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General magnetic field on convective stars

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Abstract. The presence of weak general magnetic field for 21 stars with vigorous convection (spectral types F9–M3 and luminosity classes I–V) is detected. Variation of the general magnetic field as a function of stellar rotation is determined for two solar-like stars: ξ Boo A and 61 Cyg A.

Key words: stars: magnetic fields – stars: late-type

1 Introduction

Currently, we have a wealth of spectroscopic data indicating locally strong magnetic fields (1000–4000 G) on the surface of main-sequence stars of F-G-K-M spectral classes (see, for example, Rueedi et al. (1997); Johns-Krull et al. (1999)). The existence of local concentrations of strong magnetic fields on the surfaces of rapidly rotating RS CVn stars (K0 dwarfs AB Doradus and LQ Hydrae, and K1 subgiant HR 1099=V711 Tauri) was determined using the spectropolarimetric technique of Zeeman-Doppler imaging from observations collected at the Anglo-Australian Telescope (Donati et al. 2003).

It is generally believed that almost all manifestations of solar and convective stars activity (spots, flashes, chromosphere, transition region, coronae, winds, etc.) are related to magnetic fields. The study of large-scale magnetic fields allows us to reveal main processes causing the activity of a star as a whole (Parker (1979); Krause & Rädler (1980); Vainshtein et al. (1980)). Therefore, the program of systematic measurements of general magnetic fields on slowly rotating stars with convective envelopes was started in the Crimea in 1989.

The observations and data reduction were carried out using the 2.6 m Shajn telescope, Stokesmeter, coudé spectrograph and "Flip-Flop Zeeman Measurement Technique" (Plachinda & Tarasova 1999). Spectrograms were taken in the spectral region 6130–6270 Å. The reciprocal linear dispersion was 3 Åmm^{-1} (0.066 Å$pixel^{-1}$), and the resolving power of spectra was approximately 3×10^4 (3.0 pixel). Signal-to-noise ratios of a single polarized spectrum were typically 300–400 for continuum level.

2 General Magnetic Field on Cool Stars

The surface-averaged value of the longitudinal component of small- and large-scale magnetic structures is the General Magnetic Field (GMF). Table 1 summarizes the published results of general magnetic field measurements. The first column contains the object name. In the second and third columns the spectrum and the color are given. Column four gives the GMF (B_e) and its observed error. In the fifth column we give ratios of $B_e/\sigma \geq 3$. In the 6th column devices and references are given.

In the 6th column 'SM' indicates observations which were carried out using the Stokesmeter and 2.6 m Shajn telescope at Crimean Astrophysical Observatory, 'MM' stands for observations which were carried out using the Multislit Magnetometer. Presence of weak GMF has been detected with high statistical assurance for 21 stars with convective envelopes (spectral types F9-M3 and luminosity classes I-V). For two solar-like stars, variation of the general magnetic field as a function of stellar rotation has been determined: for ξ Boo A GMF variations have been measured from –10 G to +30 G (Plachinda & Tarasova 2000); for 61 Cyg A variations of the GMF have been measured, from –10 G to +4 G (see Fig. 1). Measurements obtained with the 2.6 m Shajn Telescope at Crimean Astrophysical Observatory are shown by filled squares (1998–1999) and filled circles (2002). The bottom filled triangle shows the single measurement by Borra et al. (1984) obtained with the Multislit Magnetometer. The single measurement obtained by Brown & Landstreet (1981)

Table 1: Results of Measurements of General Magnetic Field

	Object	Spectrum	B-V	B_e(Gauss)	B_e/σ	Ref.
1	ϵ Gem[a)]	G8 Ib	1.39	11.1 ± 2.7	4.1	SM [8)]
2	ϵ Peg[*)]	K2 Ib	1.53	-5.3 ± 0.9	5.9	SM [8)]
3	ϵ Leo	G1 II	0.80	49.2 ± 6.1	8.1	SM [2)]
4	ζ Cyg	G8 II-III	0.99	5.4 ± 1.7	3.2	SM [3)]
5	ζ Hya	G9 II-III	1.00	-15.3 ± 2.9	5.3	SM [3)]
6	η Psc	G7 III	0.97	11.4 ± 3.9	2.9	SM [3)]
7	κ Gem[*)]	G8 III	0.93	13.0 ± 3.8	3.4	SM [3)]
8	μ Peg[*)]	G8 III	0.93	-20.1 ± 3.3	6.1	SM [3)]
9	ϵ Vir	G8 III	0.94	-10.8 ± 3.2	3.4	SM [3)]
10	ξ Her	G8 III	0.94	-28.1 ± 4.5	6.2	SM [2)]
11	γ Tau	K0 III	0.99	19.8 ± 5.2	3.8	SM [2)]
12	ϵ Cyg[*)]	K0 III	1.03	9.3 ± 2.5	3.7	SM [3)]
13	ϵ Tau	K1 III	1.02	-22.3 ± 5.4	4.1	SM [2)]
14	α Boo	K2 III	1.23	3.3 ± 0.5	6.6	MM [1)]
15	δ And[*)]	K3 III	1.28	8.5 ± 2.8	3.0	SM [3)]
16	β And	M0 III	1.58	12.6 ± 2.2	5.7	SM [3)]
17	μ Gem	M3 III	1.64	9.1 ± 2.0	4.6	MM [1)]
18	ζ Her	F9 IV	0.65	-10.1 ± 3.1	3.3	SM [4)]
19	ξ Boo A[b)]	G8 V	0.76	-10, +30	—	MM [1,9)], SM [5)]
20	ϵ Eri [c)]	K2 V	0.88	21.3 ± 4.5	4.7	SM [6)]
21	61 Cyg A[d)]	K5 V	1.18	-10, +4	—	MM [1,9)], SM [7,8)]

[*)] $B_e/\sigma > 3.0$ were registered twice; [a)] $B_e/\sigma > 3.0$ were registered 5 times; [b)] general magnetic field varies from −10 to +30 G as a function of stellar rotation phase of the period $P = 6.1455$ days; [c)] $B_e/\sigma > 3.0$ were registered 3 times; [d)] general magnetic field varies from -10 up to +4 G as a function of stellar rotation phase of the period $P = 36.617$ days.

[1)] Borra et al. 1984; [2)] Hubrig et al. 1994; [3)] Tarasova 2002; [4)] Plachinda & Tarasova 1999; [5)] Plachinda & Tarasova 2000; [6)] Tarasova et al. 2001; [7)] Plachinda et al. 2001; [8)] present paper; [9)] Brown & Landstreet 1981.

using the Multislit Magnetometer is shown by the upper triangle. In both cases of multislit magnetometer measurements errors are big (40 G and 14 G, respectively). The figure scale covers two total periods. Phases are calculated with a zero epoch at the peak value of the magnetic field:

$$HJD_{max} = 2450989.2 + 36.617 \pm 0.054. \quad (1)$$

Most of the GMF observations represented in Table 1 were carried out at Crimean Astrophysical Observatory using the Stokesmeter and "Flip-Flop Zeeman Measurement Technique" (Plachinda & Tarasova 1999). In the case of uniform sample of high-accuracy magnetic field measurements the reliability of the results is the principal question. The following criteria of reliability are examined:

1. Systematic control of adjustment of the Stokesmeter.
2. Reproducing the known magnetic curve of a magnetic star.
3. Reproducing the zero field of a nonmagnetic star and knowledge of the value of the systematic instrumental shift.
4. Knowledge of statistical distribution characteristics of experimental values: whether the mean and standard deviations are unbiased estimates or not, i.e. the statistical distribution is symmetric (similarly to those with normal distribution) or not.
5. Presence of coincidence between the numerical simulation value (Monte Carlo method) of the standard deviation and the experimental standard deviation using normal or known experimental statistical distribution.

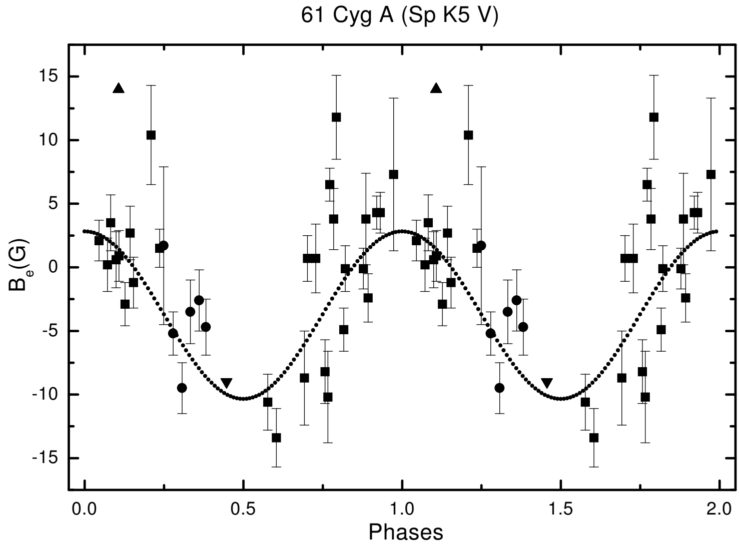

Figure 1: *61 Cyg A.*

6. Use of a homogeneous sample of measurements for estimation of the mean and its rms error.

7. Reproducing the known magnetic curve of a star with a weak field.

8. Flip-Flop Zeeman Measurement Technique — internal Stokesmeter test on the presence or absence of significant stochastic or time-dependent spurious Stokes signatures.

1. *Systematic control of adjustment of the Stokesmeter.*
Before each run of observations the adjustment of the Stokesmeter was examined using any bright star. The efficiency of the Stokesmeter is 94–95%, including the inefficiency of the calibration device.

2. *Reproducing the known magnetic curve of a magnetic star.*
The value and the sign of the magnetic field of the magnetic star β CrB are used for testing in order to reproduce the known magnetic curve (see Fig. 2 in the paper by Plachinda & Tarasova (1999)). This figure demonstrates the real discrepancy between magnetic field curves for different spectral lines. It is the old and well-known effect, and also an important and complicated problem not only for Ap-stars, which we must bear in mind when high-accuracy measurements are analyzed. This phenomenon of discrepancy between different spectral line measurements is known for the measurements of the general magnetic field of the Sun as a star as well (Kotov & Setyaeva 2002), but the nature of this phenomenon may be different.

3. *Reproducing the zero field of a nonmagnetic star and knowledge of the value of the systematic instrumental shift.*
Comparison of the Crimean data for Procyon ($B_e = -1.34 \pm 1.0$ G) (Plachinda & Tarasova 1999) with the data obtained by Bedford et al. (1995) with a magneto-optical filter ($B_e = -1.86 \pm 0.9, 0.49 \pm 0.8$ G) shows good agreement within the observational errors. Using 27 observing nights in 1989–1997, the systematic instrumental shift was determined as $< B_e >= -0.12 \pm 0.99$ G (Plachinda & Tarasova 1999).

4. *Knowledge of the statistical distribution characteristics of experimental values: whether the mean and standard deviations are unbiased estimates or not, i.e. the statistical distribution is symmetric (similarly to those with normal distribution) or not.*
Using magnetic field measurements of the supergiant ϵ Peg (Sp K2Ib), the statistics associated with polarization measurements were evaluated (the number of measurements N = 971). The measurements including weak spectral lines with $z \times (r_0 - r_c) < 0.2$ were used for the analysis (z — Landé factor, r_0 — contour restriction level, and r_c — the central line depth in continuum units (see Plachinda & Tarasova 1999). For fitting by normal distribution the skewness is negligible, $S = -0.154 \pm 0.078$, the positive kurtosis ("peakedness") is essential, $E = 2.280 \pm 0.157$, and the probability of normality $P = 93.7\,\%$, using Kolmogorov-Smirnov test.

The total experimental distribution is symmetric: *the mean and standard deviation are unbiased estimates.*

By virtue of testing for normality, we eliminate spectral lines for which $z \times (r_0 - r_c) < 0.2$ and then use a more homogeneous sample of observations with $10 < \sigma_i < 15$ G for four supergiants: β Aqr (Sp G0 Ib), α Aqr (Sp G2 Ib), ϵ Gem (Sp G8 Ib), ϵ Peg (Sp K2 Ib). For $N = 460$ values of B_e, skewness $S = -0.115 \pm 0.114$

and kurtosis $E = -0.020 \pm 0.227$, with the probability of normality $P \approx 96.4\%$, using Kolmogorov-Smirnov test. *One can use the mean and standard deviation for analysis as unbiased estimate because the experimental distribution is symmetric and normal.*

5. *Presence of coincidence between the numerical simulation value (Monte Carlo method) of the standard deviation and the experimental standard deviation, using the normal or known experimental statistical distribution.*

In order to test the observational errors by using a full sample of unblended spectral lines, the Monte Carlo method with a generator of normal distribution numbers was applied. For N = 2545 measurements of magnetic fields on four yellow supergiants (β Aqr (Sp G0 Ib), α Aqr (Sp G2 Ib), ϵ Gem (Sp G8 Ib), ϵ Peg (Sp K2 Ib)), including weak unblended spectral lines, the relation between the mean Monte-Carlo simulated standard error, $<\sigma_{(m-c)}>$, and the mean experimental standard error, $<\sigma>$, was estimated as $<\sigma_{(m-c)}> = 1.033 <\sigma>$. Further, spectral lines for which $z \times (r_0 - r_c) < 0.2$ were eliminated for strengthening the data uniformity. For $N = 1844$ measurements $<\sigma_{(m-c)}> = 0.968 <\sigma>$. In both cases, the dates with the observations, for which the probability of discrepancy between the observed and Monte Carlo errors was significant, were excluded (P $\geq$ 95 %: 5 out of 31 observational nights). The discrepancy is 3.3 % in the first case and the discrepancy is 3.2 % in the second case; *both appear to be very small.*

6. Use of the homogeneous sample of measurements for estimation of the mean and its rms error.

As a rule, different spectral lines form under different physical conditions, so longitudinal magnetic field measurements may give us a variety of magnetic field strengths. In the case of solar-like spectrum and signal-to-noise ratio $S/N \approx 400$, the errors lie between 4–5 and 20–25 G, depending on magnetic sensitivity, half-widths and depths of used spectral lines, therefore we have to use a uniform sample of spectral lines for magnetic field calculations. The weighted values are proper, if the statistical assurance of the discrepancy between experimental and Monte Carlo standard errors is less than 95 %. Otherwise, when $P > 95\%$, we must calculate the arithmetic mean B_e, its σ, and analyze sources of the discrepancy. In the case of Table 1 the weighted arithmetic means of B_e were calculated for ϵ Gem, ϵ Peg and 61 Cyg A.

7. *Reproducing the known magnetic curve of a star with a weak field.*

The investigations were carried out using the solar-like stars ξ Boo A (Plachinda & Tarasova 2000) and 61 Cyg A (see Figure 1). Because this is the first study of the general magnetic field as a function of rotation on a solar-like star other than the Sun, we have no possibilities to reproduce the known magnetic curve of a star with a weak field. But Stokesmeter measurements have shown good agreement with multislit magnetometer measurements by Brown & Landstreet (1981) and Borra et al. (1984).

8. *Flip-Flop Zeeman Measurement Technique — internal Stokesmeter test on the presence or absence of significant stochastic or time-dependent spurious Stokes signatures.*

In the case of using "Flip-Flop Zeeman Measurement Technique" (Plachinda & Tarasova 1999) we have an important internal device possibility to control the presence or absence of significant stochastic or time-dependent spurious Stokes signatures. When using pairs of exposures out of three, skipping the intermediate one, as shown in Fig. 2, spectra with identical circular polarizations are projected on the same place of the CCD. Therefore, we can calculate the value of the spurious magnetic field, which must be equal to zero in the case where all spurious effects are negligible. In order to test the reliability of obtained magnetic field values of the four supergiants, we evaluate "zero field" ($B_{test} \pm \sigma_{test}$) using pairs of exposures in the manner mentioned above. The results of this test are shown in Table 2. The first column contains the Heliocentric Julian Date. In the second column the number of GMF measurements is given. Column 3 gives the GMF (B_e) and its observed error. In the forth column we give the ratio $k = B_e/\sigma \geq 3$. The fifth column contains B_{test} and its error σ_{test} and the 6th column gives the ratio $k_{test} = B_{test}/\sigma_{test}$. For the date JDH 2452306.310 only two exposures were made. Therefore, the above-mentioned testing is not possible for this date. The reliability of this result is argued because of the insufficient statistical assurance ($P \approx 65\%$) of the discrepancy between the Monte Carlo and experimental errors. One can see that for all 6 dates the ratio $k_{test} = B_{test}/\sigma_{test} < 3.0$. Therefore, the statistical assurance of the registered GMFs is reliable.

3 Summary

A). The "Flip-Flop Zeeman Measurement Technique" (Plachinda & Tarasova 1999) used in magnetic field observations permits detection of weak magnetic fields with high accuracy. The efficiency of the Stokesmeter is 94–95%, including the inefficiency of the calibration device. The systematic instrumental shift is absent with accuracy $<B_e> = -0.12 \pm 0.99$ G. The use of the mean and standard deviations for analysis as unbi-

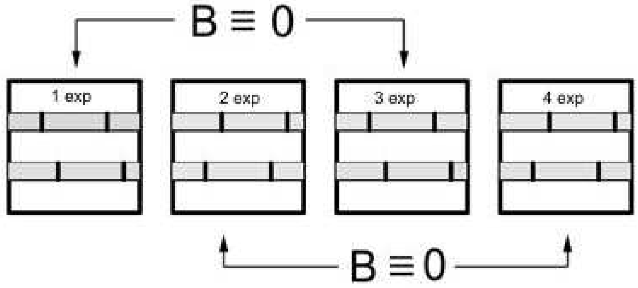

Figure 2: *Spurious Magnetic Field Test.*

Table 2: Test of "Zero field"

	JDH (+2400000.000)	N	$B_e \pm \sigma$ (Gauss)	k	$B_{test} \pm \sigma_{test}$ (Gauss)	k_{test}
			ϵ Gem (Sp G8 Ib)			
1	51907.500	79	11.1 ± 2.7	**4.1**	3.8 ± 3.0	**1.3**
2	51912.219	44	9.8 ± 2.5	**3.9**	-4.4 ± 2.2	**2.0**
3	52217.516	108	-10.5 ± 3.0	**3.5**	7.2 ± 3.4	**2.1**
4	52306.310	13	38.1 ± 7.4	**5.1**		
5	52309.356	77	5.3 ± 1.5	**3.5**	0.1 ± 1.6	**0.1**
			ϵ Peg (Sp K2 Ib)			
6	51035.468	178	-5.3 ± 0.9	**5.9**	0.3 ± 1.0	**0.3**
7	52509.493	206	-2.7 ± 0.8	**3.4**	-0.7 ± 0.9	**0.9**

ased estimates is possible because the experimental distribution is symmetric and normal. The discrepancy between the observed and Monte Carlo errors is only 3.2 %. When using the "Flip-Flop Zeeman Measurement Technique", we have an important internal device possibility to control the presence or absence of significant stochastic or time-dependent spurious Stokes signatures, when pairs of exposures out of three, omitting the intermediate one, are used.
B). The presence of weak general magnetic field for 21 stars with vigorous convection (spectral types F9–M3 and luminosity classes I–V) is detected.
C). The variation of the general magnetic field as a function of stellar rotation is determined for two solar-like stars: ξ Boo A and 61 Cyg A.

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