First Direct Detection of Magnetic Fields in Starspots and Stellar Chromospheres

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Abstract. Here we report on the first detection of circular polarization in molecular lines formed in cool magnetic regions (starspots) and in chromospheric emission lines formed in hot plages on the surfaces of active stars. Our survey of G-K-M stars included young main-sequence dwarfs and RS CVn-type giants and subgiants. All stars were found to possess surface magnetic fields producing Stokes V LSD signals in atomic lines of 0.05% to 0.5%. Several stars clearly showed circular polarization in molecular lines of 0.1% to 1%. The molecular Stokes V signal is reminiscent of that observed in sunspots. Chromospheric magnetic fields were detected on most active targets in Stokes V profiles of emission lines with peak polarization up to 2%. The observed molecular circular polarization on M dwarfs indicates single-polarity magnetic fields covering at least 10% of the stellar disk. Smaller signals on K stars imply that their magnetic fields are apparently weaker, more entangled than on M dwarfs, or more diluted by the bright photosphere.

1. Introduction

Studying magnetic activity on stars other than the Sun provides an opportunity for detailed tests of solar and stellar dynamo models, since an extensive sample of stars of various activity levels provides a wider range of global stellar parameters. The multitude of magnetic phenomena are observed on cool active stars, including starspots in the photosphere, chromospheric plages, coronal loops, UV, X-ray and radio emission, and flares.

Starspots and chromospheric plages are the best studied proxies of stellar magnetism. Large stellar brightness variations and indirect imaging of stellar surfaces with the Doppler Imaging technique indicate immense starspot regions as compared to sunspot sizes (Berdyugina 2005). Molecular lines provide 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 K2 star whose spectral type was not compat-
Table 1. Observed targets. Peak circular polarization $V/I_c$ (%) in atomic and molecular lines was 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 | $V/I_c$ | $V/I_c$ | Star       | Sp. class | $V/I_c$ | $V/I_c$ |
|------------|-----------|---------|---------|------------|-----------|---------|---------|
| EK Dra     | G1 V      | 0.09°   | ≤0.2    | AU Mic     | M1 V      | 0.39°   | 0.4°    |
| V478 Lyr   | G8 V      | 0.12°   | ≤0.1    | FK Aqr     | M2/M3Ve   | 0.30°   | 0.5°    |
| ξ Boo A    | G8 V      | 0.06    | ≤0.1    | EV Lac     | M3.5Ve    | 0.28°   | 1.1°    |
| ξ Boo B    | K4 V      | 0.06    | ≤0.2    | V1054 Oph  | M3.5Ve    | 0.14°   | 0.4°    |
| 61 Cyg A   | K5 V      | 0.03°   | ≤0.1    | λ And      | G8 IV     | 0.09°   | ≤0.1    |
| 61 Cyg B   | K7 V      | ≤0.01   | ≤0.1    | HK Lac     | K0 III    | 0.08°   | ≤0.1    |
| V833 Tau   | K5 V      | 0.29°   | 0.2°    | XX Tri     | K0 III    | 0.14°   | ≤0.2    |
| EQ Vir     | K5 V      | 0.36°   | ≤0.3    | 29 Dra     | K1 III    | 0.14°   | ≤0.1    |
| AX Mic     | K7 V      | 0.02°   | ≤0.1    | BM CVn     | K1 III    | 0.19°   | ≤0.1    |
| BY Dra     | K4/M0V    | 0.05°   | ≤0.2    | IM Peg     | K1 III    | 0.05°   | ≤0.1    |
| SZ UMa     | M0eV      | 0.04°   | ≤0.2    | V1762 Cyg  | K1 IV     | 0.07°   | ≤0.1    |
|           |           |         |         | II Peg     | K2 IV     | 0.36°   | 0.1°    |

2. Observations

Observations were carried out on July 14–16, 2005, and on August 1–3, 2006, at the Canada-France-Hawaii Telescope (CFHT) with the new spectropolarimeter ESPaDOnS. Measurements were made in the circular polarization mode with four subsequent exposures at different waveplate angles. The calibration and reduction were made with the 'libre esprit' software provided at the CFHT and 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: 15 G–M dwarfs and 8 G–K components of RS CVn-type systems (Table I). The selected stars are
moderate rotators ($v \sin i \leq 24 \text{ km/s}$) 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 four M dwarfs (Fig. 1). Two stars (AU Mic and EV Lac) were known to have strong ($\sim 4 \text{ kG}$) surface magnetic fields measured from Zeeman-broadened atomic lines (Saar 1992; Johns-Krull & Valenti 1996) and these observations confirm those measurements. This is, however, the first detection of magnetic fields on both components of the FK Aqr and V1054 Oph binaries, each consisting of two M dwarfs. The shape of the Stokes $V$ signal is reminiscent of that observed in sunspots (Berdyugina et al. 2000). A simple modeling of the observed circular polarization indicates single-polarity magnetic fields covering at least 10% of the stellar disk (Afram et al. 2006).

A Stokes $V$ signal in the TiO band was also detected on two very active K stars from our sample, V833 Tau and II Peg, with an amplitude of only 0.1–0.2% (Table 1). The detection on other stars was limited by the noise level of 0.1–0.2% on average. 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 but one (61 Cyg B) 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 of B-field from atomic lines (Table 1, Fig. 2). Note that the largest signals in the
atomic Stokes $V$ profiles were observed on those stars, where the TiO Stokes $V$ signals were prominent as well. 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 and magnetic sensitivities will allow us to disentangle the contributions from the photosphere, faculae, and starspot umbrae and penumbrae.

The stars from our sample are known to have active chromospheres as evidenced by emission in lines such as Ca II H&K, Hα, infrared triplet Ca II lines, Na I D lines, etc. The most active stars, for which the largest LSD and TiO Stokes $V$ signals were detected, also exhibited strong polarization signals (up to 2%) in these emission lines. Examples for the four active M dwarfs are shown in Figs. 3 and 4. An analysis of such data will provide direct measurements of stellar chromospheric magnetic fields.
First Detection of Circular Polarization in Starspots and Stellar Chromospheres

Figure 3. Observed Stokes $I/I_c$ (upper panels) and Stokes $V/I_c$ (lower panels) of the Hα line on the active M dwarfs.

Figure 4. Observed Stokes $I/I_c$ (upper panels) and Stokes $V/I_c$ (lower panels) in one of the infrared Ca II lines on the active M dwarfs.

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