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Molecular Diagnostics of the Internal Structure of Starspots and Sunspots

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Abstract. We have analyzed the usefulness of molecules as a diagnostic tool for studying solar and stellar magnetism with the molecular Zeeman and Paschen-Back effects. In the first part we concentrate on molecules that are observed in sunspots such as MgH and TiO. We present calculated molecular line profiles obtained by assuming magnetic fields of 2–3 kG and compare these synthetic Stokes profiles with spectro-polarimetric observations in sunspots. The good agreement between the theory and observations allows us to turn our attention in the second part to starspots to gain insight into their internal structure. We investigate the temperature range in which the selected molecules can serve as indicators for magnetic fields on highly active cool stars and compare synthetic Stokes profiles with our recent observations.

1. Introduction

Atoms have been heavily used in the past years to study stellar photospheres. Nevertheless molecules possess clear advantages for analyzing solar and stellar magnetism with the Zeeman and Paschen-Back effects.

Since molecular lines are extremely temperature sensitive, they can probe the thermal and magnetic structure of sunspots and starspots. In addition they can be treated in LTE in higher layers (unlike atoms) which allows us to extend sunspot models via inversions: different molecules are formed at different depths and therefore probe the atmospheric stratification, even on a fine grid, if several lines of the same molecule are used (Fig. 1). In examining spatially unresolved cool stellar spots the use of molecular over atomic lines is favorable, as the latter obtain strong contribution from outside the spot umbra. The effect can be demonstrated with the help of sunspot observations (Fig. 2). Compared to the photospheric spectrum without signal in circular polarization (Stokes V), atomic signals already appear in the penumbral spectrum, while molecular lines weakly show up in the lightbridge spectrum and become striking in the umbral spectrum. A review of the Zeeman and Paschen-Back effects in molecules is given by Asensio Ramos (2006).

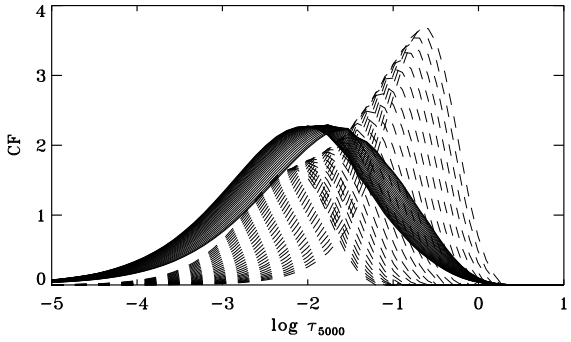

Figure 1. Contribution functions of the normalized, Stokes-I line depression of the bands of TiO $\gamma(0,0)\mathrm{R}_3$ (solid lines) and MgH A-X$(0,0)\mathrm{Q}_1$ (dashed lines), for $T_{\mathrm{eff}} = 3750\,\mathrm{K}$ (from Berdyugina, Solanki, & Frutiger 2003).

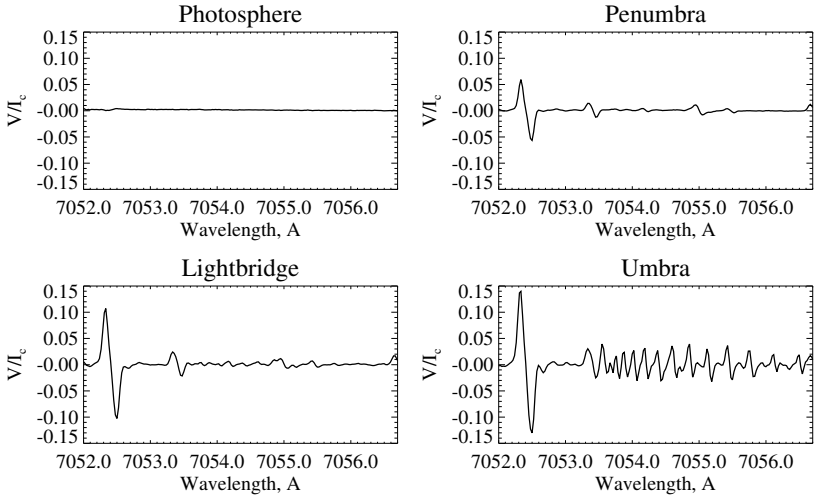

Figure 2. Stokes-V signal in the TiO band-head observed on the quiet Sun, sunspot penumbra, lightbridge, and umbra. Atomic lines start to show up in the penumbra. TiO lines appear in the lightbridge and become dominant in the umbra.

2. Sunspots

Direct Modeling. In order to test whether our current understanding of the molecular Zeeman and Paschen-Back splitting is good enough for calculating and reproducing Stokes profiles observed in sunspots, we carried out the forward spectral synthesis of Stokes parameters for the molecular TiO $\gamma(0,0)\mathrm{R}_3$ band head at 7055 Å and the MgH A-X(0,0) transitions at 5200 Å with the code STOPRO (Solanki 1987; Frutiger et al. 2000; Berdyugina, Solanki, & Frutiger 2003). TiO has to be treated in the Zeeman regime and MgH in the Paschen-Back regime, with the new Paschen-Back algorithm implemented in STOPRO according to the theory by Berdyugina et al. (2005).

Comparison of the synthetic profiles for MgH and TiO with profiles obtained from THEMIS observations (Arnaud et al. 2006) shows reasonable fits to the

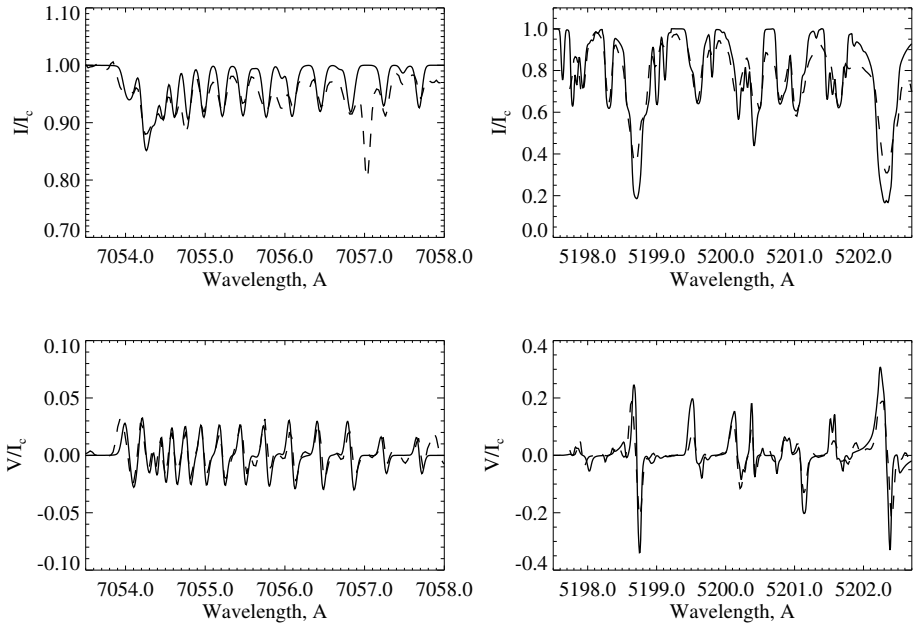

Figure 3. TiO (left panels) and MgH (right panels) line profiles. Sunspot observations (dashed lines) and comparison with calculated Stokes I and V profiles (solid lines) for atmospheric models (Kurucz 1993) with $T_{\rm eff} = 4250$ K and $T_{\rm eff} = 4000$ K, field strengths of 3 kG and 2 kG, and filling factors of 0.55 and 0.85, for TiO and MgH, respectively.

main features of Stokes I (Fig. 3, upper panels). The fits are not perfect since not all blends are identified and the intensity spectrum is very sensitive to small changes in opacity, which cannot be taken into account sufficiently by using forward modeling. This however does not influence Stokes V, which can be well fit (Fig. 3, lower panels), because the above mentioned unidentified blends are not magnetically sensitive.

Better fits to Stokes-I profiles can be achieved by using inversions. The direct modeling is still useful as preparation for the inversions since it allows an estimation of the input parameters for the inversion from its results.

Inversions. Using the inversion code SPINOR by Frutiger et al. (2000, which includes direct modeling by STOPRO) and the THEMIS spectra, we first inverted Fe I lines at 5250 Å as a test of the inversion code. Due to their comparative temperature insensitivity, the model deduced from these lines alone does not give an excellent representation of the simultaneously observed molecular lines. The model can be improved dramatically if molecules are included into the inversions due to their large temperature sensitivity, since different molecules probe different depths of the atmosphere and provide us with a more complete model of the sunspot. Here we used two Fe I lines, four (blended) MgH lines and eleven (blended) TiO lines. These results are the first incorporation of MgH and TiO lines into inversions. A two-component model with one quiet-Sun and one magnetic component was employed, where the former is responsible for stray light in the measurements (Fig. 4). Simultaneous inversions of atomic and

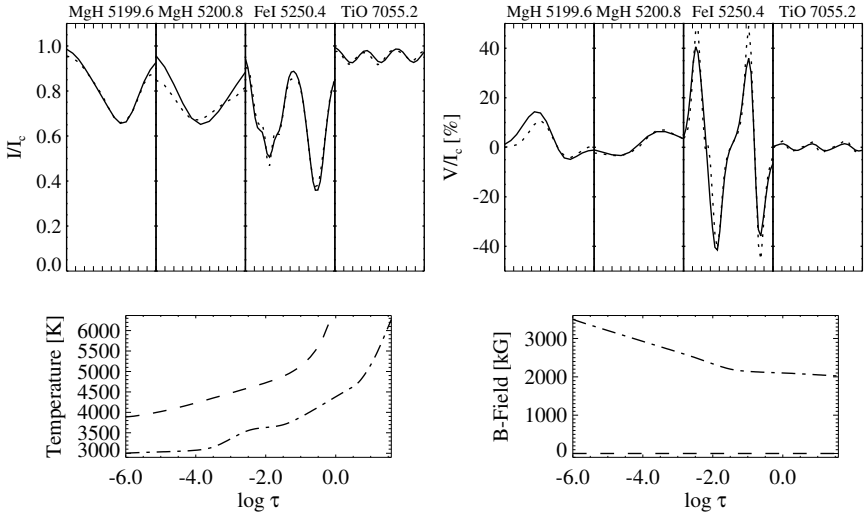

Figure 4. Simultaneous inversion of MgH, TiO, and Fe I lines. The fits (solid lines) to the observed Stokes I and V profiles (dashed lines) are shown in the upper panel. The umbral atmosphere deduced from this inversion (only temperature and magnetic field) is plotted in the lower panel representing a two-component model with one magnetic (dashed-dotted lines), and one photospheric (dashed lines) component.

molecular lines as shown in the foregoing examples are still work in progress. However, these preliminary results look very promising.

3. Starspots

Expectations. The good results for sunspots allow us to extend our investigations to the more challenging topic of cool stars. On cool stars with magnetic activity, molecular lines can provide measurements of the magnetic field directly in spatially unresolved spots, wherein they are formed.

As preparation for our observations at the Canada-France-Hawaii Telescope (CFHT) with the new spectro-polarimeter ESpADOnS in July 2005, we used a model assuming a spot size of 10% of the stellar disc and a spot comprising only longitudinal magnetic fields (left panel in Fig. 5) and estimated the strength of the Stokes-V signal in molecular lines that could be expected to be observed from starspots.

We combined different photosphere and spot models to calculate the Stokes-V signal for MgH and TiO and obtained a maximum signal of $\sim 0.5\%$–1.0% in both. In the right panel of Fig. 5, an example with $B = 2\,\mathrm{kG}$, $T_{\mathrm{phot}} = 5000\,\mathrm{K}$, and $T_{\mathrm{spot}} = 4000\,\mathrm{K}$ is shown for MgH and TiO.

Modeling Observations. Our observations at CFHT with ESpADOnS (Berdyugina et al. 2006) revealed Stokes-V profiles of TiO in the spectra of several M dwarfs that were very similar to those obtained by our simple modeling. This was the very first detection of circular polarization in molecular lines forming in magnetic fields on the surfaces of cool active stars!

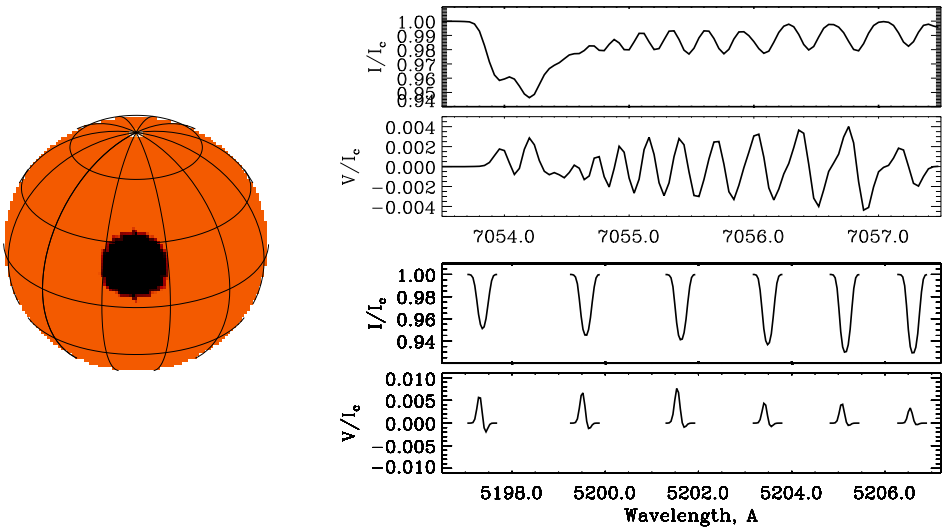

Figure 5. Combinations of the photosphere and spot models for a model star with $v \sin i = 10$ km/s, 10% longitudinal magnetic field of 2 kG, $T_{\rm phot} = 5000$ K, $T_{\rm spot} = 4000$ K. *Upper panels:* TiO. *Lower panels:* MgH

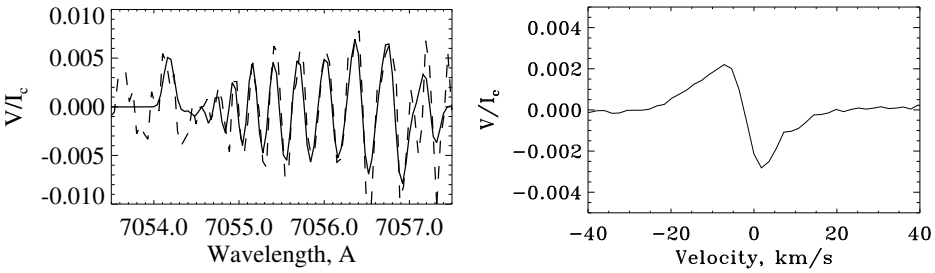

Figure 6. Modeled (solid lines) and observed (dashed lines) Stokes V/I_c of the TiO lines on the active M dwarf EV Lac (left panel), and its average atomic Stokes V profile extracted with the LSD technique (right panel).

We applied our simple model to all the observed stars and only adjusted magnetic field strengths and temperatures. In the left panel of Fig. 6 observed and modeled circular polarization in the TiO 7055 Å band for the active M dwarf EV Lac is shown. The model with longitudinal magnetic fields of 3.8 kG for 10% of the stellar disc, $T_{\rm phot} = 3750$ K, and $T_{\rm spot} = 3000$ K fits the observation almost perfectly. In the right panel of Fig. 6 the average atomic Stokes-V profile (extracted with the LSD technique developed by Donati et al. 1997) for the same star is shown. It appears to be an almost antisymmetric profile indicating a single polarity field as in our model. The same applies also for another observed M dwarf FK Aqr with the difference that the signal in the atomic LSD profile reveals it as a binary. The fits for EV Lac (left panel in Fig. 6) and FK Aqr (left panel in Fig. 7) with our model are fairly good unlike for the M dwarf AU Mic (right panel in Fig. 7) which can be explained by examining the atomic LSD profile: On AU Mic a mixed polarity field seems to cause cancelations in the spectrum, leading to a poorer fit to our single polarity model.

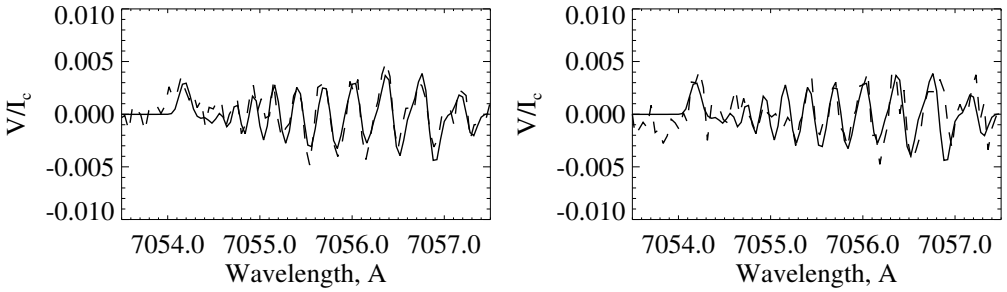

Figure 7. Modeled (solid lines) and observed (dashed lines) Stokes V/I_c of the TiO lines on the active M dwarfs FK Aqr (left) and AU Mic (right).

4. Conclusions

We have discussed the use of molecular lines for analyzing solar and stellar magnetic fields by the means of the molecular Zeeman and Paschen-Back effects. It has been shown that Stokes profiles observed in sunspots can be well fit by synthetic profiles obtained with the molecular Zeeman and Paschen-Back theories.

The information deduced from the direct modeling was applied to inversions to improve sunspot models. Including molecular lines as MgH and TiO into inversions seems to be a promising tool to make the sunspot models more reliable and to obtain a three dimensional picture of sunspots. Definitely more simultaneous inversions of atomic and molecular lines should be carried out.

The good results for sunspots allowed us to extend our study to cool stars where we modeled various scenarios prior to our observations to calculate the expected circular polarization signal in MgH and TiO lines. The successful first ever observation of circular polarization in molecular lines on several M dwarfs supported the predictions of our modeling.

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