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Ultra-weak magnetic fields in Am stars: β UMa and θ Leo

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Abstract. An extremely weak circularly-polarized signature was recently detected in the spectral lines of the Am star Sirius A. With a prominent positive lobe, the shape of the phase-averaged Stokes V line profile is atypical of stellar Zeeman signatures, casting doubts on its magnetic origin. We report here on ultra-deep spectropolarimetric observations of two more bright Am stars: β Uma and θ Leo. Stokes V line signatures are detected in both objects, with a shape and amplitude similar to the one observed on Sirius A. We demonstrate that the amplitude of the Stokes V line profiles depend on various line parameters (Landé factor, wavelength, depth) as expected from a Zeeman signature, confirming that extremely weak magnetic fields are likely present in a large fraction of Am stars. We suggest that the strong asymmetry of the polarized signatures, systematically observed so far in Am stars and never reported in strongly magnetic Ap stars, bears unique information about the structure and dynamics of the thin surface convective shell of Am stars.

Keywords. Stars: magnetic field, stars: chemically peculiar

1. Introduction

Magnetic fields play an important role in the evolution of hot stars (O, B, A stars). However, the origin and even the basic properties of hot star magnetic fields remain mostly unknown. About 7% of hot stars (Wade *et al.* 2013) are found to be strongly magnetic, with a longitudinal magnetic field in excess of 100 G. Apart from this well-identified fraction of magnetic stars, extremely weak longitudinal magnetic fields have also been discovered in the A star Vega (Lignières *et al.* 2009), and in the Am star Sirius A (Petit *et al.* 2011). Circularly polarized line signatures observed in this last case were not of null integral over the line profile as in other magnetic massive stars, since the Stokes V line profile exhibits a positive lobe dominating over the negative one (in amplitude and area). Here, we present the results of an ultra-deep magnetic field search carried out for two other bright Am stars: β UMa and θ Leo. The fundamental parameters of both stars are presented in Table 1. These two metal-rich stars possess a similar effective temperature, $\log g$, mass, radius and age. As most Am stars, they also feature a low projected rotational velocities, as compared to normal A stars (Abt 2009).

Table 1. Fundamental parameters of β UMa and θ Leo

	β UMa	θ Leo
spectral type	A1V	A2V
$T_{\rm eff}$	9480K[a]	9280K[a]
$\log g$	4.33	4.47
Mass	2.64 $M_\odot$[a]	2.94 $M_\odot$[a]
Radius	1.85 $R_\odot$[b]	1.65 $R_\odot$[b]
vsini	46 km/s[c]	23 km/s[c]
L	72 $L_\odot$[a]	127 $L_\odot$[a]
Metallicity	−0.03[d]	−0.13[d]

[a] Zorec & Royer (2012) [b] Pasinetti Fracassini *et al.* (2001)
[c] Royer *et al.* (2002) [d] Anderson & Francis (2012)

2. Data analysis

All data were taken with the NARVAL spectropolarimeter, installed at the 2-meter Bernard Lyot Telescope (TBL) at the summit of the Pic du Midi in the French Pyrénées. This fiber-fed spectropolarimeter is especially designed and optimized to detect stellar magnetic fields through the line polarization they generate. Both stars were observed in polarimetric mode measuring Stokes V (circular polarization). To test whether β UMa and θ Leo are magnetic, we applied the Least-Squares Deconvolution (LSD) technique (Donati *et al.* 1997; Kochukhov *et al.* 2010) on each spectrum of both stars. LSD is a cross-correlation technique for computing average pseudo-line profiles from a list of spectral lines in order to get a multiplex increase of the signal-to-noise ratio. Here, we choose to compute the LSD pseudo line profiles for all available photospheric lines. The masks adopted for each star are created from a list of of about 1,100 atomic lines extracted from the VALD database (Piskunov *et al.* 1995; Kupka & Ryabchikova 1999), using the effective temperature and log g of both targets. Using the mask corresponding to each star, we have extracted the LSD Stokes I and V profiles for each spectra, and also obtained two "Null" control parameter (hereafter Null1 and Null2) to check for spurious signatures (Donati *et al.* 1997). In spite of the multiplex gain obtained through this cross-correlation method, the typical SNR of LSD Stokes V profiles remain far too low to detect polarized signatures as weak as the one previously reported for Sirius (Petit *et al.* 2011). To improve the situation, we repeated the method successfully used for Vega and Sirius A by coadding all LSD profiles for each star (around 150 available observations in each case). Using this simple strategy, the final SNR is about 500,000 for both stars.

3. Results

The Stokes I, V, Null1 and Null2 co-added LSD profiles of β UMa and θ Leo are shown in Fig. 1. They display clear Stokes V signatures at the radial velocity of the Stokes I line profiles. The circularly-polarized signal obtained for both stars covers most of the width of the line, and is mostly symmetric about the line centroid. In both cases, a positive lobe dominates the signal. No detectable counterpart of the Stokes V signal is seen in the Null1 and Null2 control profiles, which strongly supports a physical origin of the signatures in the Stokes V profiles.

The peculiar shapes of the signatures in the Stokes V profiles (mainly consisting of a positive lobe) are not expected in the standard theory of the Zeeman effect. We performed a series of tests to ascertain the Zeeman origin of the recorded signal. The basic idea is that the amplitude of Zeeman signatures is expected to depend on various line parameters

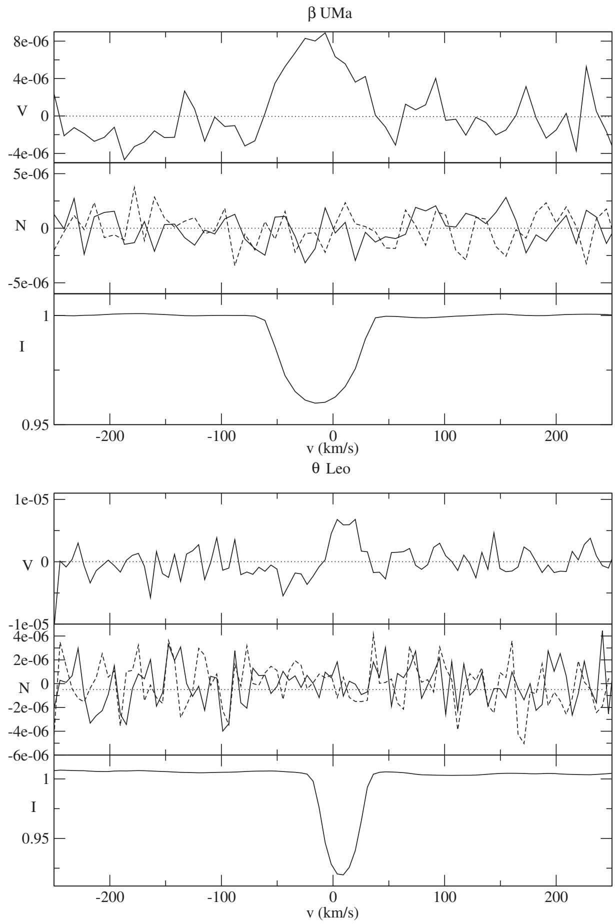

Figure 1. Normalized co-added LSD profiles in Stokes I (bottom) and V (top). The two available "null" control parameters Null1 and Null2 are shown in the middle panel. Top: β UMa observations. Bottom: same figure for θ Leo.

(Landé factor, wavelength, line depth), so that a careful selection of spectral lines for the LSD procedure should confirm or refute this dependence in our data. We therefore ran again the LSD procedure using a number of new line lists, extracted from our original list but featuring a selection of lines where one line parameter has been restricted to a given range. As a reference, we use here the standard Ap star α^2 CVn, using a NARVAL observation downloaded from PolarBase (Petit *et al.* 2014) and already used by Silvester *et al.* (2014). α^2 CVn is a bright, variable A0p star with $v \sin i$=18 ± 0.5 km s^{-1}, an effective temperature of 11600 ± 500 K and a logarithmic surface gravity equal to 3.9 ± 0.1 (Silvester *et al.* 2014). Its spectral properties are therefore reasonably similar to β UMa and θ Leo, except its slightly higher surface temperature. α^2 CVn exhibits a strong and organized surface magnetic field. We applied our tests to this reference star to better highlight the expected result in the presence of a magnetic field.

In a first test, we run LSD for two sub-masks containing lines with an average Landé factor g lower (resp. greater) than the mean Landé factor of the original line list. The resulting Stokes V profiles are plotted in Fig. 2 for the two Am stars and the control Ap star. In spite of a higher noise level than obtained with the complete line mask, the high-g profiles of β UMa and θ Leo display a higher amplitude than their low-g

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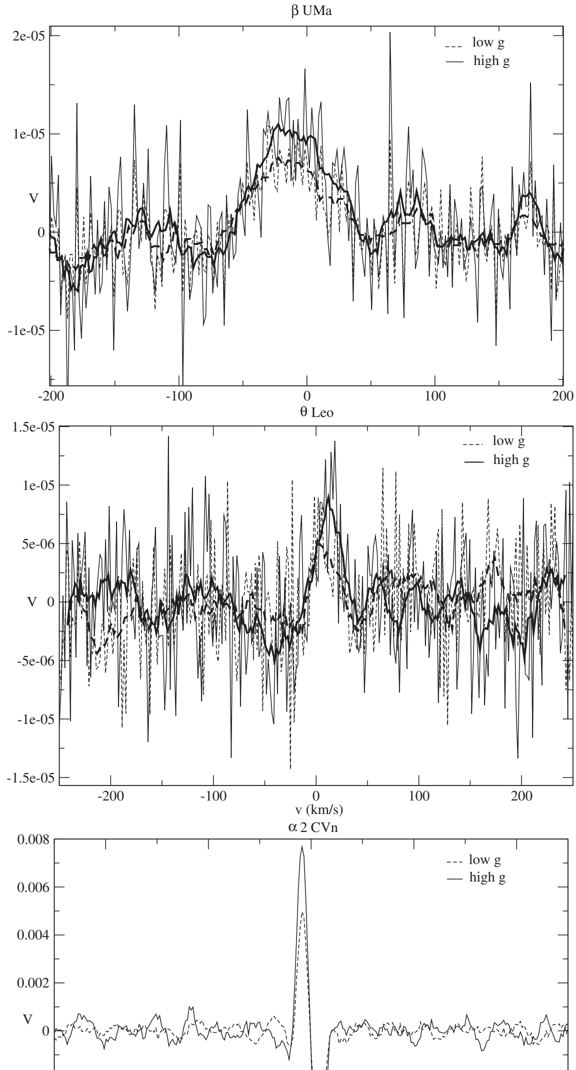

Figure 2. Top: Comparison of the Stokes V profiles obtained by selecting photospheric lines of low (thin dashed line) and high (thin solid line) magnetic sensitivity for β UMa. The thick dashed and solid lines represent a moving average, over three spectral bins, of the thin lines. Center: same figure for θ Leo. Bottom: same for α^2 CVn.

counterpart, with an amplitude ratio roughly consistent with the ratio of the g values used for normalization of the LSD profiles.

As second test, the two sub-lists are defined from our original list by containing lines with a wavelength shorter (resp. longer) than the mean wavelength of the original list. The amplitude of the Stokes V profiles for the low and high wavelength line list are similar for the three stars, as expected when adopting a same wavelength for normalization of the LSD profiles.

As a last test, we define two sub-lists using spectral lines with an average depth lower (resp. greater) than the mean depth of the original list. The Stokes V LSD profiles obtained from the sub-lists clearly show, for our two Am stars and our reference star, a lower amplitude whenever the average line depth is smaller, as expected in the case of a signature of magnetic origin.

4. Discussion and Conclusion

From the series of tests described in the previous section, we gather further support in favour of the Zeeman origin of the polarized signal, in spite of an unexpected shape featuring one single lobe. Single lobe Stokes V profiles are reported in small-scale magnetic elements of the solar surface (e.g. Viticchié & Sánchez Almeida 2011 and references therein). Asymmetric (though double-lobed) Stokes V profiles were also reported in cool active stars (Petit *et al.* 2005; Aurière *et al.* 2008). In the solar context, Stokes V asymmetry is generally interpreted as a combination of vertical gradients in both velocity and magnetic fields inside magnetic elements (e.g. López Ariste 2002 and references therein). The detection of a microturbulent broadening and asymmetries in the intensity line-profiles of tepid stars (up to an effective temperature of 10000 K for Am stars) demonstrates the existence of a thin superficial convective zone in Am stars. Moreover, some hydrodynamical models predict the presence of shocks in these superficial layers (Kupka *et al.* 2009). Strongly distorted Stokes V profiles may therefore be linked to the gradients of velocities and magnetic fields related to the supersonic convection.

These observations of two new targets and the related LSD tests confirm the magnetic origin of the signatures detected in the Stokes V profiles. We have 100% magnetic detection rate in Am stars so far, although three Am stars only were observed with the required accuracy. The Stokes V asymmetry may contain new informations on the interaction between magnetic fields and convection at photospheric level. New observations are currently being carried out to identify the physical origin of weak magnetic fields in Am stars and in other stellar classes of intermediate mass.

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