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Solar and Stellar Magnetic Fields: the Molecular Zeeman Effect as a Probe

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Abstract. We present a short overview of magnetic properties of molecular lines observed in optical and near IR spectra of the solar umbra, penumbra and photosphere. These lines demonstrate a range of magnetic sensitivities and undergo magnetic splitting either in the Zeeman or Paschen-Back regime at magnetic field strengths typical for the Sun and cool stars. We show that calculated Stokes profiles of lines in the different regimes fit observations reasonably well and conclude that these lines can be used for future studies of solar and stellar magnetic fields.

1. Introduction

In the visible part of the sunspot spectrum, lines of about 10 diatomic molecules have been identified. They arise due to electronic-vibration-rotational transitions. In the red and near IR, lines of the FeH, CN A–X, TiO γ and δ, MgH A–X and CaH A–X systems dominate the spectrum. In the green part, these are α, β, γ' systems of TiO, A–X and B–X systems of MgH and CaH. In the blue, these are CN B–X and three CH systems. Also, lines of the C_2 Swan system appear in spectra of penumbrae at around 5000 Å.

Molecular lines are often an irritation, when studying profiles of atomic lines, since most of the latter seem to be blended by molecular lines in the sunspot spectrum. Also, Stokes V profiles of molecular lines often exhibit a puzzling behaviour (Nicholson 1938; Harvey 1973, 1985; Rüedi et al. 1995). For example, the observations by Harvey (1985) revealed a reversal of the circular polarization of IR OH lines within the same band system. Observations indicate that, in addition to their high temperature and pressure sensitivity, at least some molecular lines are magnetically sensitive. To date, however, few observations of Zeeman-split molecular lines have been made (Wöhl 1969) and even fewer calculations are available (Schadee 1978; Illing 1981; Berdyugina et al. 2000). It is the aim of this contribution to give an overview of magnetic properties of molecular lines observed in the visible sunspot spectrum.

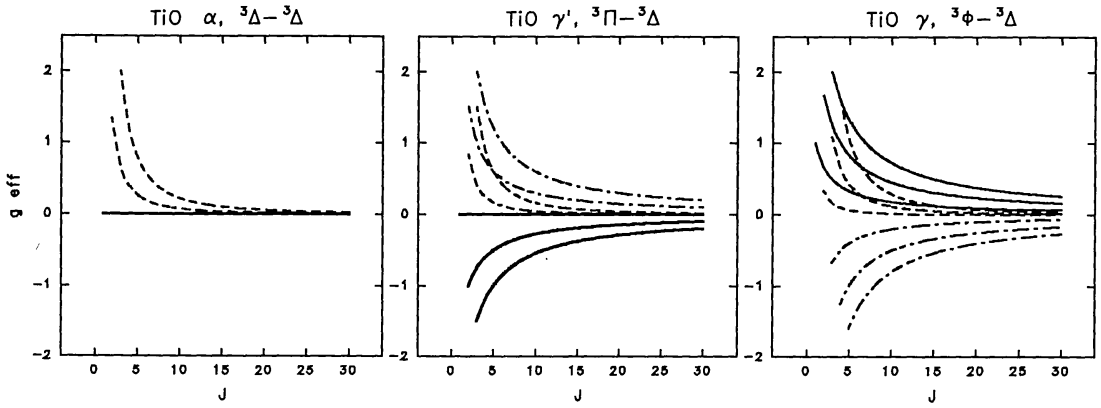

Figure 1. Calculated effective Landé factors for lines of different rotational branches of the TiO α, γ' and γ systems (the Zeeman regime). R, Q and P branches are plotted with solid, dashed and dashed-dotted lines, respectively; J is the total angular momentum number of the lower level. Note that all P and R branches have zero Landé factors in the α-system. In the γ'-system, all branches arising from the first multiplet sublevel, i.e. R_1, Q_1, P_1, have $g_{\rm eff} = 0$. The magnetically sensitive P and R branches always possess $g_{\rm eff}$ of opposite signs.

2. The molecular Zeeman effect

As in the atomic case, molecular lines can appear either in the Zeeman or Paschen-Back regime, depending on the strength of the applied magnetic field and the molecular constants.

In *the Zeeman regime* (ZR), the magnetic splitting of molecular sublevels is smaller than their multiplet or rotational splitting. At the solar surface field strengths, this is the case for all TiO band systems, CH A–X and C_2 systems as well as for a few first rotational sublevels of FeH. In this regime, the magnetic splitting of levels and lines is symmetrical, and partial sums of strengths of π and σ components are equal, so that lines are not shifted with respect to their zero-field positions (e.g. Berdyugina et al. 2001). The splitting is larger for low J numbers and decreases with increasing J. We calculated the effective Landé factors, $g_{\rm eff}$, for all systems in this regime and found the following properties.

- $g_{\rm eff}$ of P and R branches, if not zero, always have opposite signs, so that lines can show reverse polarization profiles.

- Two band systems, TiO α and C_2 Swan, are not magnetically sensitive, i.e. the $g_{\rm eff}$ of their P and R branches equal zero. Lines of Q branches appear as simple Zeeman triplets, but their total intensity is very small (Figure 1).

- In the TiO γ'-system, all branches arising from the first multiplet sublevel, i.e. R_1, Q_1, P_1, have $g_{\rm eff} = 0$. The largest splitting is achieved in the R_3 and P_3 branches: $|g_{\rm eff}| \leq 2$ (Figure 1).

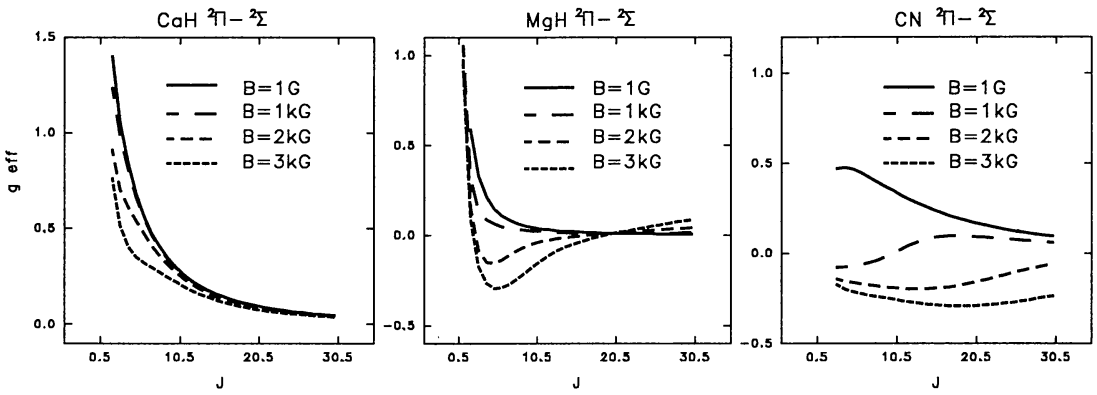

Figure 2. Calculated effective Landé factors for the R_2 branches of the A–X systems of CaH, MgH and CN at different magnetic field strengths (the Paschen-Back regime).

- Out of all TiO systems, the γ-system is the most magnetically sensitive, especially the P_3 and R_3 branches with $|g_{\rm eff}| \leq 2.1$ (Figure 1).

- The singlet TiO β- and δ-systems show moderate magnetic sensitivity with $|g_{\rm eff}| \leq 1.6$.

- Lines of the CH A–X system can be treated in the ZR approximation at solar magnetic field strengths. The largest splitting is expected for lines of the main branches R_2 and P_2 with $|g_{\rm eff}| \leq 1.9$ and of the satellite branches R_{21} and P_{21} with $|g_{\rm eff}| \leq 2.1$.

- At least the few first rotational FeH lines are in the ZR at sunspot magnetic field strengths ($J \leq 5.5$). From the main branches, only lines of Q branches show non-zero splitting and appear as simple Zeeman triplets ($g_{\rm eff} \leq 2.2$). Larger splitting is found for satellite branches ($|g_{\rm eff}| \leq 2.9$).

In *the Paschen-Back regime* (PBR), the magnetic splitting is comparable to or larger than the fine or rotational structure splitting. This is the case for the other molecular band systems observed in the visible. The levels of the fine structure disturb each other and, as a result, the splitting of levels and lines become nonsymmetrical and the intensities of π and σ components are not balanced. Lines are shifted and their total intensities are modified (e.g. Berdyugina et al. 2001).

In this case, the effective Landé factors become dependent on the magnetic field strength. At weak fields, they behave as in the ZR, but deviations occur as the field strength increases. For example, A–X systems of CaH, MgH and CN have the same electronic transition, $^2\Pi - ^2\Sigma$, but different spin-rotational coupling constants for the lower state $^2\Sigma$. Deviations from the ZR are smaller for the stronger coupling in CaH and larger for the weaker coupling in MgH and CN (Figure 2). Even the sign of the polarization can be changed when the field strength increases. Also, since the relative strengths of π and σ components change, lines can appear as one-lobed Stokes V profiles.

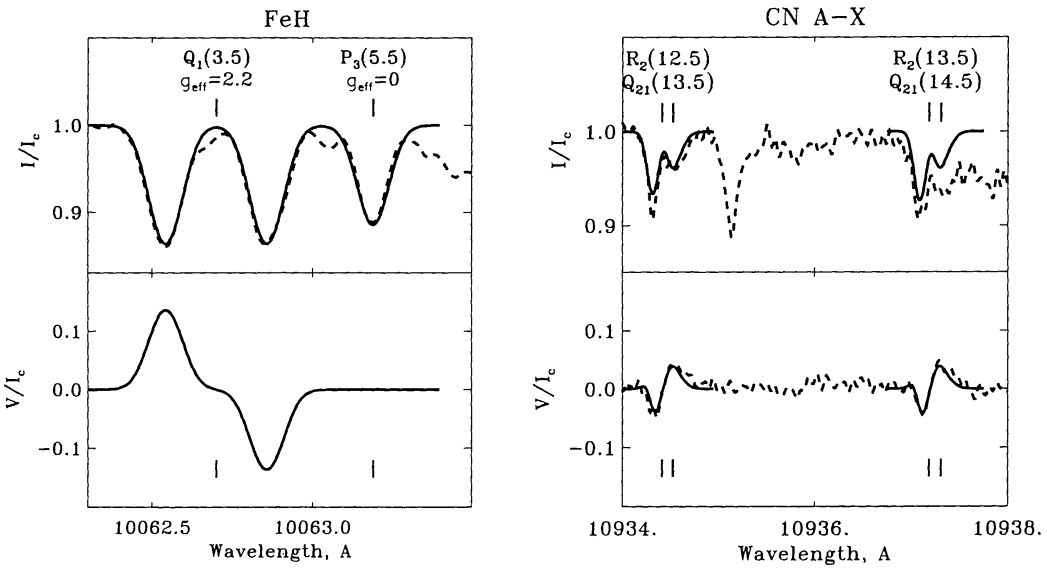

Figure 3. Stokes I and V of FeH and CN lines. Observations (dashed) are from Wallace et al. (1998) and Rüedi et al. (1995), respectively. Synthetic Stokes profiles (solid) are calculated for a field strength of 3000 G and an angle between the magnetic vector and the line of sight of 0° for FeH and 180° for CN. The zero-field positions of lines are indicated by vertical dashes.

We tested our calculations by confronting observed and synthetic Stokes profiles. With the code STOPRO (Solanki et al. 1992; Frutiger et al. 2000) we made a forward spectral synthesis of molecular Stokes parameters and found that our calculations fit well Stokes I and V of the TiO $\gamma(0,0)$ R_3 band head (ZR) and MgH A–X P_1 and P_2 lines (PBR) (Berdyugina et al. 2000). Two more examples are shown in Figure 3: FeH Q and P branch lines (ZR) and CN A–X R_2 lines with their satellite lines Q_{21} (PBR). Note that in the CN lines we observe a rather extreme Paschen-Back effect. The observed Stokes V profiles look almost normal, but, in fact, one lobe of the profile belongs to the main rotational line R_2 and the other to the satellite line Q_{21}, and, thus, the observed "splitting" of the profile is not straightforwardly related to the magnetic field strength.

3. Conclusions and future applications

We found that most of molecular lines observed in sunspot spectra are magnetically sensitive. The good fit to Zeeman-split molecular lines, including Stokes V profiles determined by the Paschen-Back effect, suggests that the theory employed is adequate. We also showed that the puzzling reverse circular polarization and unconventional Stokes V profiles of some molecular lines occur due to negative Landé factors or the Paschen-Back effect.

As a further development, inversions of molecular lines observed in spectra of solar umbrae (TiO, FeH, MgH, CaH, CN) and penumbrae (MgH, CN, C_2) can improve the current models of sunspots. With these molecules, the coolest parts

of umbrae and penumbrae at field strengths of 1–3 kG can be investigated. Also, small-scale strong and weak magnetic field regions (1-2 kG) can be studied.

On cool stars with magnetic activity, such as T Tau stars, solar type G-K dwarfs, RS CVn- and FK Com-type stars, molecular lines can provide measurements of magnetic fields directly in spatially unresolved spots, wherein they are formed. As soon as high-resolution spectropolarimetric observations of molecular lines in cool stars will be available, the inversion technique used for studying sunspots can be applied also to studying starspots and to recovering their internal thermal and magnetic structure.

Since molecular lines dominate spectra of cool Me and brown dwarfs, their magnetic fields can be measured only by means of the molecular Zeeman effect (e.g. Valenti et al. 2001). This will help in understanding how strong the magnetic fields in fully convective stars can be.

A number of magnetic white dwarfs show only molecular bands in their spectra, some of these bands being unidentified. With the development of the theory of the molecular Paschen-Back effect for very strong magnetic fields and different coupling cases, the identification of the bands as well as measurements of magnetic field strengths would be possible.

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Discussion

LANDSTREET: Have you calculated linear polarization (Q/U) spectra? Is the effect expected to be observable so that you can do vector magnetometry with these lines?
BERDYUGINA: Yes, we made calculations of Stokes Q and U of molecular lines. For lines with large Landé factors, the effect is strong enough to be observed.
VAN BALLEGOOIJEN: Have you computed the Zeeman effect in CO lines? The CO molecule is believed to play an important role in cooling the temperature minimum region, and there is some debate as to where these lines are formed. Perhaps V-profile observations of these lines can help to resolve these issues.
BERDYUGINA: We know that IR CO lines are magnetically sensitive but we have not made calculations of them yet. This is a part of our future developments.
VALENTI: Very interesting results. I have had trouble finding Landé factors for the FeH molecule. Do I understand correctly that you can calculate these Landé factors from first principles? Do the predicted Landé factors for FeH reproduce sunspot observations?
BERDYUGINA: Yes, we made calculations of the Landé factors for FeH in the Zeeman regime for all allowed branches, including satellite ones. This showed that main R and P branches have effective Landé factors equal to zero, while all other branches are strongly magnetically sensitive, especially for the transitions involving levels of $\Omega = 7/2$ and $5/2$. With these, we were able to reproduce the observed Stokes I profiles of $Q_{7/2,7/2}(3.5)$ and $P_{3/2,3/2}(5.5)$ lines, the former being completely split and the latter having $g_{\rm eff}$=0.