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Hunting for strong magnetic fields in rapidly rotating sun-like stars with Stokes-I observations

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Abstract

Stars with convective envelopes can generate strong magnetic fields through rotationally driven dynamos. Theory suggests that the maximum magnetic field strength depends on the energy budget stored in the stellar convective shell and can reach values of several kilogauss in fastest rotating stars. We test this predictions by measuring total magnetic flux and polarization in a sample of sun-like stars that rotate close to the activity saturation limit. We detect average magnetic flux densities of several hundred G in several of our targets, with the strongest field of about 1 kG in a K type star V383 Lac showing that young sun-like stars can produce average fields on the kG level.

1 Observations

Our study is based on the data collected with the ESPaDOnS spectropolarimeter mounted at the 3.6 meter Canada-French-Hawaii Telescope. The instrument covers whole visible and near-infrared wavelengths up to about 1 μm. We selected five sun-like stars with short rotation periods between 2 and 3 days. Observations were carried out in polarimetric mode with the resolving power R≈ $68\,000$. We obtained one polarization spectrum per star with a typical signal-to-noise ratio of $SNR \approx 350$ at Hα wavelengths.

2 Methods

We used the SME tool (Valenti & Piskunov, 1996) to derive atmospheric parameters ($T_{\rm eff}$, $\log(g)$, $\upsilon\sin i$, [M/H]) and individual abundances of elements Fe, Ti, Si, Mg, Ca, Cr. Magnetic flux density was measured from unpolarized Stokes-I spectra in numerous spectral regions containing Fe lines. Because all stars have relatively high projected rotational velocity ($\upsilon\sin i$, where i is the inclination angle of stellar rotation axis to the line-of-sight), we could not observe Zeeman splitting in individual lines. Instead, our measurements rely on the effect of magnetic intensification of spectral lines (Landi Degl'Innocenti & Landolfi, 2004) which states that the depth of rotationaly broadened spectral lines in the presence of the magnetic field depends on individual Zeeman patterns. Thus, one can constrain the strength of underlying magnetic field by comparing the depths of spectral lines with different magnetic parameters. We also tested the complexity of surface magnetic field by comparing field strength derived from Stokes-I (which captures magnetic field localized at all scales on the stellar surface, including, e.g., spots) and Stokes-V (which captures mostly the large scale magnetic field component). Average Stokes-V profiles for each star were computed using Least Square Deconvolution (LSD) technique (Donati *et al.*, 1997).

3 Result

Table 1 summarizes our main results, and we illustrate examples of characteristic line profiles in Fig. 1.

When fitting profiles of spectral lines we limited ourselves to a homogeneous field model, i.e. assuming that the magnetic field covers whole stellar surface. This simple approach allows us to measure magnetic field in stars with large $\upsilon\sin i$'s but does not reflect the true geometry of the magnetic field. For instance, it does not account for the presence of stellar spots. The later would require time resolved observations and application of more sophisticated magnetic mapping techniques, or at least methods that account for individual field components, similar to that used in, e.g., Shulyak *et al.* (2014). Thus, our magnetic field measurements can only capture the total magnetic flux density averaged over whole visible stellar surface (including active regions and non-magnetic photosphere), but not the topology of the magnetic field itself. We plan to carry out more detailed analysis in our future studies.

Below we summarize our main conclusions.

- We successfully measured kG magnetic fields in sun-like stars using the method of magnetic intensification of spectral lines.
- We find average magnetic flux densities of several hundred G in four of our targets. The strongest field of 1250 G was found in V383 Lac showing that young sun-like stars produce average fields on the kG level.
- While we detect strong magnetic fields from unpolarized light, the corresponding polarization signal is always weak. This indicates that the surface magnetic fields in these stars have very complex geometry associated with active regions.
- The average fields are a factor of 2-3 weaker than fields found in M dwarf stars. Faster rotating stars of similar

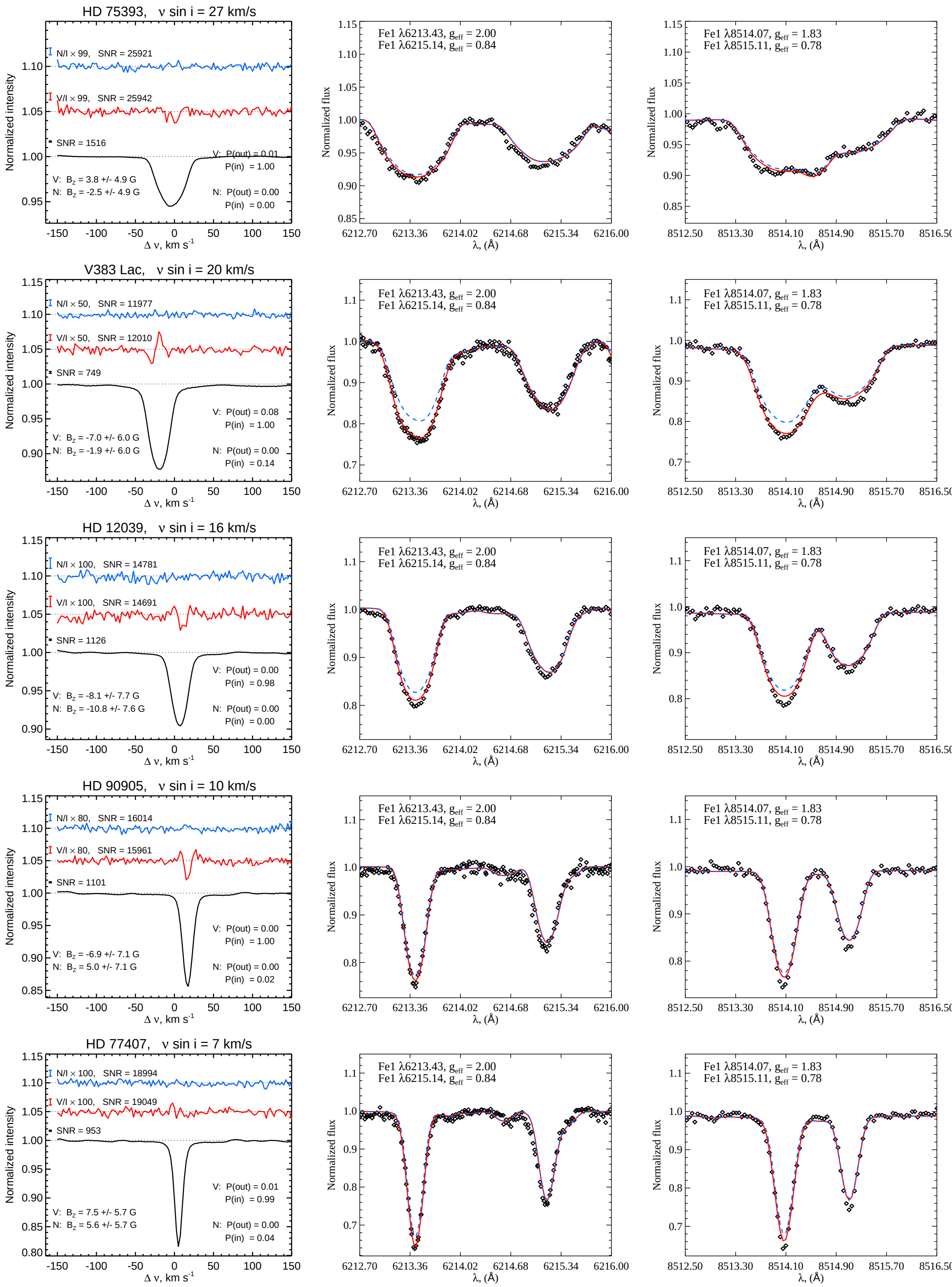

Figure 1: Magnetic field measurements in sun-like stars stars. *Column 1:* LSD profiles of Stokes-I (black, bottom), Stokes-V (red, middle), and null profile (blue, top). On each plot, $P_{\rm in}$ and $P_{\rm out}$ are the detection probabilities of the magnetic signal computed inside and outside of the region occupied by the line profile, respectively. The spectra were shifted along y-axis for better visibility. *Column 2 and 3:* example fits to Fe I lines with different magnetic sensitivity. Black diamonds – observations; red full line – best fit model; blue dashed line – zero field model. The extra deepening of magnetic sensitive lines with large Landé g-factors is clearly visible in, e.g., V383 Lac and HD 12039.

Name	SpT	$T_{\rm eff}$, K	$\log(g)$	$\upsilon \sin i$, km s^{-1}	[M/H]	P, d	B, G
HD 75393	F7	6099 ± 130	4.32 ± 0.4	27 ± 4	-0.09 $\pm$ 0.1	2.08	$<$500
V383 Lac	K1	5157 ± 170	4.28 ± 0.4	20 ± 5	-0.05 $\pm$ 0.2	2.47	1250
HD 12039	G4	5651 ± 130	4.43 ± 0.4	16 ± 3	-0.06 $\pm$ 0.1	3.03	750
HD 90905	G1	6008 ± 120	4.41 ± 0.4	10 ± 2	-0.08 $\pm$ 0.1	2.60	500
HD 77407	G0	5905 ± 100	4.52 ± 0.3	7 ± 1	-0.04 $\pm$ 0.1	2.86	750

Table 1: Parameters of investigated stars. The typical error on magnetic field is about 250 G, while for HD 75393 we can list only upper limit. Rotation periods are from (Wright *et al.*, 2011). The spectral types were extracted from NASA's SIMBAD online service.

spectral type may show stronger fields but our targets are not far from saturation, which occurs around 1.7d in these stars. Our observations are consistent with the magnetic scaling law of Christensen *et al.* (2009), i.e., maximum average fields in stars with shallow convective envelopes are expected to be weaker than in fully convective stars.

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