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# MAGNETIC FIELDS IN M DWARFS: RAPID MAGNETIC FIELD VARIABILITY IN EV LACERTAE

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## ABSTRACT

We report here our spectropolarimetric observations obtained using the CFHT Espadons high-resolution spectrograph of two M dwarf stars that standard models suggest are fully convective: EV Lac (M3.5) and HH And (M5.5). The difference in their rotational velocity makes them good targets for studying the dependence of the magnetic field topology in M dwarfs on rotation. Our results reveal some aspects of the field topology in EV Lac and HH And. We measured mean longitudinal magnetic field strengths ($B_z$) in EV Lac ranging from $18 \pm 3$ to $-40 \pm 3$ G. The $B_z$ variations are seen to occur on a timescale of less than 50 minutes, which is significantly shorter than the rotation period, and are not due to a flaring event. We discuss some formation scenarios of the Zeeman signatures found in EV Lac. For HH And we could not detect circular polarization and thus we place an upper limit on $B_z$ of 5 G.

*Subject headings:* stars: individual (EV Lacertae, HH Andromedae) — stars: low-mass, brown dwarfs — stars: magnetic fields — techniques: polarimetric — techniques: spectroscopic

## 1. INTRODUCTION

A large number of M dwarfs have been detected in the last few decades, and our knowledge of these faint stars has kept improving, but there are still many challenges for research on their magnetic activity. Main-sequence stars are expected to be fully convective if their mass lies below a certain value, about 0.3–0.4 $M_\odot$ (M3–M4 spectral types), as suggested by stellar evolution theory; this probably shifts toward lower masses due to the influence of the magnetic field (Cox et al. 1981; Mullan & MacDonald 2001). In fully convective stars, the magnetic field may be produced by dynamo processes (Durney et al. 1993) that differ from the shell dynamo at work in partly convective Sun-like stars. However, the nature of these dynamos is not clear (Liebert et al. 2003). In addition, recent models (Dobler et al. 2006; Chabrier & Küker 2006) disagree with the observations, as pointed out in Donati et al. (2006).

One way to understand the nature of magnetic activity in M dwarfs, especially in fully convective stars, is to directly measure magnetic fields. In the two last decades, magnetic fields in late-type main-sequence stars have been measured for G and K dwarf stars (Robinson et al. 1980; Marcy 1984; Saar et al. 1986; Basri & Marcy 1988; Valenti et al. 1995; Rüedi et al. 1997) and M dwarfs (Saar & Linsky 1985; Johns-Krull & Valenti 1996; Saar 2001; Reiners & Basri 2006 and references therein). The basic idea of the measurement method employed by these authors is a comparison of differential Zeeman broadening between magnetically sensitive and insensitive spectral lines, through unpolarized high-resolution spectra. These line-broadening measurements have indicated that in some active M dwarfs the stellar surface is covered with magnetic fields of 3–4 kG, with a filling factor of about 50%; however, these measurements provide poor information on the field topology. One should note that an early attempt to search for circular polarization in M dwarfs was carried out by Vogt (1980), but there was no clear detection. In this Letter, we report our analysis of polarized high-resolution spectra of two M dwarf stars: a rapidly rotating M3.5 (EV Lac) and a slowly rotating M5.5 (HH And). Based on their spectropolarimetry presented in § 2, we discuss some interesting aspects on the complex field topology in EV Lac and HH And in § 3.

## 2. TARGETS, SPECTROPOLARIMETRIC OBSERVATIONS, AND DATA REDUCTION

### 2.1. *Targets*

#### 2.1.1. *EV Lac (Gl 873)*

The star is a fast rotator for an M dwarf: $v \sin i = 4.5$ km s$^{-1}$ (Johns-Krull & Valenti 1996); with this rotational velocity EV Lac is expected to have a strong magnetic field. This is therefore a good target to study the dependence of the magnetic dynamo on rapidly rotating M stars. EV Lac is also well known as an M3.5 flare star (Osten et al. 2005 and references therein); the strong H$\alpha$ emission observed (Stauffer & Hartmann 1986) indicates a high chromospheric activity level in EV Lac. The rotational period of the star is about 4 days, derived from its rotational velocity and the corresponding radius of an M3.5 dwarf ($R \sim 0.36\ R_\odot$; Chabrier & Baraffe 1997; Favata et al. 2000). Pettersen et al. (1992) have also well determined a photometric period of 4.4 days for EV Lac. The mean field measurements using synthetic spectrum fitting have previously been reported: $|B| = 4.3$ kG, $f = 85\%$ in Saar (1994); and $|B| = 3.8$ kG, $f = 50\%$ in Johns-Krull & Valenti (1996). However, no measurements of its longitudinal magnetic field $B_z$ have been reported so far.

#### 2.1.2. *HH And (Gl 905)*

The M5.5 dwarf star, in contrast with EV Lac, is a slow rotator: $v \sin i < 1.2$ km s$^{-1}$ (Delfosse et al. 1998). This is therefore a good target to study the dependence of the magnetic dynamo on slowly rotating M stars. That no H$\alpha$ emission is detected (Stauffer & Hartmann 1986) indicates a very low chromospheric activity level in HH And. Its rotational period is longer than 7 days, derived from an upper limit for $v \sin i$ as given above and an M5.5 dwarf radius ($R \sim 0.17\ R_\odot$; Cha-

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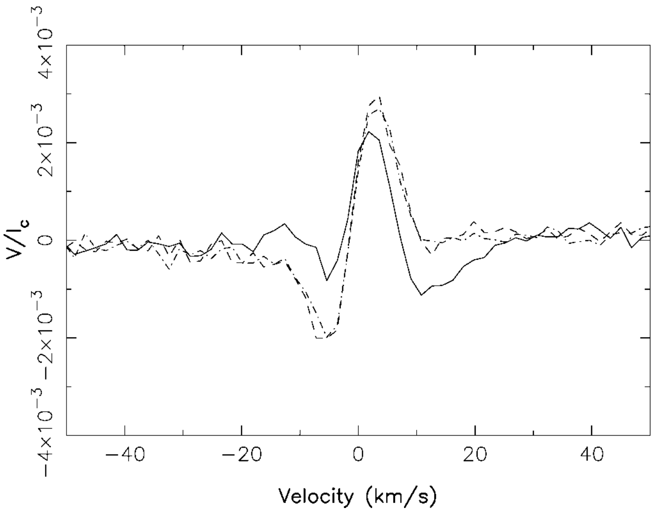


FIG. 1.—Stokes $V$ profiles of EV Lac (Gl 873; M4.5). *Solid line*, First exposure; *dashed line*, second exposure; *dash-dotted line*, third exposure. Each exposure was 50 minutes. A positive blueward component (*solid line*) implies a mixed polarity in the first exposure.

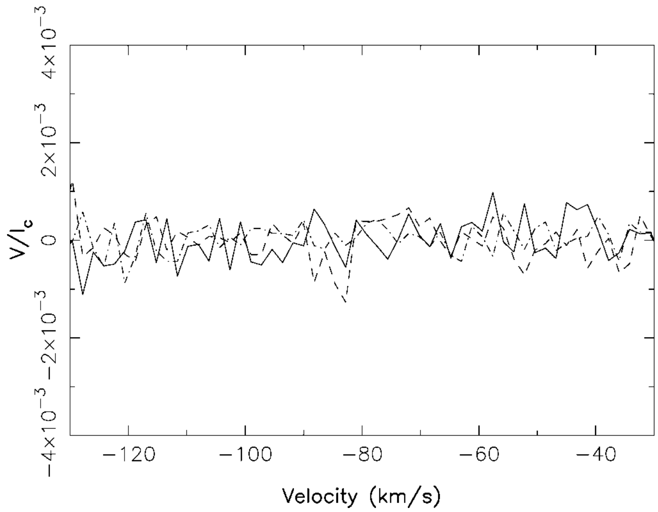


FIG. 2.—Stokes $V$ profiles of HH And (Gl 905; M5); three exposures were taken, 40 minutes for each one. No longitudinal magnetic field has been detected; we set up an upper limit of 5 G on $B_z$.

brier & Baraffe 1997). There have been no measurements of its magnetic field. The X-ray observations (Schmitt & Liefke 2004) of nearby stars have implied that the coronal activity level in EV Lac is from 10 to 100 times higher than in HH And.

### 2.2. *Spectropolarimetric Observations and Data Reduction*

We observed EV Lac and HH And with the Canada-France-Hawaii Telescope Espadons high-resolution spectrograph ($R = 65{,}000$; Donati 2003), which provides a wavelength coverage of 370–1000 nm, in spectropolarimetric mode to measure Stokes $I$ and $V$ parameters. For each star we took three successive exposures, 50 minutes each for EV Lac and 40 minutes each for HH And. We obtained high signal-to-noise spectra of about 270 : 1 and 150 : 1 for EV Lac and HH And, respectively. Wavelength-calibrated unpolarized and polarized spectra corresponding to each observing sequences are extracted with the dedicated software package Libre-ESpRIT (Donati et al. 1997; J.-F. Donati et al. 2006, in preparation) following the principles of optimal extraction Horne (1986).

To compute the mean longitudinal magnetic field of the stars from the photospheric lines, we use the least-squares deconvolution multiline analysis procedure[6] given in Donati et al. (1997), producing mean Stokes $I$ (unpolarized) and $V$ (circularly polarized) profiles for all collected spectra. Figures 1 and 2 show our mean Stokes $V$ profiles of EV Lac and HH And. In the case of EV Lac, the mean longitudinal field strengths corresponding to the three successive exposures are $B_z = 18 \pm 3$, $-40 \pm 3$, and $-37 \pm 3$ G, respectively. It is very interesting to note that using the formula given in Wade et al. (2000), the mean longitudinal field strengths estimated from the chromospheric lines are much stronger than from the photospheric lines, and they are different between the Balmer lines ($B_z = 260 \pm 10$ G) and the Ca II infrared triplet (IRT) ($B_z = 150 \pm 20$ G, an average over the three triplet lines). We defer a discussion of this result to § 3.

For HH And, the Stokes $V$ profiles from our observations have not revealed a significant magnetic field, $B_z = -5 \pm 2$ G. We have therefore set an upper limit of 5 G on $B_z$ for the star.

## 3. DISCUSSION

In this Letter, we have not detected a circularly polarized signature in HH And, but we have detected it in EV Lac. The explanation might be a difference in the kind of magnetic dynamo that dominates in each star. Since EV Lac (M3.5) and HH And (M5.5) have low enough masses, ~0.35 $M_\odot$ for EV Lac and ~0.15 $M_\odot$ for HH And (Delfosse et al. 2000), they are therefore expected to be fully convective (Chabrier & Baraffe 1997). If this is the case, a turbulent dynamo (Durney et al. 1993) may dominate in HH And and may generate a small-scale structure that is not accessible to us. In the case of EV Lac, the magnetic field is probably generated from both a turbulent dynamo and another kind of dynamo. The latter may only work in rapidly rotating stars and may produce a large-scale structure whose magnetic fields are able to be detected, e.g., in EV Lac (this Letter) or V374 Peg (Donati et al. 2006).

Figures 3–6 show the Stokes $V$ and $I$ profiles of the H$\alpha$ line at 656.28 nm and the Ca II IRT at 849.802, 854.209, and 866.214 nm, respectively, for the last exposure. The difference in the Stokes $V$ profile between the H$\alpha$ lines and the Ca II IRT reflects (1) an imhomogeneous and complex field topology in EV Lac; (2) different shapes of the emission cores ($V \sim \delta I/\delta\lambda$); (3) differences in the effective Landé factors and $\sigma$-component distributions of the lines; and (4) differences in line formation heights of the H$\alpha$ lines and the Ca II IRT, and in the field strengths at those heights (Vernazza et al. 1981).

During our observations, the Balmer lines as well as the emission cores of the Ca II IRT in EV Lac indicate chromospheric (and therefore magnetic) activity. This supports the idea that the Zeeman signatures of the Balmer lines and the Ca II IRT have a chromospheric origin. On the other hand, the longitudinal magnetic field strength computed from the Balmer lines ($B_z = 260$ G) is much stronger than that from the Ca II IRT ($B_z = 150$ G), implying that the Zeeman signatures of the

[6] For this work, we used a line list (Kurucz 1993) corresponding to M spectral types matching that of EV Lac and HH And. About 5000 intermediate to strong atomic spectral lines with average Landé factor $g_{\rm eff}$ of about 1.2 are used simultaneously to retrieve the average polarization information in line profiles, with typical noise levels of ≈0.06% (relative to the unpolarized continuum level) per 1.8 km s$^{-1}$ velocity bin and per individual polarization spectrum, corresponding to a multiplex gain in S/N of about 10 with respect to a single average line analysis.

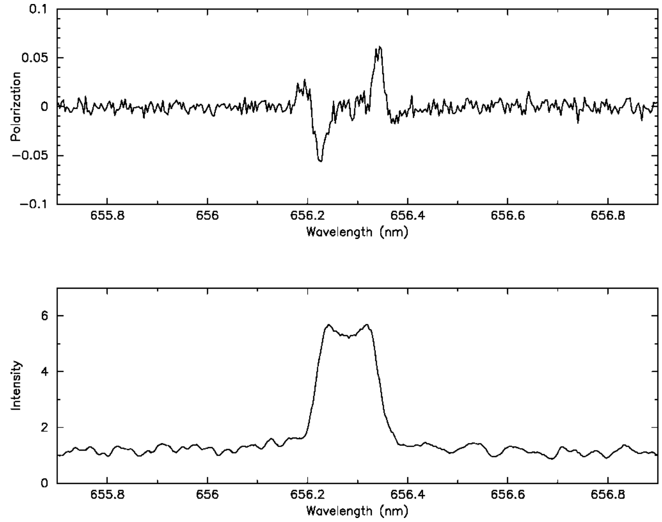


FIG. 3.—Stokes *V* (*top*) and *I* (*bottom*) profile (exposure 3) of the H$\alpha$ line at 656.28 nm. Additional components in the Stokes *V* profile (a positive component at 656.19 nm and a negative one at 656.38 nm) imply a mixed polarity.

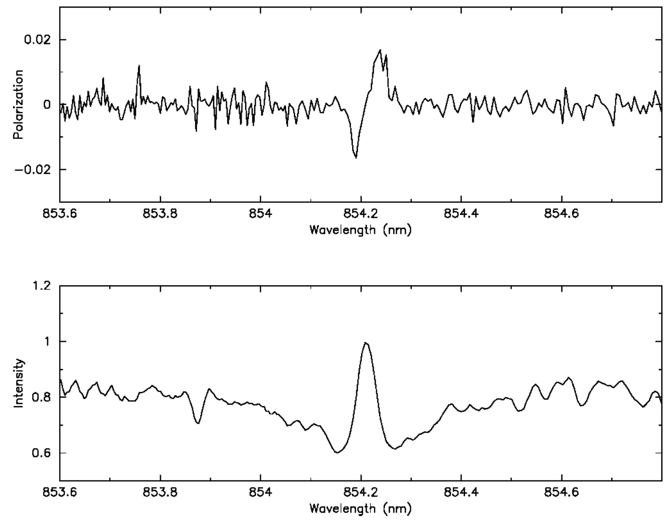


FIG. 5.—Stokes *V* (*top*) and *I* (*bottom*) profile (exposure 3) of the Ca II IRT at 854.209 nm.

Balmer lines and the Ca II IRT might be formed at different heights (Vernazza et al. 1981).

Our observations have also indicated a significant variability of the field in EV Lac: an opposite sign of $B_z$ observed in the first exposure compared with the second and the third one. The timescale of this variability is very short, i.e., less than 50 minutes. We consider several possibilities that could explain the variability. First, the possibility of star rotation changing the field vector is ruled out since in the case of EV Lac its rotational period of 4 days could not significantly change the field vector in 50 minutes or ~0.8% of a whole phase. Second, the possibility of a strong flare during our observations, modifying the Zeeman signature obtained in the first exposure, is also precluded since we do not find any significant change in the H$\alpha$ profile, whose equivalent width is about 3.3 Å for all three exposures. Finally, with high probability the magnetic field in EV Lac is intrinsically variable. This again indicates an imhomogeneous and complex field in the star, which probably leads to the observational results discussed above.

More spectropolarimetric observations at different rotational phases will allow us to reconstruct the EV Lac field topology not only on the stellar surface but also in three dimensions by using different lines coming from different layers of the star. This will lead to a strong improvement of our understanding of the magnetic field in EV Lac and hence in low-mass stars.

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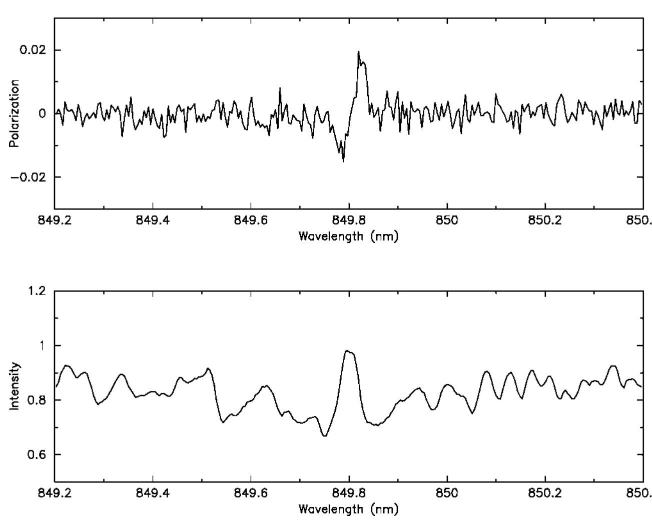


FIG. 4.—Stokes *V* (*top*) and *I* (*bottom*) profile (exposure 3) of the Ca II IRT at 849.802 nm.

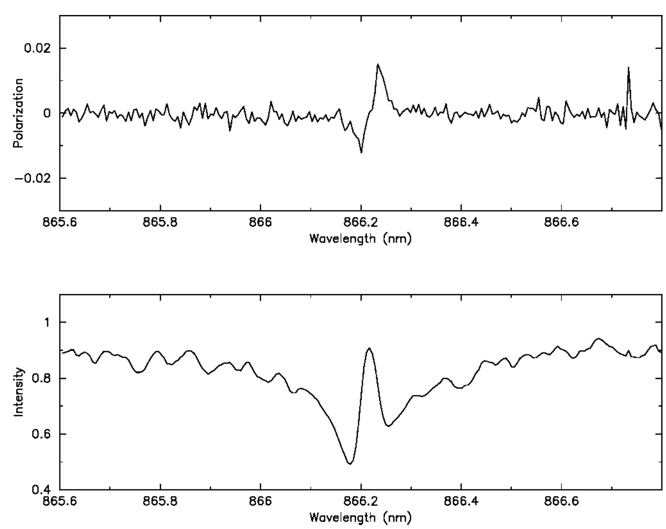


FIG. 6.—Stokes *V* (*top*) and *I* (*bottom*) profile (exposure 3) of the Ca II IRT at 866.214 nm.

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