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New stars with strong magnetic fields

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Abstract. During realization of the program of search for new magnetic stars at the 6 m telescope we managed to discover 6 stars with very strong magnetic fields with the longitudinal component stronger than 4 kG. Three of them, HD 45583, HD 178892 and HD 221936 have been studied in details.

1) The star HD 45583 has a complex field structure, the longitudinal magnetic field curve shows double–wave variations from −2 kG to +4 kG. Modeling of the curve predicts the surface magnetic field value up to 20–30 kG.

2) HD 178892 shows one of the strongest dipolar magnetic fields among cool CP stars with the longitudinal component up to +7 kG and the surface magnetic field value $B_s = 17.5$ kG. The magnetic field configuration can be represented as a dipole with the dipolar strength $B_d = 23$ kG.

3) Clearly observed Zeeman splitting of some lines in the spectrum of HD 221936 indicates a surface magnetic field with the value of 25–30 kG. At the same time the longitudinal component varies from −2.5 kG to +2.5 kG. There are some reasons to believe that the field of this star may have a complex structure.

1 Introduction

Since 2000, a program of searching for magnetic chemically peculiar stars has been carried out with the 6 m telescope of the Special Astrophysical Observatory. The basic results of this research are presented in the paper by Kudryavtsev et al. (2006). The urgency of this work is conditioned by a relatively small number of known CP stars and by the emerged possibility of measuring magnetic fields by direct methods in noticeably fainter objects than it was possible earlier. Further investigations of detected objects are capable to provide new data useful for the development of such the active directions of modern astrophysics as the researches of chemically peculiar stars and physics of stellar atmospheres.

In this paper, we would like to consider in more details a few stars with extremely strong magnetic fields discovered in the course of realization of our program. These objects are certainly most outstanding of all the list of new magnetic stars. For this reason, their further, more careful investigation is necessary. We have started additional observations of stars with extremely large magnetic fields with spectrographs of moderate ($R = 15000$) and high ($R = 50000$) resolution. The first results of these observations will be presented in this paper.

2 Observations

The observations were performed with two spectrographs: the Main stellar spectrograph (MSS) with moderate resolution and the high-resolution Nasmyth echelle spectrograph (NES) (Panchuk et al. 2002) of the 6 m telescope.

Table 1: Stars with strong magnetic fields

Star	m_V	Pec	B_e extrema	Cluster
HD 45583	8.0	Si	$-2000/+4000$	NGC 2232
HD 178892	8.9	SrCrEu	$+2000/+7000$	
HD 221936	9.2	Si	$-2500/+2500$	Stock 12
HD 258686	9.7	Si	$+5000/+6500$	Collinder 95
HD 293764	9.5	SrCrEu	$+3000/+4200$	
HD 343872	9.9	Si	$-750/+4600$	
HD 349321	9.3	Si	$-4500/+2000$	

Using of moderate resolution allows one to make spectropolarimetric measurements for relatively faint objects with the least time losses. For this purpose a circular polarization analyzer with a double image slicer and a rotated $\lambda/4$ plate (Chountonov 2004) was mounted in the slit part of the spectrograph. The applied image slicer has a diaphragm of about $5''$, cutting the incoming beam into 7 slices for each polarization, which makes it possible to perform observations most effectively even with bad seeings. Two spectra were observed at a different orientation of the $\lambda/4$ plate for every measurement of the longitudinal magnetic field, which allows for compensation of the influence of instrumental effects during subsequent reduction.

The observations with the MSS were performed in a wavelength region of 4400–4600 Å, which is rich of metal lines, mostly Fe and Cr, which allows performing the longitudinal magnetic field measurements with the highest possible accuracy. The procedure of the measuring is described in more details in the paper by Kudryavtsev et al. (2006). The measurements were performed with the code of Kudryavtsev (2000).

High resolution observations are being carried out with the NES spectrograph of the 6 m telescope. The spectropolarimetric technique, however, is not applied here, because most of new magnetic stars are too faint for spectropolarimetry with high S/N ratio. In observations with the NES spectrograph we use a standard configuration of a spectrograph with an image slicer, cutting the incoming beam into three slices. The wavelength range is 4700–6100 Å. Most of the high-resolution spectra observed with the NES still require reduction and analyzing. Here we present only some results concerning the star HD 178892.

3 Results

During realization of our program, we succeeded in detection of 6 stars showing the value of the longitudinal magnetic field of more than 4 kG. The general information about these objects is presented in Table 1. The star HD 221936 is also included in the Table. In spite of the normal strength of the longitudinal component (about 2.5 kG), an analysis of spectra allows suspecting that the star has a very strong surface magnetic field, that will be discussed below. Table1 shows the stellar magnitude, peculiarity type, extrema of the longitudinal magnetic field, and membership in open clusters. It should be noted that for majority of stars the number of magnetic field measurements is not sufficient and does not cover the whole rotation period of the star. For this reason, the real extrema of the longitudinal magnetic field may be larger in some cases.

For most of stars presented in the Table, the observational data have already been published in the paper by Kudryavtsev et al. (2006). In this paper we discuss new data obtained for the stars HD 45583 and HD 178892. In addition, we have found the magnetic CP star HD 221936, the magnetic field measurements for which are presents for the first time.

Table 2: Longitudinal magnetic field measurements for HD 45583

JD 2450000+	$B_e \pm \sigma$	S/N ratio
3273.550	$+3060 \pm 770$	240
3274.581	$+3850 \pm 510$	190
3275.570	-1650 ± 860	150
3363.401	$+3780 \pm 590$	300
3364.323	$+2010 \pm 320$	270
3365.493	$+2130 \pm 330$	370
3667.600	$+1950 \pm 280$	350
3717.560	$+2690 \pm 500$	260
3717.572	$+3560 \pm 340$	250
3718.332	$+3450 \pm 230$	570
3718.515	$+1920 \pm 470$	520
3719.394	$+1330 \pm 420$	270
3784.416	$+2570 \pm 350$	320
3786.285	-2140 ± 310	410
3786.417	-80 ± 400	290

3.1 HD 45583

The star is a member of the open cluster NGC 2232 with an estimated age of 30 Myr. The longitudinal magnetic field B_e reaches 4 kG, a partial Zeeman splitting of lines is observed in the spectrum. Kudryavtsev et al. (2006) have suspected that the star has a non-sinusoidal curve of B_e variations, that points to the presence of a complex non-dipole magnetic field in the star. The number of measurements, however, was not sufficient for a definite conclusion.

We continued observations of this star. Table 2 presents the magnetic field measurements obtained earlier and the new ones.

The rotation period (P = 1.177177 days) of the star was estimated by North (1987) from the photometric variability. The variability curve of B_e that we constructed from our measurements with the period reported by North (1987), is shown in Fig. 1. The curve is explicitly double-wave. Thus, we can assert that we have found a star with essentially non-dipole structure of the global magnetic field.

Using the curve of B_e measurements, we made an attempt to simulate the magnetic field configuration at the surface with the program FLDCURV, written by J. D. Landstreet. In the simplest case the curve can be drown under the assumption that the field structure is a combination of a strongly non-central dipole and an octupole component coaxial with the dipole. We have derived two resembling models which describe the observed curve in an approximately similar manner:

1. $i = 50^\circ$, $\beta = 130^\circ$, $B_d = -17500$ G, $a = 0.59$, $B_{oct} = -35000$ G
2. $i = 40^\circ$, $\beta = 120^\circ$, $B_d = -17000$ G, $a = 0.61$, $B_{oct} = -45000$ G

Here i is the tilt angle of the rotational axis to the line of sight, β is the tilt angle of the magnetic axis to the axis of rotation, B_d is the magnitude of the dipolar component, a is the shift of the dipole expressed in the fractions of the star's radius, B_{oct} is the strength of the octupole component.

The surface magnetic field of the star predicted by models must vary within 20–30 kG depending on the rotation phase. The figure 2 shows a part of a spectrum of the star in left and right circular

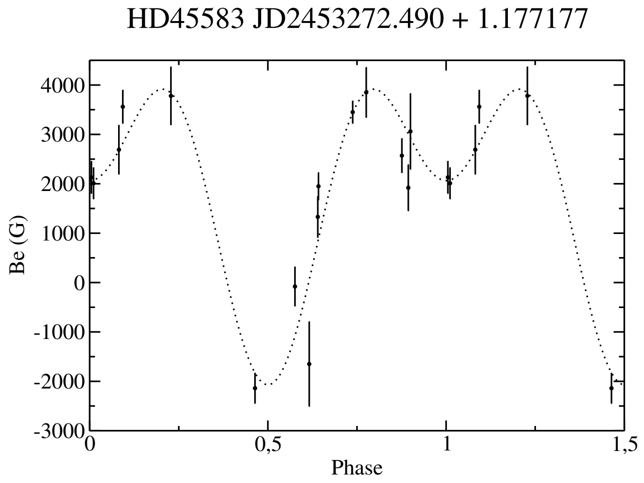

Figure 1: The longitudinal magnetic field variations of HD 45583 with rotation period, calculated by North (1987).

polarizations obtained simultaneously. It can be clearly seen that spectra in different polarizations are considerably different, there are signs of the partial Zeeman splitting. Such effects may only be caused by the presence of a strong magnetic field, sufficient to become apparent against rather rapid rotation of the star, $v \sin i = 75\, km/s$ (Uesugi & Fukuda 1981), which considerably broadens spectral line profiles.

Using the derived model of the magnetic field, we have made an attempt to calculate a synthetic spectrum using the programm ZEEMAN2, written by J. D. Landstreet. Fig. 3 shows the result of modeling of one region in the spectra of Stokes I and V parameters. The model was calculated for the temperature $T_e = 13000$ K. The spectral line profiles (Stokes I) are fitted rather well. A preliminary very rough estimate of the chemical composition shows the abundances Fe: -3.7, Ti: -5.8, Cr: -4.8, Si: -2.6. At the same time it is evident that the Stokes parameter V is not described by the suggested model.

Summing up, it can be noted that we have found a star with a strong magnetic field of complex structure. However, the configuration of the magnetic field is still open to question. Most likely, an accurate description of the magnetic field structure can only be made by the method of Doppler-Zeeman imaging.

3.2 HD 178892

Results of our observation of HD 178892 were presented in paper by Ryabchikova et al. (2006), therefore now we only repeat shortly previously published data.

HD 178892 shows the largest value of the longitudinal magnetic field, which reaches the value of 7 kG. It is very interesting that the star has SrCrEu peculiarity type while such the extremely strong magnetic fields were found previously only in hotter Si type stars, for exception of cool SrCrEu star HD 154708 (Hubrig et al. 2005) with $T_e = 6800$ K and longitudinal field about 7.5 kG. Thus HD 178892 and HD 154708 are very unusual objects and more detailed study of them is needed.

We have made a series of spectropolarimetric observations of HD 178892 allowing the rotation period of the star to be determined and a curve of the longitudinal magnetic field B_e variations to be plotted. Afterwards, in the paper by Ryabchikova et al. (2006) the period was refined by using photometric data. The curve of the B_e variations with this period, $P = 8\overset{d}{.}2478$, is presented in Fig. 4.

We have also obtained several spectra with the NES spectrograph of the 6 m telescope

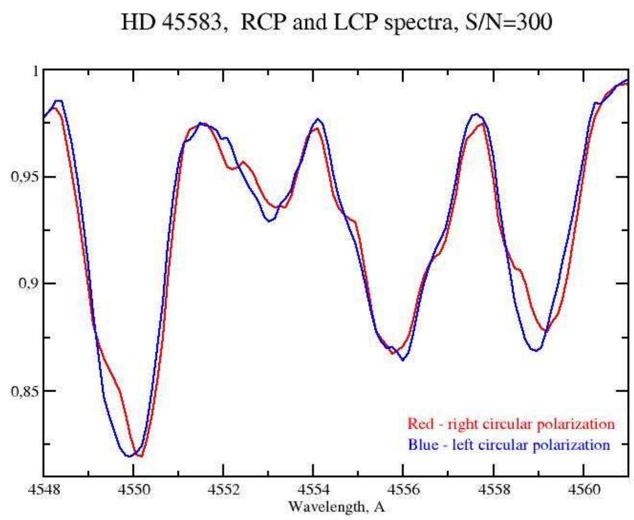

Figure 2: A spectrum of HD 45583. Red line — right circular polarization, blue line — left circular polarization.

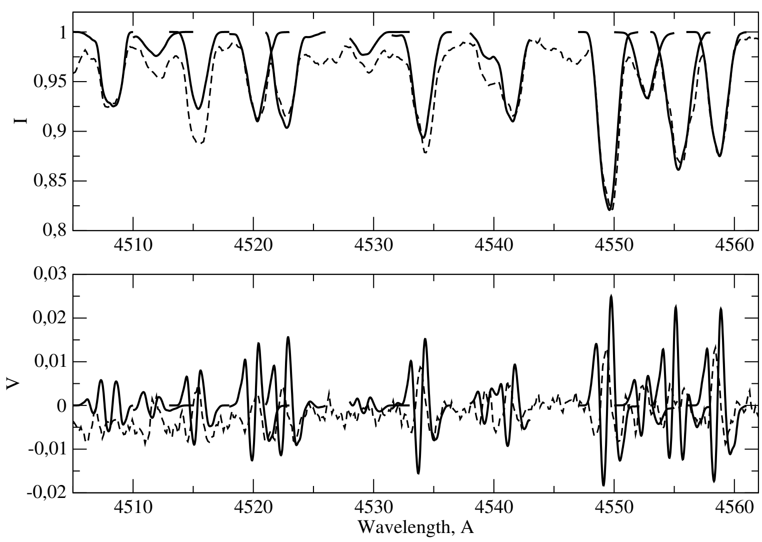

Figure 3: Stokes I and V spectra for HD 45583. Dashed line — observed spectra. Solid line — synthetic spectra calculated with the dipole+octupole magnetic field model, derived from the longitudinal magnetic field curve.

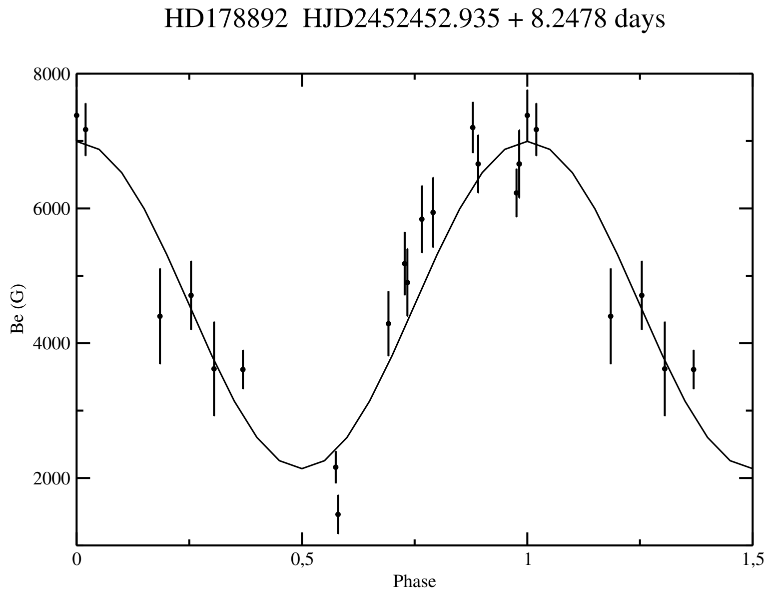

Figure 4: The longitudinal magnetic field variations of HD 178892 with rotation period.

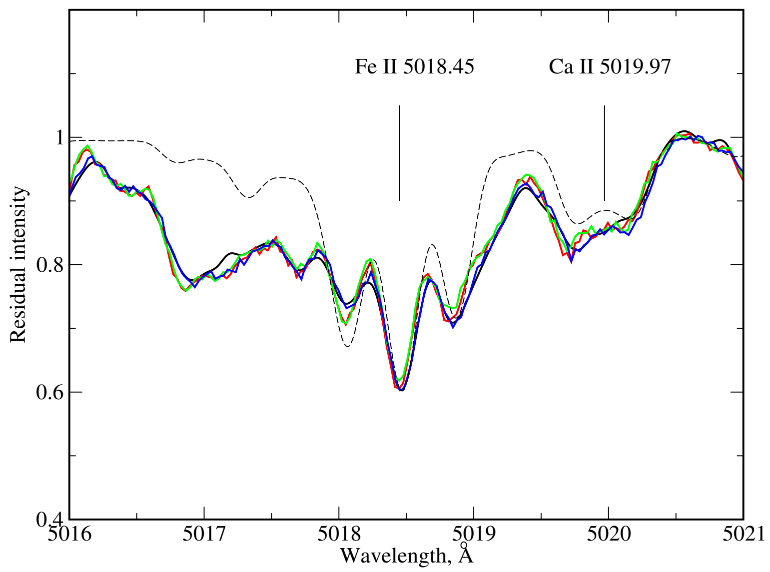

Figure 5: The Zeeman splitting of Fe II λ5018.45 Å line in the NES spectra.

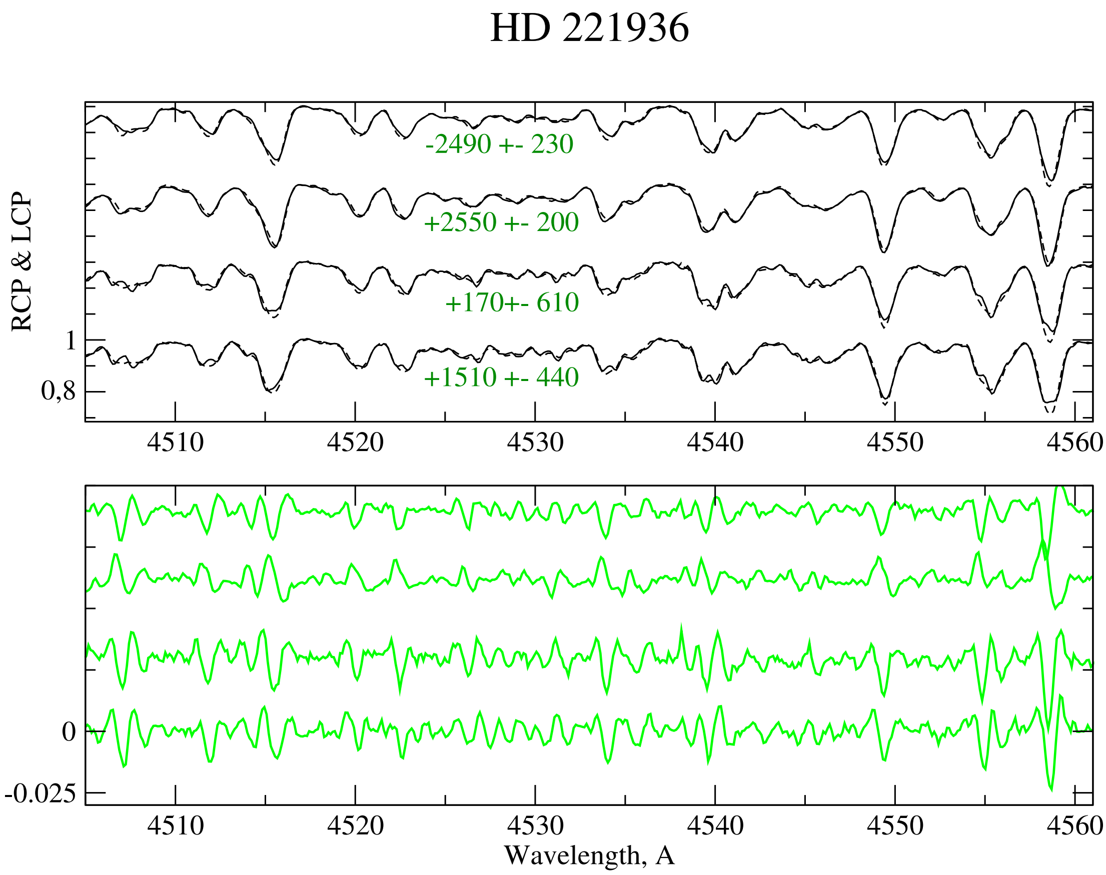

Figure 6: Top: the Zeeman splitting in polarized spectra of HD 221936, solid line — left circular polarization, dashed line — right circular polarization; bottom: Stokes V parameter for the same spectra.

(Panchuk et al. 2002) with a spectral resolution $R = 40000$. These spectra clearly show the Zeeman splitting of spectral lines (Fig 5). By the results of modeling of spectra presented in paper by Ryabchikova et al. (2006), the surface magnetic field has been estimated as $B_s = 17.5$ kG. Estimates of the chemical composition and parameters of the star have also been obtained: $T_e = 7700$ K, $\lg g = 4.0$, $v \sin i = 9$ km/s.

The model of the star's magnetic field has been obtained using both the curve of longitudinal magnetic field variations and measured B_s values: $i = 36°$, $\beta = 37°$, $B_d = 23000$ G.

3.3 HD 221936 (V 629 Cas)

For HD 221936 we have obtained the first data giving an evidence that the star has an extremely strong surface magnetic field. The star is rather faint ($m_V = 9.29$) and poorly studied. The type of peculiarity is Si. The star is a member of the open cluster Stock 12. According to the database WEBDA, the age of the cluster is about 280 million years.

We have obtained four spectra of the star showing usual values of the longitudinal magnetic field varying from -2.5 kG to $+2.5$ kG. However, in Zeeman spectra one can clearly see a Zeeman splitting whose value corresponds to a strong surface magnetic field of about 25–30 kG.

The upper part of Fig. 6 shows the Zeeman spectra in the right (dashed line) and left (solid line) circular polarizations. The presented spectra have rather high quality, the S/N ratio is over 300. In the left circularly polarized spectra at two phases the Zeeman splitting of lines is clearly observable.

The lower part of the figure shows the corresponding spectra of the Stokes V parameter reaching the value of about 2.5%. Thus, one can state with confidence that a strong surface magnetic field is present in the star. However, it should be noted that the effect of splitting with the given spectral resolution ($R \sim 15000$) will be noticeable only in polarized spectra, a usual spectrum will show no splitting.

$v \sin i$ of the star does not exceed 60 km/s. Panov & Schoeneich (1976) determined the rotation period of the star from light variations as $P = 0.63195$. If the period is correct, then with a typical for CP stars radius of $2 - 3R_{\odot}$ and the observed $v \sin i$, the angle i must be not larger than 20–25°. At the same time, the longitudinal magnetic field of the star shows a variation of polarity, the variation being rather fast (no more than 24 hours), which confirms the fast rotation of the star.

A relatively small longitudinal magnetic field combined with a strong surface field and, at the same time, changing polarity allow one to make an assumption that the star has a magnetic field of complex structure. Observation of HD 221936 will be continued.

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