Zeeman Broadening in Cool Stars

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Abstract. We investigate detectability of magnetic fields by Zeeman broadening of well-isolated spectral lines in F, G and K type stars. Data of unprecedented quality were taken with CES[1] mounted on the 3.6m ESO telescope at La Silla, Chile, in three campaigns in the optical range between 5770Å and 6280Å, each with a wavelength coverage of roughly 40Å. We use the `SPINOR/STOPRO` (cf. Frutiger et al. [1]) package developed by ETH[2] and MPS[3] to perform spectral line inversion via χ^2 minimization. Starting from constraints given by previous measurements of stellar parameters, we fit a number of extracted spectral lines. Eventually, our goal is to determine the product of the magnetic field strength B and the surface filling factor, $B \times f$.

Our work is in progress and thus no final measurements can be presented at this stage.

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INTRODUCTION

First measurements of magnetic fields in stars using Stokes I line profiles were reported by Marcy [2], Gray [3], and others more than 20 years ago.

The displacement of the circularly polarized sigma components from line center due to the Zeeman effect broadens the wings of spectral lines. In the case of a normal Zeeman triplet, this displacement can be approximated by (see, e.g. Marcy [2])

$$\Delta\lambda \approx 4.67 \times 10^{-13}\, g_{\text{eff}}\, B\, \lambda^2\ . \tag{1}$$

Here g_{eff} is the effective Landé factor of the line, and can be calculated from the Landé values of the involved excited states according to Beckers [4]. Note that this equation merely illustrates the λ^2 dependence of the Zeeman effect and motivates the distinction between Zeeman sensitive (high $\mathrm{g_{eff}}$) and Zeeman insensitive (low $\mathrm{g_{eff}}$) spectral lines. `STOPRO` does not use effective Landé factors, but the individual quantum configurations of the involved states.

Other broadening effects, for instance stellar rotation, may conceal the Zeeman effect at optical wavelengths, whereas analyses in the infrared benefit from the λ^2 dependence. We investigate whether the radiative transfer inversions done by `SPINOR` can reveal Zeeman broadening in our high-quality optical data. Once the analysis has been

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TABLE 1. Objects with previously reported magnetic fields matching our sample. 'y' indicates availability from a given campaign. See references for previously reported measurements on these objects.

HD Identifier	Alternative Identifier	Measured by	5770Å	6137Å	6220Å
10700	τ Ceti	Marcy [2], et al.	y		
22049	ε Eri	Saar [6], et al.	y		
115383	59 Vir	Saar [7]		y	y
115617	61 Vir	Gray [3]		y	y
131156	ξ Boo A	Saar [7], et al.			y

completed, our results will be compared to previously reported magnetic field measurements.

ANALYSIS

Spectra with a wavelength coverage of roughly 40Å were taken in three campaigns starting at 5770Å (Oct. 2000 and Oct. 2001), 6173Å (May 2005) and 6220Å (Apr. 2002). The resolution of these spectra is approximately 235,000 with a signal-to-noise ratio well above 200. This enables us to conduct high precision line fitting and to investigate magnetic field detectability in data of this kind. For information on data reduction and normalization, as well as sample resolution and signal-to-noise determinations from the two earlier campaigns, see Reiners and Schmitt [5].

Stars matching our sample with previously reported magnetic fields are compiled in table 1. Availability from a given campaign is indicated by a 'y'. We will first focus on these objects and compare our results with the previous ones. Subsequently, we will continue analyzing the data from the remaining objects of our sample.

We use spectra from all three CES campaigns, with a focus on the ones at higher wavelengths. Unfortunately, data from more than one campaign is available for only a few objects. This results in a small number of spectral lines available for fitting, due to the small wavelength coverage of the spectra.

We choose the spectral lines for extraction according to a number of criteria. Lines with high Landé factors, such as Fe I at 6173.3Å or 6232.6Å are sensitive to the magnetic field strength. Lines with lower g_{eff} values provide information on the surface fraction covered by magnetically inactive components, for instance Fe I at 6252.6Å. In addition, more temperature sensitive, but Zeeman insensitive, lines, e.g. Ti I at 6258.1Å, can be used to further constrain our model parameters.

We focus on fitting well-isolated lines in order to limit our sensitivity to errors due to strong line blends. Nevertheless, we do include the 6173.3Å Fe I line in our analysis, despite the abundant present line blends from Eu II, S I, and Fe I. Since this line is the most magnetically sensitive Fe I line in our spectra ($g_{\text{eff}} = 2.5$) and has been used repeatedly for magnetic field measurements, it is of particular interest for fitting.

Spectral line information is obtained from VALD [8] and from the Kurucz Atomic Line Database [9] at the CfA research website.

Stellar parameters from Valenti and Fischer [10] are used as constraints for $\log g$, $v \sin i$, effective temperature, and elemental abundances relative to the sun. The latter are thus merged with their respective Solar values as published in Asplund et al. [11]. For elements with no available stellar abundance, we use solar abundances and shift them by the average metalicity given in Valenti and Fischer [10].

`SPINOR` and `STOPRO`

`STOPRO` is the forward calculation and `SPINOR` the line inversion part of the `SPINOR/STOPRO` package developed and supported by MPS and ETH.

Relevant atomic line information including oscillator strength, abundance, excitation potentials, and electronic configurations as well as line profiles, input model atmospheres, and model parameters and keywords are passed to the code via input files.

Multiple temperature components and and their fractional coverage of the photosphere can be defined. This enables us to model starspots or plage networks which exhibit stronger magnetic fields than the stellar surface and differ in temperature from the quiet photosphere.

Model parameters include $\log g$, $v \sin i$, micro- and macro turbulence, the instrumental broadening profile [in km/s], magnetic field strength, and the surface fractions of the temperature components. Limb darkening is accounted for by disk integration.

The results from line inversion via χ^2 minimization are saved in multiple output files. The achieved fit can be visualized using `IDL` procedures included in the package.

RESULTS

Preliminary examples

We have primarily investigated 61Vir until now, since it is the slowest rotator for which data from two campaigns is available to us and since a magnetic field

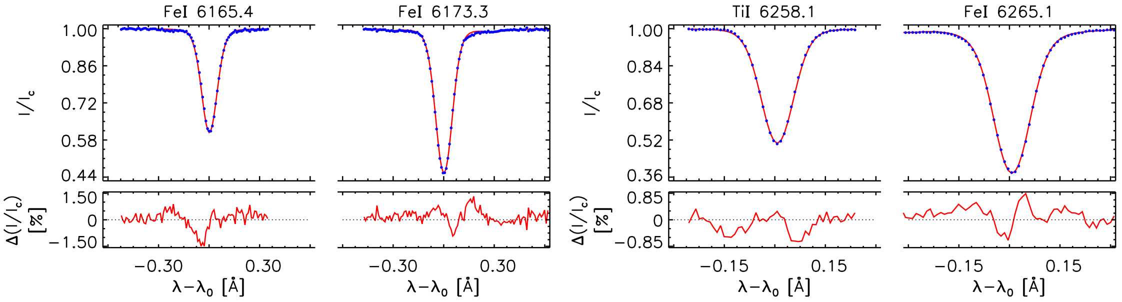

FIGURE 1. Simultaneously fitted lines without magnetic fields. Dots are real data, solid lines indicate fits. **Left:** Magnetically insensitive line at 6165.4Å ($g_{\text{eff}} = 1.0$) and blended sensitive line at 6173.3Å ($g_{\text{eff}} = 2.5$). **Right:** Ti I at 6258.1Å ($g_{\text{eff}} = 1.0$) and Fe I at 6265.1Å ($g_{\text{eff}} = 1.6$).

measurement has been reported by Gray [3]. However, the introduction of a magnetic component could yet not be shown to significantly improve fit quality, considering the increase in the number of free parameters. Fig. 1 illustrates two cases where two lines are inverted simulatenously. Line blends are taken into account where the required information could be found.

The statistical interpretation of our results is most influenced by the number of free parameters and the assumed signal-to-noise ratio specified in the input files. The latter will be treated in detail in the future. Systematic errors may derive from line blends, input model atmosphere, uncertainties in oscillator strength, abundance, etc. A detailed investigation of systematic and random errors is yet to be conducted.

CONCLUSIONS

This article outlines our work in progress. Constraining model parameters is of greatest importance to arrive at physically meaningful results and to circumvent the fitting problems due to degeneracy effects from rotational broadening, micro- and macroturbulence, and the uncertainties in temperature, oscillator strength, abundance, etc.

Future comparison with previous measurements and analyses will ensure the physical realism of our results.

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