Detection of the Molecular Zeeman Effect in Circular Polarization on Cool Active Stars

S.V. Berdyugina\textsuperscript{1,2}, P. Petit\textsuperscript{3}, D.M. Fluri\textsuperscript{1}, N. Afram\textsuperscript{1}, J. Arnaud\textsuperscript{4}

\textsuperscript{1} Institute of Astronomy, ETH Zurich, 8092 Zurich, Switzerland
\textsuperscript{2} Astronomy Division, PO Box 3000, 90014 University of Oulu, Finland
\textsuperscript{3} Max-Planck-Institut für Sonnensystemforschung, Max-Planck-Str. 2, D-37191 Katlenburg-Lindau, Germany
\textsuperscript{4} Laboratoire d’Astrophysique de Toulouse et Tarbes (LATT) OMP, 14, Avenue Edouard Belin, F-31400 Toulouse, France

Abstract. We report on the first ever detection of circular polarization in molecular lines forming in magnetic regions on the surfaces of active stars. The new observations were obtained with the high-resolution spectropolarimeter ESPaDOnS recently installed at the Canada-France-Hawaii Telescope. In July 2005 we carried out a survey of 17 G-K-M stars including active main-sequence dwarfs and RS CVn-type giants and subgiants. All stars were found to possess surface magnetic fields producing average atomic Stokes V signals of 0.05\% to 0.5\%. Three stars clearly showed circular polarization in molecular lines of 0.5\% to 1\%. The molecular Stokes V signal is reminiscent of that observed in sunspots.

1. Introduction

Starspots are the best studied proxy of stellar magnetism. Large stellar brightness variations and indirect imaging of stellar surfaces with the Doppler Imaging (DI) technique indicate immense starspot regions as compared to sunspot sizes. Molecular lines provide an additional evidence of cool spots on the surfaces of active stars. If the effective temperature of the stellar photosphere is high enough, molecular lines can only be formed in cool starspots. The first detection of molecular bands from starspots was reported by Vogt (1979) for a star whose spectral type K2 was not compatible with the presence of TiO and VO bands. From the relative strengths and overall appearance of the molecular features, an equivalent spectral type of the spot spectrum was estimated as late as M6.

Polarimetric measurements of starspots help to investigate the nature of the underlying magnetic fields. However, most of our current knowledge about magnetic fields on cool stars and in starspots is based on Zeeman broadening measurements, which reveal the distribution of magnetic field strengths with little dependence on the unknown field geometry. An overview of the published measurements of magnetic fields on the surfaces of cool stars (Berdyugina 2005) indicates a tendency for cooler dwarfs to have stronger magnetic fields and larger areas covered by them. Also, there is evidence that different techniques reveal different activity signatures, such as spot umbrae and penumbrae, or even faculae. The latter two, being brighter and possessing relatively strong magnetic fields, would be better seen in atomic lines. This is also supported
by results obtained with the Zeeman-Doppler Imaging (ZDI) technique, which reveals stronger magnetic fields for intermediate brightness regions, and the magnetic field distribution does not coincide with the darkest spots in the temperature images (e.g. Donati & Collier Cameron 1997). Thus, it appears that umbral magnetic fields have not been measured as yet.

Spectropolarimetry in molecular lines which are only formed in starspot umbras can provide measurements of magnetic fields directly in spatially unresolved spots. For example, the strongest TiO band at 7055 Å is magnetically quite sensitive, having effective Landé factors up to 1 (Berdyugina & Solanki 2002; Berdyugina et al. 2003). Thus, a clear Stokes V signal in the TiO band is expected from starspots (Berdyugina 2002; Afram et al. 2006). Here we report the results of our spectropolarimetric survey of active G-K-M stars.

2. Observations

Observations were carried out in July, 14–16, 2005, at the Canada-France-Hawaii Telescope (CFHT) with the new spectropolarimeter ESPaDOnS (Donati 2006). All measurements were made in the circular polarization mode with four subsequent exposures at different polarization angles. The calibration and reduction procedures included corrections for the dark current, flat-field, Fabry-Pérot calibration, etc. The maximum polarimetric accuracy achieved was $10^{-3}$.

Our survey included a sample of cool active stars: ten G–M dwarfs and seven G–K components of RS CVn-type systems (Table 1). The selected stars are moderate rotators ($v \sin i \leq 24$ km/s) and brighter than $\sim 10$th magnitude. All are known to have cool spots on their surfaces.

3. Results

A clear Stokes V signal in the TiO 7055Å band (up to 1%) was detected on three M dwarfs (Fig. 1). Two stars (AU Mic and EV Lac) were known to have strong ($\sim 4$ kG) surface magnetic fields measured from Zeeman-broadened atomic lines (Saar 1992; Johns-Krull & Valenti 1996). It is however the first detection of magnetic fields on both components of FK Aqr. A simple modeling of the observed circular polarization indicates single-polarity magnetic fields on the three stars covering at least 10% of the stellar disk (Afram et al. 2006).

No Stokes V signal in the TiO band above the noise level of 0.1–0.2% was detected on the G–K dwarfs and giants from our list (Table 1). This implies that the magnetic fields on these stars are apparently weaker, more entangled than on M dwarfs, or more diluted by the bright photosphere.

A magnetic field was actually detected on all stars in average atomic Stokes V profiles extracted with the Least Squares Deconvolution (LSD) technique (Donati et al. 1997). For most stars this is the first detection (Table 1, Fig. 2). Note that the largest signals in the atomic Stokes V profiles were observed in the three coolest M dwarfs, where the TiO Stokes V signals were prominent as well, and in the two coolest K stars EQ Vir and II Peg, where perhaps the higher noise level prevented detection of TiO. On all these stars Stokes V profiles in individual atomic lines were also recorded. A simultaneous analysis of the Stokes I and V signals from many atomic and molecular lines with different temperature
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Table 1. Observed targets. The last two columns provide peak circular polarization (%) in atomic and molecular lines measured from LSD profiles and the TiO 7055 Å band, respectively. Upper limits are estimated from the noise level. Asterisks mark cases with first detections.

| Star    | Sp. class | V   | $v\sin i$ | P  | $V/I_c$ | $V/I_{c,TiO}$ |
|---------|-----------|-----|-----------|----|---------|---------------|
| EK Dra  | G1 V      | 7.8 | 17        | 2.6| 0.09*   | ≤0.2          |
| V478 Lyr| G8 V SB1  | 7.7 | 21        | 2.15| 0.12*   | ≤0.1          |
| ξ Boo A | G8 V      | 4.5 | 3         | 6.43| 0.06    | ≤0.1          |
| ξ Boo B | K4 V      | 7   |           |    | 0.06    | ≤0.2          |
| EQ Vir  | K5 V      | 9.3 | 11        | 3.96| 0.36*   | ≤0.3          |
| BY Dra  | K4/M0 V   | 8.1 | 8/7       | 3.83| 0.05*   | ≤0.2          |
| SZ UMa  | M0e V     | 9.3 | <3        |    | 0.04*   | ≤0.2          |
| AU Mic  | M1 V      | 8.6 | 7         | 4.85| 0.39*   | 0.4*          |
| FK Aqr  | M2/M3e V  | 9.1 |           | 4.39| 0.30*   | 0.5*          |
| EV Lac  | M3.5e V   | 10.1| 7         | 4.38| 0.28*   | 1.1*          |
| λ And   | G8 IV     | 3.9 | 10        | 53.95| 0.09*   | ≤0.1          |
| HK Lac  | K0 III    | 6.8 | 24        | 24.46| 0.08*   | ≤0.1          |
| XX Tri  | K0 III    | 8.7 | 17        | 24  | 0.14*   | ≤0.2          |
| 29 Dra  | K1 III    | 6.7 | 8         | 31.5| 0.14*   | ≤0.1          |
| BM CVn  | K1 III    | 7.4 | 15        | 20.6| 0.19*   | ≤0.1          |
| IM Peg  | K1 III    | 5.8 | 24        | 24.65| 0.05    | ≤0.1          |
| II Peg  | K2 IV     | 7.7 | 22        | 6.7 | 0.36    | ≤0.2          |

Figure 1. Observed Stokes $I/I_c$ (upper panels) and Stokes $V/I_c$ (lower panels) of the TiO $\gamma(0,0) R_3$ band head on the active M dwarfs AU Mic, FK Aqr and EV Lac. Note a close similarity to the Stokes signals in a sunspot.
Figure 2. Observed atomic LSD Stokes $V/I_c$ profiles.

and magnetic sensitivities will allow us to disentangle the contributions from the photosphere, faculae and starspot umbrae and penumbrae.

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