992) and are being increasingly widely used. Inverting the Stokes parameters of the blending OH lines along with the Fe I lines greatly improves the reliability of magnetic, thermal and dynamic quantities deduced from these lines in sunspot umbrae.

With the inversion code described by Frutiger et al. (2000), we carried out the inversion of Stokes parameters observed in the central part of an umbra where the strength of molecular lines was the largest. These observations are fully described by Mathew et al. (in preparation). Our simplified model included two components, one magnetic and one nonmagnetic. The first represents the umbra itself, while the second describes the contribution from the photospheric stray light. Two inversions were carried out, one disregarding the blending

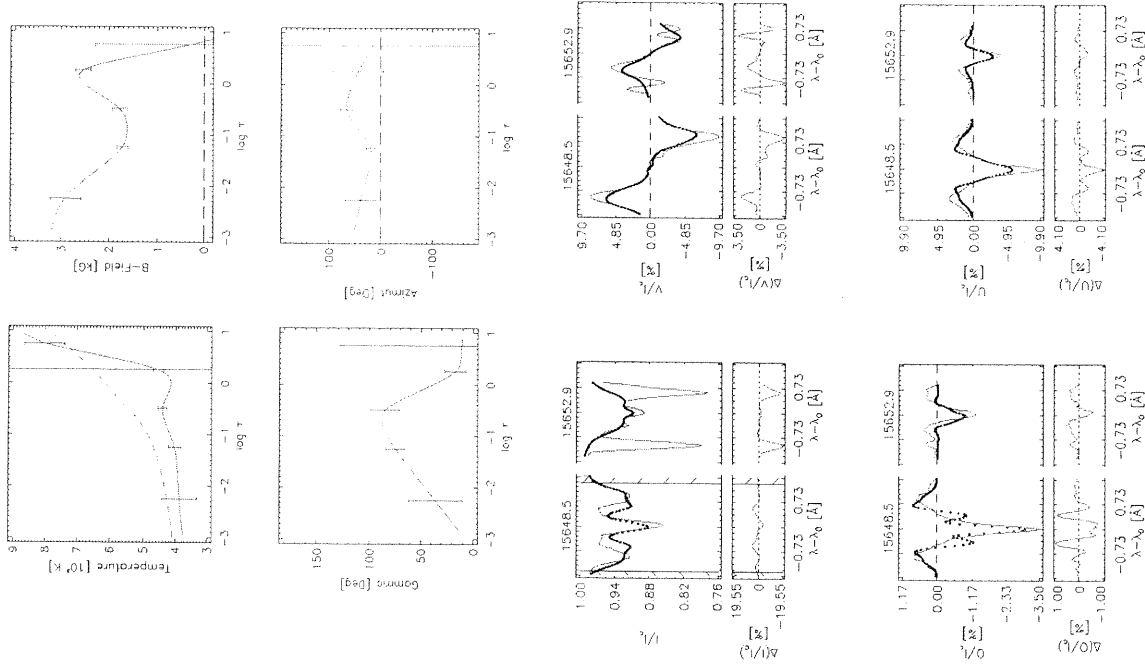


Figure 3. The umbral atmosphere deduced from the inversion of Fe I profiles only (upper 4 panels) and the corresponding fits (dots) to the observed Stokes profiles (solid lines; lower 4 panels). In the atmosphere plots, the solid curves represent the magnetic component of the model, while the dashed curve shows the temperature distribution in the nonmagnetic component.

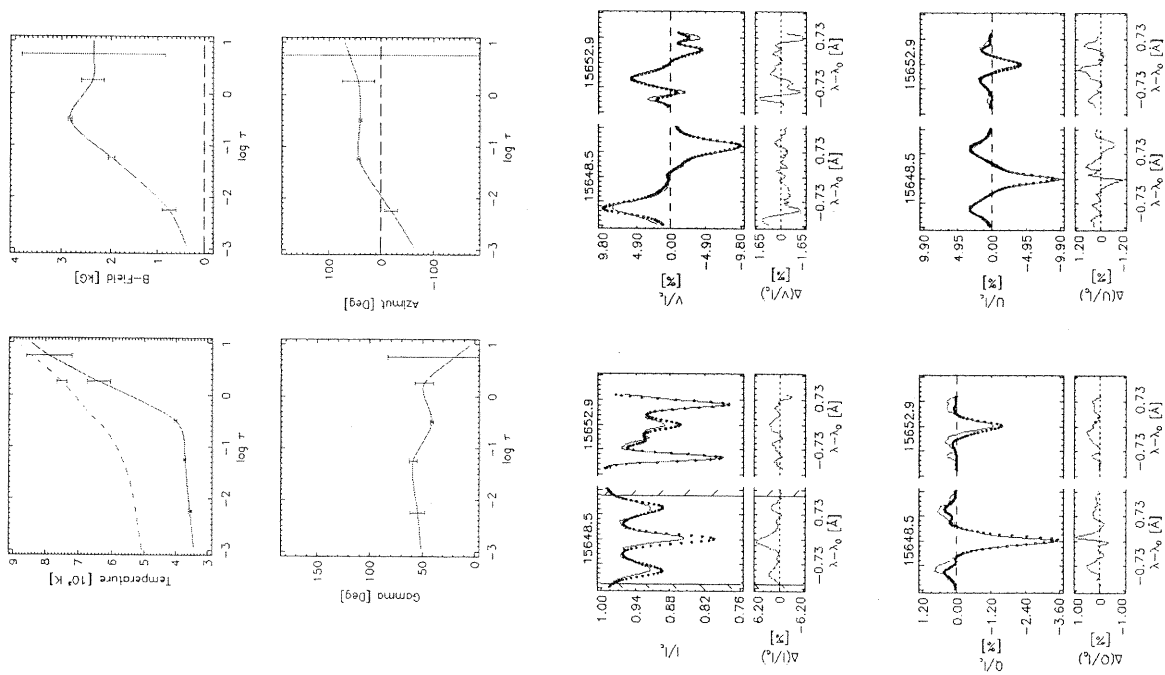


Figure 4. The same as Fig. 3 for the inversion including both Fe I and OH lines.

OH lines, the other including them. As the Fe I and OH lines are formed in different parts of the umbral atmosphere, the effect of including the OH lines was largest in the upper layers, at optical depths $\log \tau \leq -1$. Without OH lines, the nonmagnetic component is too cool, the field strength in the magnetic component grows unreasonably towards smaller optical depths and the vector of the field changes its direction with respect to the line of sight (Fig. 3). Also, the fit to the Stokes parameters is not satisfactory (Fig. 3). If the OH lines are included in the calculations, the behavior of the magnetic component is more reasonable, i.e. the field strength smoothly drops towards higher layers and the field direction corresponds well to the observed position of the sunspot on the solar disk. Also, the nonmagnetic component becomes as hot as the photosphere (Fig. 4). Finally, the fit to the profiles becomes acceptable for such a simple model (Fig. 4). Further calculations are needed to test if this result is robust.

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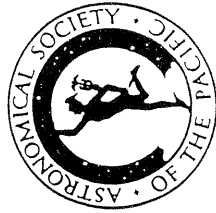
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Edited by

Alexei A. Pevtsov
National Solar Observatory, Sacramento Peak, Sunspot, New Mexico, USA

and

Han Uitenbroek
National Solar Observatory, Sacramento Peak, Sunspot, New Mexico, USA